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CPSL 2023

28th February 2023 – 2nd March 2023
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Dr.-Ing. David Herberger
M. Sc. Marco Hübner
Prof. Dr.-Ing. Volker Stich

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Senator-Burda-Straße 31a,
77654 Offenburg
Germany

E-mail: info@cpsl-conference.com
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Foreword

We are delighted to present the proceedings of the fourth Conference on Production Systems and Logistics (CPSL 2023 - 1), held at the esteemed campus of Tecnológico de Monterrey (Tec de Monterrey) in Querétaro, Mexico. This unique edition of the conference was organized in close collaboration with the FIR of RWTH Aachen and was held in conjunction with the E-Mas Conference, together forming the Congress I4R – Innovation for Realization.

The collaboration between CPSL, FIR, and the E-Mas Conference has cultivated a synergistic atmosphere that stimulated the sharing of innovative ideas and solutions among specialists, researchers, and professionals in production systems and logistics. This collaborative effort has significantly enriched the conference experience and expanded the horizons of all attendees, which is in line with the intentions of the CPSL to create a platform for young scientists to network and exchange ideas – a place to discuss groundbreaking research findings and share perspectives on current topics with like-minded individuals.

This year's joint format with the E-Mas made it possible that we could welcome over 250 participants to our event in Mexico, where we enjoyed a memorable conference at Tec de Monterrey. We are very proud that the CPSL has grown to a conference committee of 28 contributing research institutions making it possible to publish 91 papers in its fourth edition with 94 hosted scientific presentations.

We extend our deepest gratitude to all partners who made this conference possible. Special thanks go to Tecnológico de Monterrey and FIR of the RWTH Aachen, whose invaluable contributions were essential for the event's organization. We also appreciate the reviewers who participated in the rigorous yet supportive review process, and our keynote speakers for their captivating and inspiring presentations. Lastly, we thank all participants and fellow researchers who generously shared their research knowledge and experiences, making CPSL a remarkable event.

We eagerly anticipate welcoming you again at CPSL 2023 - 2 in Stellenbosch, South Africa, from November 14th to 17th, 2023.

Dr.-Ing. David Herberger
Conference Chair

M. Sc. Marco Hübner
Conference Chair

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Review Process

The Conference on Production Systems and Logistics (CPSL) is an international forum for the scientific exchange on current findings in the field of production engineering.

For the submission of a paper, an abstract had to be uploaded considering the following main topics:

- Automation
- Business Administration
- Digitalization & Industry 4.0
- Factory Planning
- Knowledge Management
- Lean Manufacturing
- Machine Learning & Data Mining
- Production Planning & Control
- Process Management
- Supply Chain Management
- Sustainability
- Technology Driver

The submitted abstracts were evaluated in an internal review process, whereby successful submissions were invited to upload a full paper. Full papers had to adhere to a specific template and format provided on the CPSL website.

The submitted full papers were reviewed in a two-stage peer review process by experienced scientists from renowned research institutions as well as authors of other submitted papers. This process ensures a constant and high quality as well as the influence of all participants on the papers and reviews. Consequently, each paper submitted was sent to at least two reviewers, with a third reviewer being requested in case of non-consensus between the first two reviewers, if applicable.

The reviewers were asked to review the submitted papers on the basis of a provided evaluation template and were encouraged to give detailed comments and suggestions for improvement. Among others, the following key questions were considered:

- Does the title reflect the contents of the paper?
- How do you rate the comprehensibility and logical presentation of the paper?
- How do you assess the relevance and originality of the topic described?
- How do you assess the practical relevance of the paper?
- Do you consider the work a proof of a thorough research and knowledge of the latest literature in the field of research?
- Are the conclusions clear and valid?

After completion of the reviews, all authors were given sufficient time to improve their papers according to the remarks of the reviewers. All papers that received major remarks in the first review loop were reviewed again in a second review loop and were also accepted, provided that the remarks were conscientiously incorporated.
For more information on the review process and the “Publication Ethics and Publication Malpractice Statement” please visit the conference website.

Acknowledgements

Our sincere thanks goes to our outstanding supporters who made this great event possible.

Publishing

Scientific Societies

Hosting and Organization

Reviews & Scientific Support

Keynote Speakers 2023

A special THANK YOU goes to our outstanding Keynote speakers, who joined the conference onsite or online and inspired our participants beyond their presentations with cutting-edge and highly interesting topics

Digitalization in Business and Society – The New Normal

Prof. Dr.-Ing. Volker Stich

Managing Director of FIR at RWTH Aachen &
Director of Cluster Smart Logistic

Digitalization has started to change our lifes, behaviours, ways of communication and social interactions. Sometimes we are aware of these changes, sometimes not, because it is a gradual process, but with exponentional speed. The presentation tries to highlight, what has happenend already and what could be the future of „New Normal"

Sustainable Manufacturing for Circular Economy

Prof. Ibrahim S. Jawahir, Ph.D.

Professor and James F. Hardymon Chair in Manufacturing Systems & Director of Institute for Sustainable Manufacturing at the University of Kentucky

New opportunities for sustainable value creation in all involved technological elements of Circular Economy (CE) through Sustainable Manufacturing (SM) principles will be presented. A systematic metrics-based approach for new product/process development for sustainable manufacturing including the 6Rs (Reduce, Reuse, Recycle, Recover, Redesign and Remanufacture) with closed-loop total life cycle (Pre-manufacturing, Manufacturing, Use and Post-use) considerations to facilitate SM will be presented. Sustainable value creation in closed-loop SM will be shown as the basis for achieving and advancing CE, with digital technologies to serve all stakeholders (manufacturers, users, and the society at large).

Keynote Speakers 2023

A special THANK YOU goes to our outstanding Keynote speakers, who joined the conference onsite or online and inspired our participants beyond their presentations with cutting-edge and highly interesting topics

Digital Leadership to Master the Twin-Transition

Prof. Dr. Paul Mugge & Dr. Haroon Abbu

Business Analytics Initiative, Poole College of Management, North Carolina State University, Raleigh, USA

Dr. Gerhard Gudergan & Gerrit Hoeborn

FIR at RWTH Aachen University

Hardly any other question is currently occupying corporate executives more than the question of how you can lead your company into a completely new future against the backdrop of globally recognized climate targets and the potentials of digital transformation. The associated challenges summarized under the title of so-called twin Transition are occupying companies with the highest intensity and at a rapid pace. While some companies are achieving trailblazer status, others are finding it difficult to change and therefore lag behind. Digitization is considered a key factor in this context: It can be used to develop data-based, new business models and thus reshape entire value chains - and this will make it possible to realize concepts such as the circular economy. Digital leaders play a pivotal role in this transition because they can increase the confidence of their organizations behind often risky and disruptive initiatives needed to achieve the change. Thus, building trust in the entire organization is becoming a key element. Before this background, it is not enough to adapt existing leadership concepts; a completely new understanding of leadership must be implemented in many areas.

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CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
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4th Conference on Production Systems and Logistics

An Expert System-Based Approach For Improving Energy Efficiency Of Chamber Cleaning Machines

Borys Ioshchikhes*, Ghada Elserafi, Matthias Weigold
*Technical University of Darmstadt, Institute of Production Management, Technology and Machine Tools (PTW), Otto-Berndt Str. 2, 64287 Darmstadt, Germany

Abstract

Increased transparency and domain expertise are often prerequisites for identifying energy savings potentials and improving energy efficiency in manufacturing systems. Small and medium-sized enterprises pursuing a reduction in CO_2 emissions are especially faced with challenges from the complexity of process data and limited domain expertise. Against this background, this paper presents an expert system for preliminary energy diagnostics using automated energy analysis of production machines and providing measures for improving energy efficiency. Due to their significant energy consumption and increasing importance along various process chains, the use case is developed for chamber cleaning machines. A knowledge base is combined with artificial intelligence techniques for data processing to reveal efficiency potentials based on machine load profiles. The knowledge base created by experts assigns domain-specific information to the automatically processed input data. Key performance indicators are then utilized for internal and external benchmarking and quantification of energy potential, narrowing down promising energy efficiency measures. The suitability of the proposed approach is demonstrated by applying the expert system to two different chamber cleaning machines.

Keywords

sustainable manufacturing; artificial intelligence; energy analysis; parts cleaning; knowledge management

1. Introduction

With rising energy costs and increasing pressure towards production sites to reduce carbon dioxide emissions, the industry sector is faced with the challenge of introducing measures for a more sustainable production, while keeping up with consumer demand and maintaining process quality [1]. Combined with a lack of knowledge surrounding process factors influencing the resource efficiency of production processes, operators often struggle with allocating and exploiting efficiency potentials [2]. Against the backdrop of German industrial energy consumption, where process heat represented around two thirds of final energy consumption in 2020 [3], process heat applications such as industrial cleaning machines harbor a variety of energy and resource savings potentials [4].

Meanwhile, the metal-working industry has been seeing a steady rise in the importance of parts cleaning along various process chains. Specifically, this process is often crucial for downstream processes, such as coating or joining, as well as lifetime and performance of the treated parts [5]. Hence, rising quality requirements – especially within the automobile industry – push manufacturers and users towards optimizing the parts cleaning process [6]. This is reflected in the acknowledgement of parts cleaning processes as elementary processes in their respective value chains [7].

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To contribute to tackling the mentioned challenges while focusing on energy consumption, we present an expert system-based approach for detecting energy saving potentials in the operation of industrial chamber cleaning machines. The approach aims to increase transparency by employing machine learning (ML) algorithms in identifying machine processes based on the machine's load profile and deducting suitable energy efficiency measures to present to the user.

The following work starts with an introduction to chamber cleaning machines and expert systems including the structure of the developed approach in section 2. Section 3 focuses on the implementation of the expert system and its individual components, while the specific use case and the corresponding expert system performance are subsequently presented and discussed in section 4. Finally, a conclusion is drawn and the outlook is considered in section 5.

2. Background

The following section provides an introduction to the fundamentals of chamber cleaning machines in subsection 2.1 and expert systems in subsection 2.2.

2.1 Chamber cleaning machines

According to DIN 8592, parts cleaning is described as the process of removing unwanted substances, i.e., soils, from the surface of parts up to a certain degree. The cleaning task can be carried out by a variety of cleaning techniques. [8]

Based on a survey conducted in 2020, aqueous parts cleaning processes are by far the most common in the German industry. Aqueous parts cleaning is most often performed in chamber cleaning machines, making them the most significant type of parts cleaning machine in terms of representativity and total energy savings potential in German industry. [7] Hence, the examined use case focuses on single chamber cleaning machines for spray cleaning. The corresponding process steps and most important machine components are presented in the following subsections.

2.1.1 Process steps

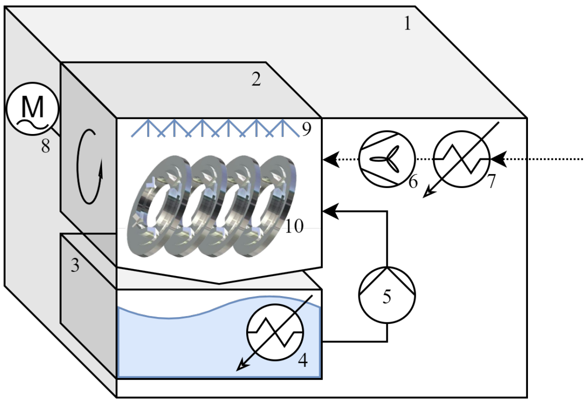
The parts cleaning process comprises of three main process steps: cleaning, rinsing (optional) and drying. Depending on the cleaning task, these steps may vary in length and repetition or include further intermediate steps, such as dripping or process pauses. [5]

The cleaning step aims to separate the soils from the surface of the parts. In aqueous cleaning, this task is conducted by a cleaning liquid containing an aqueous cleaning agent at a certain concentration. The type and concentration of the cleaning agent are manually chosen based on the cleaning task. The cleaning agent requires a certain temperature range to be effective in soil-removal. Furthermore, in the case of spray cleaning, the cleaning liquid is ejected at an elevated pressure through spray nozzles onto the part's surface to mechanically remove the soil. Additional movement of the cleaning basket or nozzle frame (e. g. rotation) further supports soil removal through mechanical action. The rinsing step is sometimes required to flush the parts from the soil-saturated cleaning liquid to ensure this does not subsequently cause unwanted residue on the part's surface. Rinsing usually operates at a similar temperature as cleaning and only varies in the soil-saturation and cleaning agent concentration of the liquid. Finally, the drying step is required to remove the cleaning or rinsing liquid from the parts surface to avoid corrosion of the metal part or enable following critical production processes. Drying can be performed evaporatively or non-evaporatively and is most often based on convection through blow-down with pressurized air or hot air. [5]

The following use case focuses on single-tank cleaning machines, which rely on just the cleaning and drying steps, eliminating the rinsing step. Furthermore, since chamber cleaning machines operate batch-wise, they must be loaded with soiled parts before the cleaning process and unloaded afterwards, adding one more process step to the machine process.

2.1.2 Components

Based on the considered use cases, we present the most important components of chamber cleaning machines as illustrated in Figure 1. As the name suggests, single-tank chamber machines (1) are mainly comprised of a treatment chamber (2) and one media tank (3). The treatment chamber carries the cleaning basket, which is loaded with soiled parts (10) before the cleaning process. To improve mechanical action supporting soil removal during the cleaning process, the cleaning basket is fitted with an electric motor (8) to effect relative movement between the parts and the spray nozzles (9). During the cleaning step, the spray nozzle system is supplied with cleaning liquid from the media tank with the help of an electrically driven spray pump (5). An electric tank heater (4) is installed in the media tank to maintain the temperature range required by the cleaning task. After the cleaning step, the parts are dried convectively via hot air supplied by the electrically driven drying fan (6), which passes ambient air through the electrical drying air heater (7) and into the treatment chamber.



1 Chamber cleaning machine
2 Treatment chamber
3 Media tank
4 Tank heater
5 Spray pump
6 Drying fan
7 Drying air heater
8 Basket motor
9 Spray nozzles
10 Parts

Figure 1: Chamber cleaning machine schematic with most important components

2.2 Expert system

Expert systems are a subfield of artificial intelligence with the objective of solving complex problems and providing the decision-making ability of a human expert in a particular domain [9]. The basic idea of an expert system is to represent the knowledge of experts in a computer system, aggregate it and make it available to support other users in their tasks and reduce their workload [10].

Figure 2 presents the overall architecture of the developed expert system. Electrical load profiles and the human expert provide the expert system with input information. The electrical load profiles are acquired for each analyzed machine by measuring the active power consumption at the main power supply, whereas the knowledge base must be defined only initially by the human expert and is applicable to all considered machines. The knowledge base contains all information and facts that makes an expert abundantly knowledgeable in their fields. The inference engine combines the problem-related expert knowledge with the measurement data of the analyzed entity and generates conclusions. [11] The explanation component presents the conclusions to the user via an interface and explains how or why the expert system arrived at a particular solution [10].

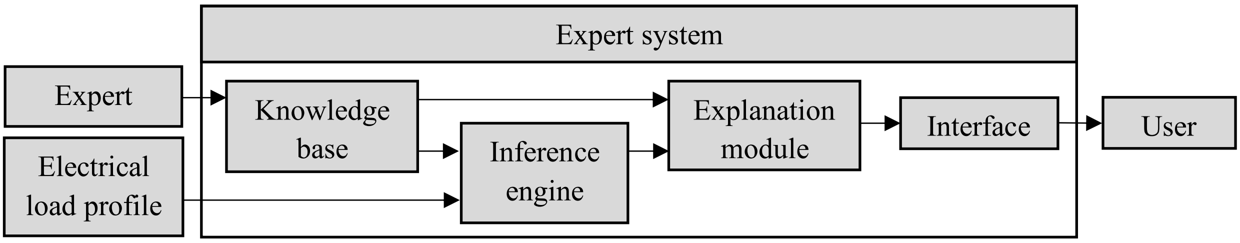


Figure 2: Expert system architecture

3. Implementation

Various methods exist for implementing the architectural features of an expert system. Since the interface is of minor importance for the proof of concept, it is implemented as a text-based output with a graph. The following section describes the other features in more detail that are implemented in Python.

3.1 Knowledge base

The knowledge base defined by the expert contains expertise as machine-readable data structures and is divided into two segments. Both segments are implemented as lookup tables. The first segment shown in Table 1 provides facts about the production process, for which the load profile is shown in Figure 3. As explained in section 2.1, parts cleaning consists of several consecutive steps. The cleaning machines investigated in the following use case operate with one media tank for the cleaning liquid, omitting the rinsing step. This leaves the processes with cleaning, drying and loading steps. The process steps are listed together with their respective identification numbers (ID) in Table 1. Other unspecified events, such as pauses between the steps, are expressed as other.

Table 1: Knowledge base for the production process of chamber cleaning machines

Process ID	Designation	Description
0	Clean	Remove soil from parts' surface (spray cleaning)
1	Dry	Remove cleaning liquid from parts' surface (hot air)
2	Load	Load/Unload parts in treatment chamber
3	Other	Unspecified events

The second segment, shown in Table 2, presents a knowledge base for improving energy efficiency by mapping energy efficiency measures to machine-readable rules. These are based on the duration $t_{i,j}$ of each identified iteration $j = 0, \dots, k_i$ of each process step i (see Figure 3). The knowledge base relates to time-based measures, as these have promising savings potential and can be easily identified and implemented.

Table 2: Knowledge base for improving energy efficiency of chamber cleaning machines

Energy efficiency measure	KPI	Rules
Minimize clean time	$t_{0,j}$	IF $t_{0,j} > \min\{t_{0,0}, .., t_{0,k_i}\}$ THEN reduce $t_{0,j}$
Minimize dry time	$t_{1,j}$	IF $t_{1,j} > \min\{t_{1,0}, .., t_{1,k_i}\}$ THEN reduce $t_{1,j}$
Minimize load time	$t_{2,j}$	IF $t_{2,j} > \min\{t_{2,0}, .., t_{2,k_i}\}$ THEN reduce $t_{2,j}$
Minimize other time	$t_{3,j}$	IF $t_{3,j} > \min\{t_{3,0}, .., t_{3,k_i}\}$ THEN reduce $t_{3,j}$

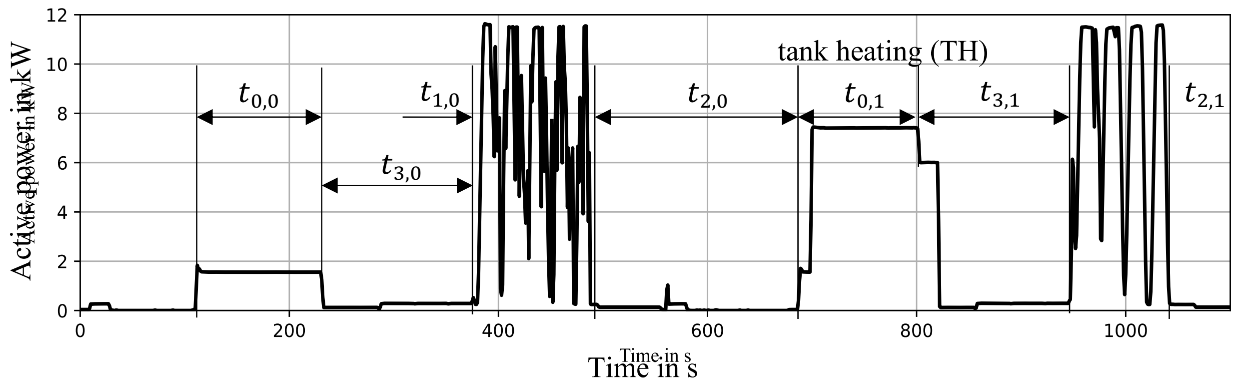


Figure 3: Visualization of a load profile with different machine processes

3.2 Inference engine

The inference engine derives promising energy efficiency measures based on electrical load profiles and knowledge. This corresponds to a typical forward chaining reasoning paradigm, as shown in Figure 4. Forward chaining from data to conclusions starts with a collection of knowledge and draws allowable conclusions [12]. In this instance, the input information is used to identify the production processes defined in Table 1. The identification of the production processes is achieved automatically by a trained ML model.

The development of the ML application for the identification of machine processes follows the Cross-Industry Standard Process for ML (CRISP-ML). CRISP-ML consists of six phases, starting from business and data understanding, which is also essential for the knowledge base and concluding with the long-term deployment of the ML model. [13] This paper focuses on the first four phases, with section 3.1 covering already the first phase, business and data understanding. The initial phase is followed by data preparation. In this phase, in accordance with [14], a supervised learning approach was pursued, using features based on a fixed window size. In the subsequent modeling several supervised algorithms, which are also considered in [14], are compared and the hyperparameters are optimized using grid search [15]. Being balanced datasets, where no machine process is vastly over- or under-represented, the results of the ML models are evaluated in the fourth phase based on the average accuracy using a 5-fold cross validation [16,17]. The Random Forest Classifier from the Python library scikit-learn [18] achieves the best results with 92.63 % for the identifiaction of unknown data of the same cleaning machine and with 90.79 % for the identifiaction of unknown data of a different cleaning machine.

Once the processes have been identified, the measurement data for each individual process is grouped into the corresponding timeslot $t_{i,j}$, as seen in Figure 3. Outliers are then processed by applying a median filter if the duration and energy demand of one timeslot deviates significantly compared to the majority of the residual timeslots of the same process. This also allows subsequent filtering of overlapping state-controlled processes, such as TH. Subsequently, energy key performance indicators (KPI) are calculated, enabling the derivation of promising energy efficiency measures on the one hand and the quantification of energy efficiency potentials and comprehensibility for the user on the other. The energy efficiency measures are mapped to the energy KPI in accordance with Table 2. The expert system prioritizes the energy efficiency measures based on the absolute energy savings potential.

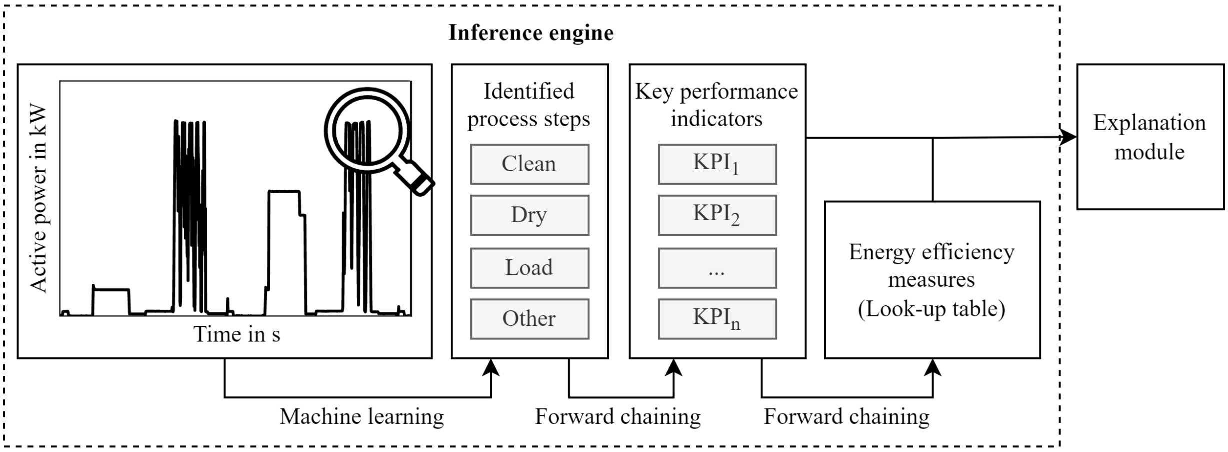


Figure 4: Inference engine architecture

3.3 Explanation module

To provide the user with an explainable presentation of concluded energy efficiency potentials and energy efficiency measures, energy KPI directly determined and calculated from the measurement data are used. For the implementation of the expert system basic KPI are first defined in Table 3, from which other energy KPI can be derived. The basic KPI include the sum of all durations $t_{i,total}$ for each process i, as well as the corresponding total energy consumption $E_{i,total}$. To later calculate the potential savings, the number of iterations k_i is also given for each process.

Table 3: KPI for the explanation module

KPI	Description	Unit
Cleaning time $t_{0,total}$	Total duration for cleaning	Second (s)
Drying time $t_{1,total}$	Total duration for drying	Second (s)
Loading time $t_{2,total}$	Total duration for (un-)loading the machine	Second (s)
Other time $t_{3,total}$	Total duration of other activities	Second (s)
Cleaning iterations k_0	Total iterations of cleaning steps	-
Drying iterations k_1	Total iterations of drying steps	-
Loading iterations k_2	Total iterations of loading steps	-
Other iterations k_3	Total iterations of other activities	-
Cleaning energy $E_{0,total}$	Total energy consumed while cleaning	Watt-hour (Wh)
Drying energy $E_{1,total}$	Total energy consumed while drying	Watt-hour (Wh)
Loading energy $E_{2,total}$	Total energy consumed while (un-)loading the machine	Watt-hour (Wh)
Other energy $E_{3,total}$	Total energy consumed during other activities	Watt-hour (Wh)

Further energy KPI are the potential relative time savings τ_i and the potential relative energy savings ε_i for each process i. These reflect the potential savings, when only the minimum time duration $t_{i,min}$ is applied to all iterations k_i of each process i, instead of the identified durations which result in the total duration. Potential time savings are the main driver of potential energy savings, since the efficiency measures recommended by the expert system are based on time. The potential relative savings, τ_i and ε_i, are calculated following equations (1) and (2):

$$\tau_i = \frac{t_{i,total} - k_i \cdot t_{i,min}}{t_{i,total}} \cdot 100\% \qquad \text{with } t_{i,min} = min\{t_{i,0}, .., t_{i,k_i}\} \tag{1}$$

$$\varepsilon_i = \frac{E_{i,total} - k_i \cdot E_{i,min}}{E_{i,total}} \cdot 100\% \qquad \text{with } E_{i,min} = min\{E_{i,0}, .., E_{i,k_i}\} \tag{2}$$

4. Use Case

The following subsections describe the experimental setup used for demonstration of the expert system and discuss the achieved results.

4.1 Experimental setup

To investigate the suitability of the approach, the expert system is applied to two batch cleaning machines at the ETA research factory at Technical University of Darmstadt, shown in Figure 5. For consideration of transferability of the expert system, machines of different manufacturers with varying constructive design were selected for the use case. The active power was measured for 3.5 hours at the main power supply of each cleaning machine, covering a number of at least 10 processing cycles. Wherein a process cycle includes a loading, cleaning, drying and unloading process. This ensures that the data set for training the ML model covers all processes in Table 1, even those that were not explicitly defined and may overlap with other processes, such as the TH. The electrical measurements were conducted as presented in [19] without interrupting the circuit.

(a) **(b)**

Figure 5: (a) BvL OceanRC 750 and (b) MAFAC KEA at the ETA Research Factory

4.2 Results

The measurement data of the BvL OceanRC 750 used for developing and training the ML model are shown in Figure 6 (a) and the classification results of the expert system implemented on the measurement data of MAFAC KEA are shown in Figure 6 (b). The graphical representation of the classification of the machine processes is also part of the explanation module and provides a basis for the comprehension of further results.

In addition to the graphical classification of the machine processes, the user is provided with the calculated energy KPI shown in Table 4. Furthermore, the expert system returns the corresponding energy efficiency measures in the same order as in Table 2.

Table 4: Results of the expert system for MAFAC KEA

KPI	value	KPI	value
$t_{0,total}$	8170 s	$E_{0,total}$	4.67 kWh
$t_{1,total}$	1260 s	$E_{1,total}$	1.18 kWh
$t_{2,total}$	2780 s	$E_{2,total}$	0.11 kWh
$t_{3,total}$	320 s	$E_{3,total}$	0.05 kWh
τ_0	6.36 %	ε_0	10.63 %
τ_1	7.14 %	ε_1	6.38 %
τ_2	82.73 %	ε_2	68.65 %
τ_3	6.25 %	ε_3	30.21 %

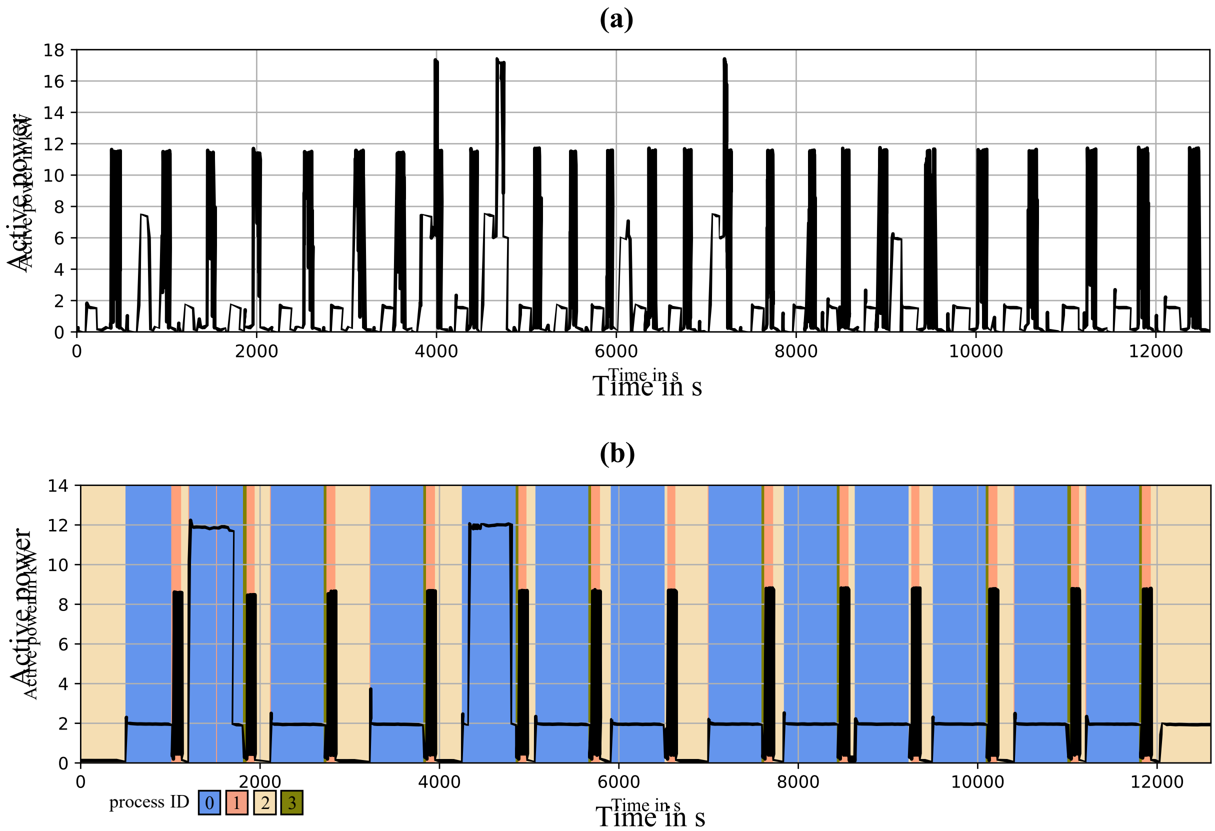


Figure 6: (a) Measurement data of BvL OceanRC 750 for training the ML model and (b) application of the expert system to measurement data of MAFAC KEA

4.3 Discussion

The expert system identifies energy saving potentials for each process and provides promising energy efficiency measures. For the presented use case, Table 4 shows that the cleaning process takes considerably longer, requires the most amount of energy and yields the highest potential absolute energy savings with 0,50 kWh. Therefore, the expert system first prioritizes to minimize the cleaning time. Significant energy savings potential is also found in the drying process with 0.08 kWh. Furthermore, due to the high potential relative time savings, the loading process shows potential energy savings of 0.08 kWh. In total, 11.02 % of energy could potentially be saved for the observation period and the production process could be shortened by 23.38 %.

The results shown in Table 4 support in determining an internal benchmark. However, energy KPI calculated by the expert system are archived, so that external benchmarks from other cleaning machines can also be applied. It should be taken into account that the maximum optimization potential relates to known processes, so it may be underestimated. Furthermore, the recommended energy efficiency measures only refer to the cleaning of parts with similar contamination and geometry. In case of deviations of the parts, batch size or strongly varying degrees of contamination, the required processes duration must be examined. The minimization of the loading time, however, is an exception where this does not have to be considered, as long as the number of parts or jigs remains the same.

5. Conclusion and outlook

This paper presents an expert system for improving the energy efficiency of chamber cleaning machines. For this purpose, a knowledge base consisting of process and energy efficiency knowledge was combined with an inference engine and an explanation module. The implementation of the expert system carried out with a BvL OceanRC 750 cleaning machine was applied to a MAFAC KEA cleaning machine. Thus, demonstrating the transferability of the expert system and the automated energy analysis with suggested energy efficiency measures. For the presented use case, the expert system identified potential energy savings of 11.02% and potential time savings of 23.38% that could be achieved by implementing time-based energy efficiency measures.

However, the expert system has its limitations in the knowledge base, the accuracy of the ML model and the defined energy KPI. Therefore, future developments will cover an extension of the knowledge base to include information regarding parts geometry, contamination, production-specific requirements and non-time-based energy efficiency measures. Furthermore, additional KPI for evaluating energy requirements and process performance can be defined. Lastly, improvements in the performance of the ML model can be achieved and the transferability of the expert system increased by extending it to other production machines.

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References

[1] Thiede, S., 2012. Energy efficiency in manufacturing systems. Springer, Berlin, New York, 1 online resource (xxii, 198).

[2] Angerer, K., Hohmann, A., Seifert, V., Tammer, C., 2019. Ökologische und ökonomische Bewertung des Ressourcenaufwands: Reinigungstechnologien in der industriellen Produktion. VDI Zentrum Ressourceneffizienz, Berlin.

[3] Buttermann, H.G., Maaßen, U., 2021. Anwendungsbilanzen zur Energiebilanz Deutschland: Endenergieverbrauch nach Energieträgern und Anwendungszwecken. Detaillierte Anwendungsbilanzen der Endenergiesektoren für 2019 und 2020 sowie. Arbeitsgemeinschaft Energiebilanzen e.V., pp. 40. https://ag-energiebilanzen.de/wp-content/uploads/2020/10/ageb_20v_v1.pdf. Accessed 29 September 2022.

[4] Blesl, M., Kessler, A., 2021. Energy efficiency in industry. Springer, Berlin, Germany, 1 online resource (1 volume).

[5] Durkee, J.B., 2006. Management of industrial cleaning processes. Elsevier, Oxford, pages cm.

[6] Koblenzer, G., 2016. Trends in der Automobil-Teilereinigung. J Oberfl Techn 56 (9), 74–76.

[7] Rögner, F.-H., Pfeilschifter, M., 2021. Market and Trend Analysis in Industrial Parts Cleaning. Fraunhofer Business Area Cleaning (FEP), Dresden.

[8] Deutsches Institut für Normung e.V., 2003. Fertigungsverfahren Reinigen: Einordnung, Unterteilung, Begriffe.

[9] Jackson, P., 1998. Introduction to expert systems, 3rd ed. Addison-Wesley Longman Publishing Co., Inc., Boston.

[10] Schäfer, K.F., 2020. Netzberechnung: Verfahren zur Berechnung elektrischer Energieversorgungsnetze. Springer Vieweg, Wiesbaden, pp. 623

[11] Ogidan, E.T., Dimililer, K., Ever, Y.K., 2018. Machine Learning for Expert Systems in Data Analysis, in: 2018 2nd International Symposium on Multidisciplinary Studies and Innovative Technologies (ISMSIT). 2018 2nd International Symposium on Multidisciplinary Studies and Innovative Technologies (ISMSIT), Ankara. 19.10.2018 - 21.10.2018. IEEE, pp. 1–5.

[12] Buchanan, B.G., Smith, R.G., 1988. Fundamentals of Expert Systems. Annual Review of Computer Science 3 (1), 23–58.

[13] Studer, S., Bui, B., Drescher, C., Hanuschkin, A., Winkler, L., Peters, S., Müller, K.-R., 2021. Towards CRISP-ML(Q): A Machine Learning Process Model with Quality Assurance Methodology. Machine Learning and Knowledge Extraction 3, 392–413.

[14] Petruschke, L., Elserafi, G., Ioshchikhes, B., Weigold, M., 2021. Machine learning based identification of energy efficiency measures for machine tools using load profiles and machine specific meta data. MM SJ 2021 (5), 5061–5068.

[15] Müller, A.C., Guido, S., 2016. Introduction to Machine Learning with Python: A Guide for Data Scientists. O'Reilly Media, Inc.

[16] Grandini, M., Bagli, E., Visani, G., 2020. Metrics for Multi-Class Classification: an Overview, pp. 17. http://arxiv.org/pdf/2008.05756v1. Accessed 29 September 2022.

[17] Liu, L., Özsu, M.T. (Eds.), 2016. Encyclopedia of Database Systems. Springer New York, New York, NY.

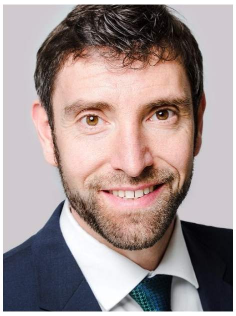
[18] Pedregosa, F., Varoquaux, G., Gramfort, A., Michel, V., Thirion, B., 2011. Scikit-learn: Machine Learning in Python, in: Journal of Machine Learning Research, vol. 12, pp. 2825–2830.

[19] Ioshchikhes, B., Piendl, D., Schmitz, H., Heiland, J., Weigold, M., 2023. Development of a holistic framework for identifying energy efficiency potentials of production machines. (Accepted for publication in: Manufacturing Driving Circular Economy - Proceedings of the 18th Global Conference on Sustainable Manufacturing)

Biography

Borys Ioshchikhes (*1995) has been a research associate at the research group Energy Technologies and Applications in Production (ETA) at the Institute of Production Management, Technology and Machine Tools (PTW) at Technical University of Darmstadt since 2021. In his research, he focuses on machine learning-based energy analysis to increase energy efficiency in production.

Ghada Elserafi (*1993) has been head of the research group Energy Technologies and Applications in Production (ETA) at the Institute of Production Management, Technology and Machine Tools (PTW) at Technical University of Darmstadt since 2022. As a research associate, she focuses on parts cleaning and drying processes.



Matthias Weigold (*1977) has been head of the Institute of Production Management, Technology and Machine Tools (PTW) at Technical University of Darmstadt since 2019. Prof. Dr.-Ing. Matthias Weigold directs the research fields of Manufacturing Technologies as well as Energy Technologies and Applications in Production with a focus on digitalization and climate neutrality in production.

4th Conference on Production Systems and Logistics

Autonomous Load Profile Recognition in Industrial DC Links Using an Audio Search Algorithm

Raoul Laribi[1], Philipp Harscher[2], Jonas Knapp[1,3], Kai Peter Birke[2,3], Alexander Sauer[1,3]

[1]*Institute for Energy Efficiency in Production (EEP)/ University of Stuttgart, Stuttgart, Germany*
[2]*Institute for Photovoltaics (IPV)/ University of Stuttgart, Stuttgart, Germany*
[3]*Fraunhofer Institute for Manufacturing Engineering and Automation (IPA), Stuttgart, Germany*

Abstract

Industrial manufacturing plants, including machine tools, robots, and elevators, perform dynamic acceleration and braking processes. Recuperative braking results in an increased voltage in the machines' direct current (DC) links. In the case of a diode rectifier, a braking resistor turns the surplus of energy into lost heat. In contrast, active rectifiers can feed the braking energy back to the AC grid, though they are more expensive than diode rectifiers. DC link-coupled energy storage systems are one possible solution to downsize the supply infrastructure by peak shaving and to harvest braking energy. However, their control heavily depends on the applied load profiles that are not known in advance. Especially for retrofitted energy storage systems without connection to the machine's control unit, load profile recognition imposes a major challenge. A self-tuning framework represents a suitable solution by covering system identification, proof of stability, control design, load profile recognition, and forecasting at the same time. This paper introduces autonomous load profile recognition in industrial DC links using an audio search algorithm. The method generates fingerprints for each measured load profile and saves them in a database. The control of the energy storage system then has to be adapted within a critical time range according to the identified load profile and constraints given by the energy storage system. Three different load profiles in four case studies validate the methodology.

Keywords

Load profile recognition; DC link; Audio search algorithm; Self-tuning control; Energy storage system

1. Introduction

Industrial applications, e.g., robots [1], machine tools, and lifts [2], perform dynamic movements. Braking processes lead to an increased DC link voltage within the machine's frequency converters [1]. A braking resistor usually wastes this surplus of energy in case there is no active rectifier for feeding the current back to the AC grid [3]. Energy storage systems represent one way to avoid the dissipation of braking energy and increase manufacturing systems' energy efficiency. Here, mechanical, electrical, electrochemical, hydraulic, and hydroelectric storages come into consideration [4]. In literature, the use of flywheel energy storage systems [1,5] as well as supercapacitors [6–8] with limited capacity is widespread. As stated in [8] and [2], a plug-and-play feature is crucial for retrofitting industrial DC links with energy storage systems. Proprietary communication units of manufacturing machines endanger this requirement [2]. Therefore, avoiding communication between the machine's and the energy storage system's control unit is a desirable feature [2]. Moreover, load profiles may vary during operation depending on the specific energy demands of manufactured products [9]. According to the product, there can be cyclically recurring load profile sequences.

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This paper deals with autonomous load profile recognition in industrial DC links to facilitate self-tuning control of retrofitted energy storage systems. A well-established audio search algorithm [10] provides a feasible solution for autonomous load profile recognition as the problem statement is similar to identifying pieces of music. Furthermore, this paper addresses measurement uncertainty. Noise amplitudes are usually smaller than a tenth of their sensors' accuracy. As a multiplication of the current and voltage signal takes place before receiving the actual load profile, their two single uncertainties add up to the total uncertainty [11]. Band-limited white noise expresses itself as a zero-mean statistical fluctuation [12]. As proposed in [11], a normally distributed random number generator provides the added white noise in this paper. Adding noise enlarges the amount of training data [11].

The rest of this paper is structured as follows. Chapter 2 illustrates the state of the art for industrial DC links as well as load profile recognition and forecasting. Chapter 3 presents the audio search algorithm and translates it according to the problem statement of this paper. Then, chapter 4 proves the validity of the algorithm using three different load profiles of a machine tool under the influence of noise. Chapter 5 concludes this paper and motivates future research work.

2. State of the art

This chapter introduces industrial DC links and distinguishes them from DC microgrids. In addition, it explains several variants of adaptive and self-tuning control. At last, this chapter discusses scientific approaches for load profile recognition and forecasting.

2.1 Industrial DC links

Figure 1 distinguishes variants of industrial DC grids connecting the AC grid to drive systems using power electronic converters. An intermediate circuit transfers energy from a rectifier to an inverter. DC links consist of at least two intermediate circuits and are usually based on one proprietary system manufacturer, e.g., for robots with more than one axis [13]. DC microgrids further extend DC links by integrating multiple drive systems, renewable energy sources, and energy storage systems [14].

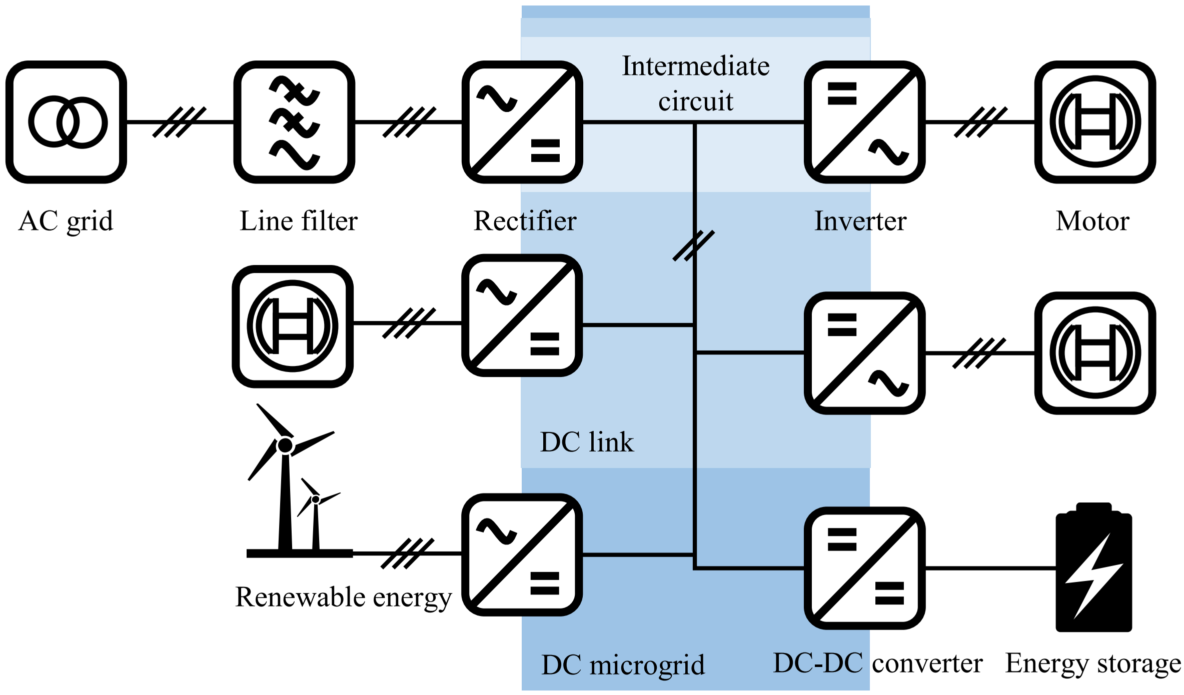

Figure 1: Topological distinction between industrial DC grids.

2.2 Adaptive and self-tuning control

There are three variants of adaptive control. The first is *gain scheduling*, often referred to as look-up table [15]. This approach is applied to energy storage systems in [16], and especially useful if the system performance and disturbances are known in advance [15]. The second variant is *model reference adaptive control* (MRAC) relying on a pre-developed model [17]. *Model identification adaptive control* (MIAC) marks the third variant. MIAC identify the process model during operation making them suitable for systems with high uncertainty [17]. MIAC and *self-tuning control* are used interchangeably [18]. Furthermore, *iterative learning control* (ILC) also belongs to self-tuning techniques [19]. *Iterative learning control* modifies the control loop's set point depending on error information of past cycles. Moreover, the quite similar *repetitive control* is appropriate for continuous processes, while *iterative learning control* returns to its initial conditions after each iteration [20].

2.3 Load profile recognition and forecasting

Forecasts are a sub-group of predictions. Both approaches rely on historical data to project future events. Forecasting represents a prediction based on time series data, whereas a prediction does not necessarily have to use time-based data [21]. This paper interprets recognition as a prediction of a load profile identifier. As soon as the applied algorithm correctly recognizes the load profile due to the knowledge of previous cycles, forecasting the future power demand seems rather trivial for deterministic processes.

This section provides the results of a literature review for load profile recognition and forecasting. Dietmair and Verl develop a generic energy consumption model for a milling machine [22]. They link system states to their specific energy consumption and simulate the G-code in advance [22]. Mühlbauer et al. forecast the energy intake of a milling machine using information from the G-code (e.g., rotational speeds, coordinates, tools, etc.). The authors compare several regression models, including linear, Gaussian process, polynomial, and random forest regression [23]. Brillinger et al. examine how decision trees and random forests can be applied when forecasting the energy use of CNC machines [24]. In order to recognize load profiles in an industrial DC microgrid and to enable adaptive control for energy storage systems, Männel et al. propose cross-correlation analysis [25]. Reger et al. combine hidden Markov models with cross-correlation analysis. Furthermore, the authors apply short-term Fourier analysis and wavelet transformation to generate features in the frequency domain [26]. K-means clustering is the basis for load profile recognition of a machining center and forecasting of an industrial robot in [9]. In addition, Barreto et al. use fuzzy c-means clustering to define typical load profiles of three industrial machines in the textile industry [27]. In [28], support vector machines for load profile forecasting are compared to neural networks and linear regression. Dietrich et al. analyze deep learning approaches, including long short-term memory networks (LSTM) and convolutional neural networks (CNN), to use demand response on the machine and factory level [29]. Efimov et al. investigate an adaptive neuro-fuzzy inference system (ANFIS) for load profile forecasting in an industrial robot [30].

Most of the described approaches rely on information provided by the machines' G-code, i.e., a widespread computer numerical control programming language. Interpreting G-code is a time-consuming challenge due to different software standards and numerous control system manufacturers. Therefore, this paper proposes a novel solution path. The authors apply a well-known audio search algorithm to measured load profiles of a DC link. A voltage, a current, and a trigger signal suffice to recognize several electrical load profiles without the need to access and analyze the machines' G-code. The proposed algorithm recognizes the load profiles within only a few seconds, is robust against noise and easily transferable onto other machines. Eventually, this allows for self-tuning energy storage control.

3. Modified audio search algorithm

This chapter introduces the adapted audio search algorithm, including its most crucial functions and calculation steps. In 2003, Wang [10] proposed a robust audio search algorithm to recognize music segments using hashed time-frequency constellations. Based on these generated fingerprints, the algorithm can identify tracks within a database containing millions of songs [10]. Multiple MATLAB implementations of the algorithm are available online. This paper uses a customized MATLAB version of [31]. The original methodology is adapted to the electrical load profile data of a machine tool. Figure 2 illustrates the adapted methodology of the load profile recognition in this paper.

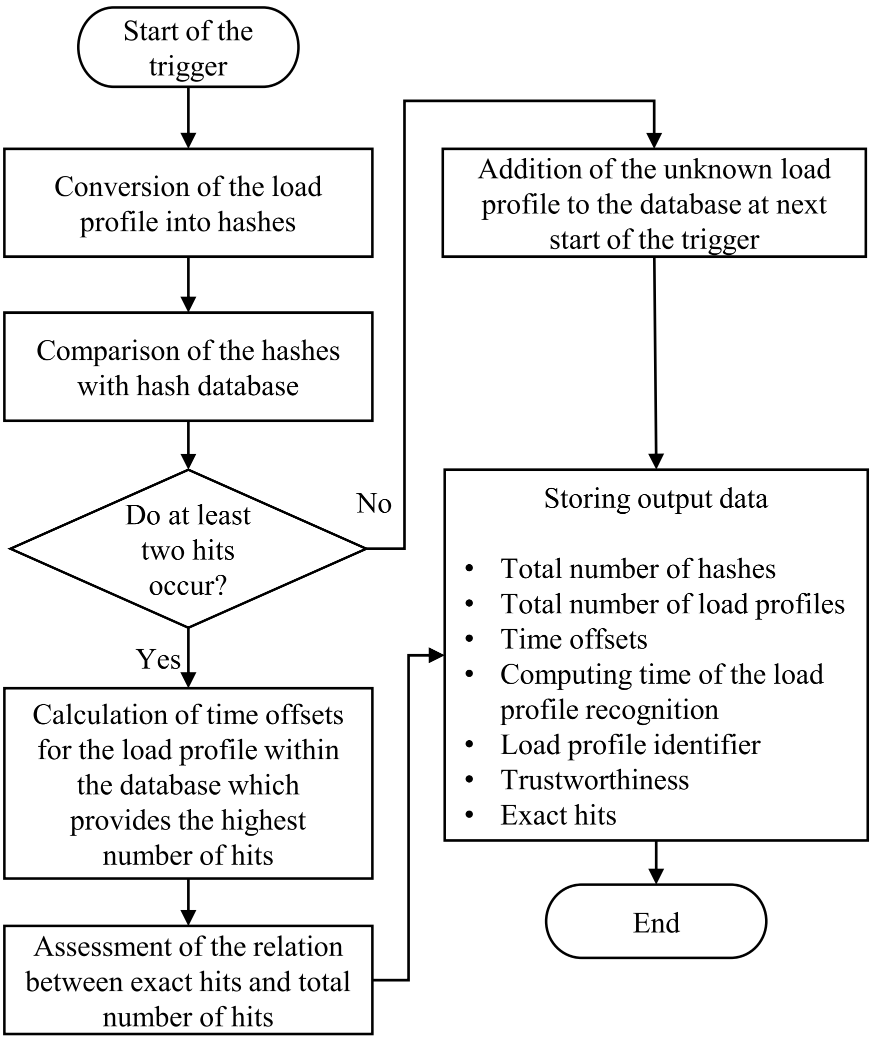

Figure 2: Simplified methodology of the load profile recognition.

First, the algorithm receives a trigger signal from the machine tool's control unit. This induces the manufacturing process as well as the DC current and DC voltage measurement located right behind the rectifier for the load profile recognition. The trigger signal solely marks the load profile's start and end. After five seconds, the algorithm starts generating so-called hashes from the load profile as well as the time vector and adds them to a table. As part of the hash generation, a filter has to smooth the load profile to eliminate irrelevant extrema and reduce disturbances. After applying the filter, the algorithm identifies the power extrema, i.e., relevant minimum and maximum power values. The hashes have a length of ten digits and are composed of four parts as described in (1):

1. Sign of the anchor point ($s_i = 0$ for negative power, $s_i = 1$ for positive power)
2. Absolute power value p_i of the anchor point rounded to one decimal place
3. Absolute power value p_{i+1} of the consecutive point rounded to one decimal place
4. Difference between the time stamp of the anchor point t_i and the consecutive point t_{i+1}

$$hash = s_i \cdot 10^9 + p_i \cdot 10^7 + p_{i+1} \cdot 10^4 + (t_{i+1} - t_i) \cdot 10^1 \quad (1)$$

Each extremum once serves as an anchor point within a loop. This logic is suitable for loads that are smaller than 100 kW and bigger than -100 kW. A higher number of digits is appropriate if the power values exceed the said limits. The number of digits also depends on the required accuracy and hash composition. Even an overflow caused by increased values would presumably not infringe on the uniqueness of a hash. To make the recognition more robust, one can easily generate additional hashes using a second consecutive extremum, as shown in Figure 3.

If at least one load profile has been measured before, another function calculates whether there are common hits between the recently generated hash table and already stored hash tables in the hash database. If a minimum of two hits is reported, the algorithm publishes the identifier of the matching load profile within the self-tuning control framework.

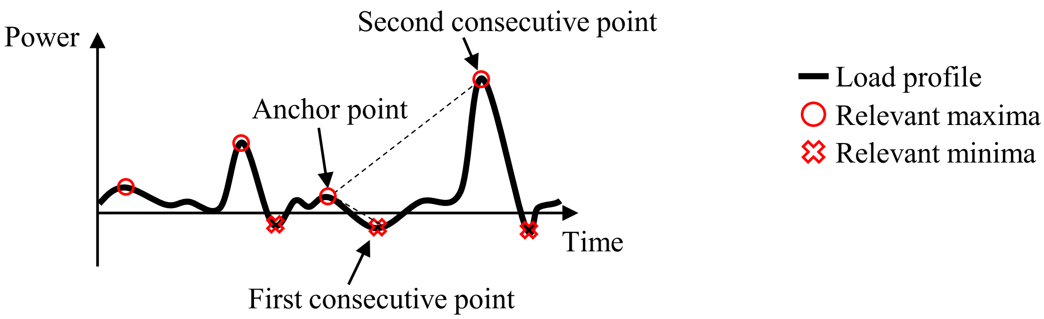

Figure 3: The load profile extrema lead to unique hashes.

Moreover, the time vectors of the currently sampled load profile and historical load profiles in the database can be put in a scatter plot to visualize hits (see Figure 4). In this example of an ideal recognition, the hits lie on a line with a slope of 1.

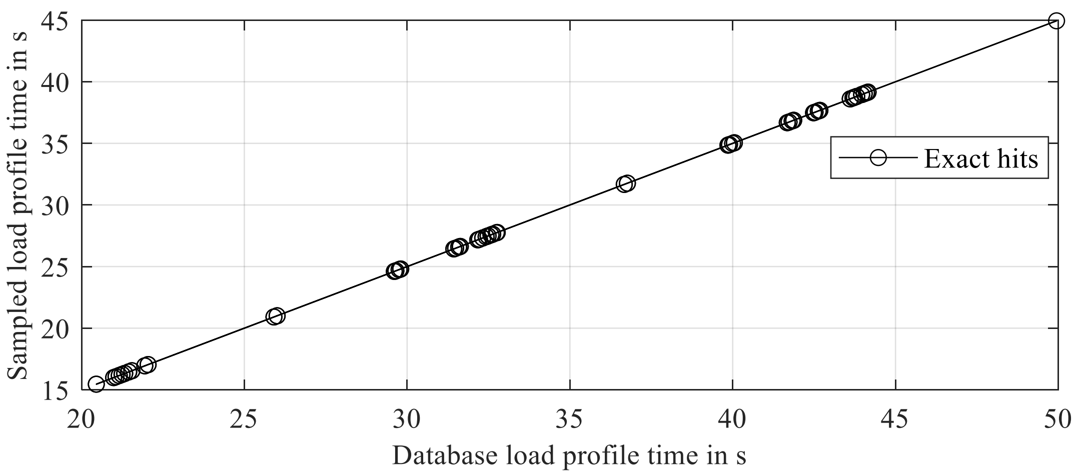

Figure 4: Exact hits in the second cycle of load profile 1 without added noise.

Eventually, the algorithm checks its trustworthiness by looking at the relation between exact hits and the total number of found hashes in (2).

$$Trustworthiness = \frac{Exact\ hits}{Total\ number\ of\ found\ hashes} \geq 50\ \% \tag{2}$$

Subsequently, either the load profile identifier is sent to the control design function or it supplies already designed trajectories for the energy storage system's state of charge and exchange power. In case the recognition of a load profile is not successful, it becomes a new part of the hash database with its own new identifier. Finally, a database stores the results.

4. Case study

The following case study validates the adapted audio search algorithm. First, the chapter focuses on the experimental design. Afterward, this chapter presents and discusses the results.

4.1 Experimental design

Three load profiles from the same machine tool are the inputs to the MATLAB simulation containing the recognition algorithm and a trigger signal that initiates the machine tool's manufacturing cycles. In the beginning, the algorithm has not yet witnessed any of the three load profiles. Therefore, the first cycle of each load profile will not lead to a recognition. Table 1 provides the chosen sequence of ten load profile cycles that all have a length of 50 s with a waiting time of 5 s at the beginning of the simulation to see the first trigger.

Table 1: Simulated sequence of load profiles.

Periods	Load profile identifiers	Number of cycles
5 s ≤ t ≤ 155 s	1	3
155 s < t ≤ 255 s	2	2
255 s < t ≤ 355 s	3	2
355 s < t ≤ 405 s	1	1
405 s < t ≤ 455 s	2	1
455 s < t ≤ 505 s	3	1

In this paper, a Savitzky-Golay filter of 15^{th} order over 501 samples serves to smooth the load profile before the generation of characteristic extrema and hashes. Furthermore, the extrema have to possess a time difference of at least 100 ms and a power difference of more than 2 kW. Moreover, white noise is added to the load profiles to check on the algorithm's robustness. The white noise accounts for measurement inaccuracies. This results in four case studies with noise amplitudes of 0.0 %, ± 0.1 %, ± 0.2 % and ± 0.5 % of the load profile's maximum power.

4.2 Results

Figure 5a depicts the load profile sequence of Table 1. The actual computing times for the recognition in Figure 5b are always less than two seconds. This computing time marks the period between the buffering of the first relevant extrema and the publishing of the load profile identifier.

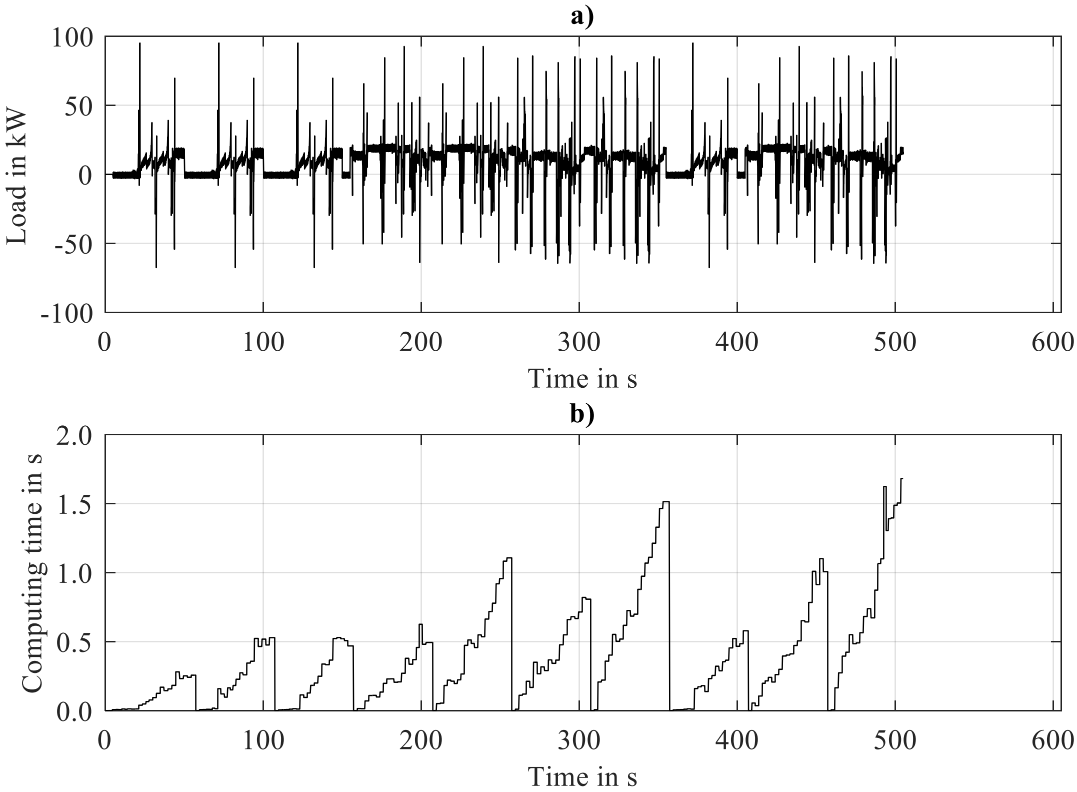

Figure 5: a) Load profile sequence, b) Computing times of the load profile recognition.

To challenge the algorithm's robustness, the authors add three noise amplitudes to the original load signal. The authors assume that ordinary sensors possess an accuracy of ± 1 %. The noise amplitudes should not exceed a tenth of this value for one sensor and, respectively a fifth of the accuracy for two sensors, i.e., 0.2 % in this specific case. Figure 6a shows the actual sequence of load profile identifiers according to Figure 5a. Figure 6b to Figure 6e depict the case study of different noise amplitudes. Figure 6f reveals the trustworthiness of each case. For a noise amplitude (NA) of 0 %, the algorithm provides almost ideal results as expected. A noise amplitude of 0.1 % also achieves good trustworthiness of over 70 %. The demanded robustness at a noise amplitude of 0.2 % is mostly achieved, but in the eighth cycle (355 s < t ≤ 405 s), the algorithm publishes the load profile identifier quite late, and the trustworthiness is sometimes lower than 50 % during the load cycle. This occurs due to the sparse number of extrema during the first 20 s of load profile 1. However, the algorithm can recognize load profiles 2 and 3 with levels of trustworthiness around 60 %. These two load profiles procure more hash information. A noise amplitude of 0.5 % pushes the algorithm beyond its limits, and the trustworthiness falls below the threshold of 50 % for most of the simulation time.

5. Conclusion

This paper has introduced the application of a well-established audio search algorithm for autonomous load profile recognition in industrial DC links to enable self-tuning control of energy storage systems. The present publication distinguishes DC links from DC microgrids, defines several variants of self-tuning control, and provides the state of the art for load profile recognition and forecasting. The methodology of the audio search algorithm is visualized, and its implementation in a case study leads to promising results. Increased added noise negatively influences the algorithm's trustworthiness.

Future research should focus on further reducing the computing time and storage space requirements. The authors have to increase the algorithm's robustness to cover applications with lower measurement accuracy. At least half of the found hashes should be exact hits to safely recognize the load profile.

Here, the filter design plays an important role. In addition, other signal features for hash generation might be suitable, e.g., in the frequency domain.

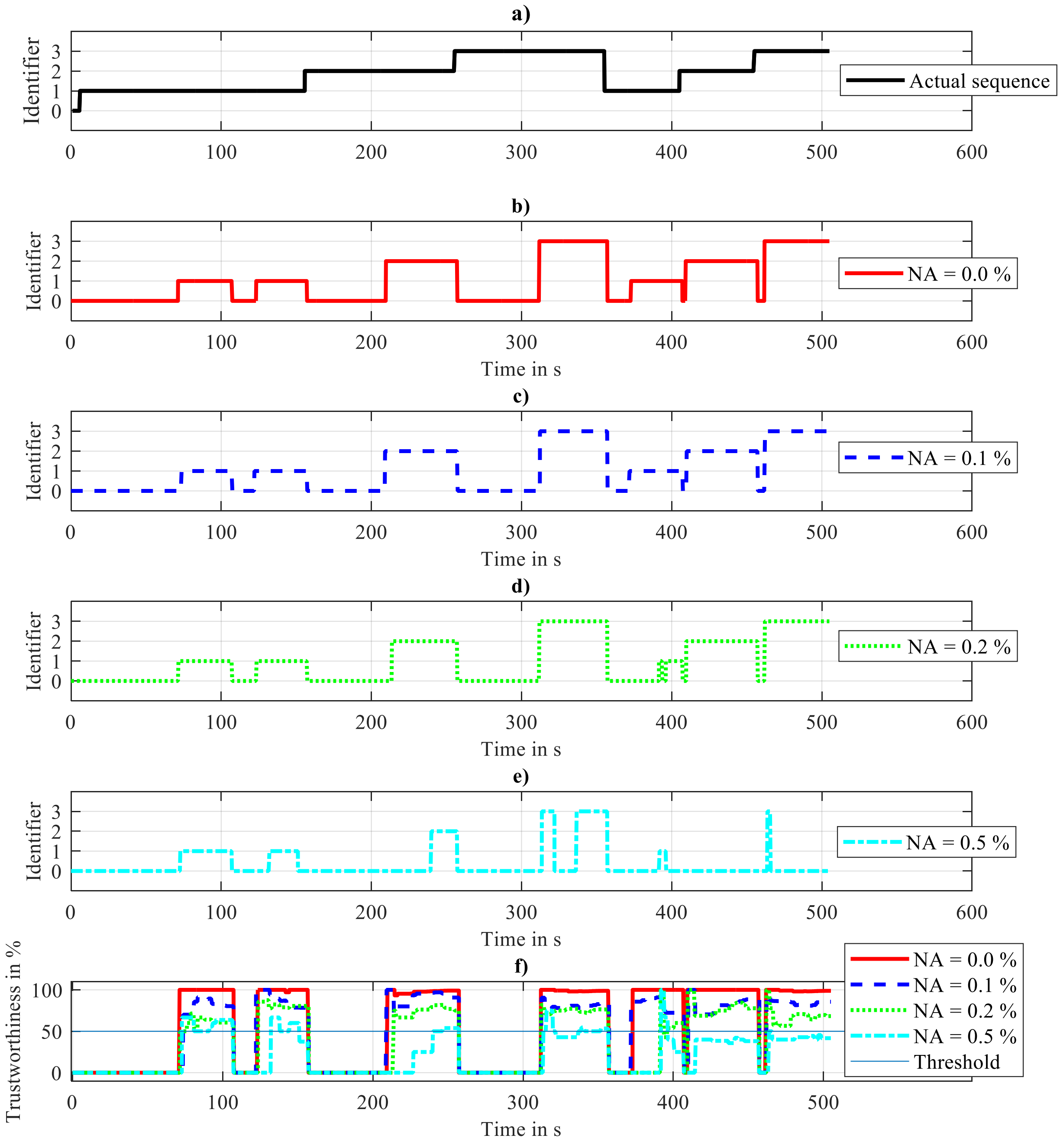

Figure 6: a) Actual sequence of the load profile identifiers and recognized load profile identifiers for noise amplitudes (NA) of b) 0.0 %, c) 0.1 %, d) 0.2 %, e) 0.5 % of the maximum occurring power, and f) trustworthiness and recognition threshold for the presented cases.

Acknowledgement

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References

[1] Hansen, C., Eggers, K., Jotlarski, J., Ortmaier, T., 2015. Comparative Evaluation of Energy Storage Application in Multi-Axis Servo Systems, in: The 14th IFToMM World Congress. The 14th IFToMM World Congress, Taipei, Taiwan. 25.10.2015-30.10.2015, pp. 201–210.

[2] Laribi, R., Lu, Y., Schaab, D.A., Dierolf, C., Sauer, A., 2020. Requirements Engineering and Morphological Analysis of Adaptive Control Strategies for Flywheel Energy Storage Systems in Industrial Applications. ECEEE Industrial Summer Study Proceedings, 273–283.

[3] Eggers, K.B., 2019. Energieeffizienter Betrieb von Industrierobotern. Dissertation, Hannover, 117 pp.

[4] Kapoor, R., Parveen, C.M. Comparative Study on Various KERS, in: , Proceedings of the World Congress on Engineering, Vol. 3, pp. 1–5.

[5] Juhász, T., Kennel, M., Franke, M., Schmucker, U., 2014. Model-Based Energy Recuperation of Multi-Axis Machines, in: . 10th International Modelica Conference, Lund, Sweden. 10.03.2014 - 12.03.2014, pp. 609–615.

[6] Gale, S., Eielsen, A.A., Gravdahl, J.T., 2015. Modelling and simulation of a flywheel based energy storage system for an industrial manipulator, in: . 2015 IEEE International Conference on Industrial Technology (ICIT), Seville. 17.03.2015 - 19.03.2015, pp. 332–337.

[7] Jabbour, N., Mademlis, C., 2016. Improved Control Strategy of a Supercapacitor-Based Energy Recovery System for Elevator Applications. IEEE Trans. Power Electron., 8398–8408.

[8] Oyarbide, E., Elizondo, I., Martinez-Iturbe, A., Bernal, C., Irisarri, J., 2011. Ultracapacitor-based plug & play energy-recovery system for elevator retrofit, in: . 2011 IEEE International Symposium on Industrial Electronics. 27-30 June 2011, pp. 462–467.

[9] Teiwes, H., Blume, S., Herrmann, C., Rössinger, M., Thiede, S., 2018. Energy Load Profile Analysis on Machine Level. Procedia CIRP 69, 271–276.

[10] Wang, A.L.-C., 2003. An Industrial-Stength Audio Search Algorithm, 7 pp. Accessed 20 August 2022.

[11] Sartorius, G., 2019. Erfassen, Verarbeiten und Zuordnen multivariater Messgrößen. Springer Fachmedien Wiesbaden, Wiesbaden.

[12] Lotichius, J., 2017. Modellbildung der Messunsicherheit resistiver Sensorsysteme. Dissertation, Darmstadt, 147 pp.

[13] Sauer, A. (Ed.), 2021. The DC-Factory: Energy efficient. Robust. Forward-looking. Hanser, München, 204 pp.

[14] Schaab, D.A., Weckmann, S., Kuhlmann, T., Sauer, A., 2018. Simulative Analysis of a Flexible, Robust and Sustainable Energy Supply through Industrial Smart-DC-Grid with Distributed Grid Management. Procedia CIRP 69, 366–370.

[15] Trächtler, A., Gausemeier, J., 2018. Steigerung der Intelligenz mechatronischer Systeme, 1st ed. Springer, Berlin, Heidelberg, 259 pp.

[16] Laribi, R., Schaab, D.A., Sauer, A., 2020. Adaptive State of Charge Control for Droop Controlled Industrial DC-Microgrids, in: . 2020 IEEE 14th International Conference on Compatibility, Power Electronics and Power Engineering (CPE-POWERENG), Setubal, Portugal. 08.07.2020 - 10.07.2020, pp. 187–193.

[17] Müller, H., Villegas, N., 2014. Runtime Evolution of Highly Dynamic Software, in: Tom Mens, A., Serebrenik, A.C. (Eds.), Evolving Software Systems, 1 ed. Springer, Berlin, Heidelberg, pp. 229–264.

[18] Bohn, C., Unbehauen, H., 2016. Identifikation dynamischer Systeme: Methoden zur experimentellen Modellbildung aus Messdaten, 1st ed. Springer Fachmedien, Wiesbaden, 713 pp.

[19] Noack, R., 2018. Beitrag zur selbsteinstellenden Ladedruckregelung von aufgeladenen Ottomotoren. Dissertation, Rostock, 151 pp.

[20] Bristow, D.A., Tharayil, M., Alleyne, A.G., 2006. A survey of iterative learning control. IEEE Control Syst. 26 (3), 96–114.

[21] Chugh, V., 2020. Estimation, Prediction and Forecasting: Estimation vs prediction. Prediction vs Forecast. Read along for a quick distinction. https://towardsdatascience.com/estimation-prediction-and-forecasting-40c56a5be0c9. Accessed 20 September 2022.

[22] Dietmair, A., Verl, A., 2009. Energy Consumption Forecasting and Optimisation for Tool Machines. MM Science Journal, 62–65.

[23] Mühlbauer, M., Würschinger, H., Polzer, D., Hanenkamp, N., 2021. Energy Profile Prediction of Milling Processes Using Machine Learning Techniques, in: Beyerer, J., Maier, A., Niggemann, O. (Eds.), Machine Learning for Cyber Physical Systems, vol. 13. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 1–11.

[24] Brillinger, M., Wuwer, M., Abdul Hadi, M., Haas, F., 2021. Energy prediction for CNC machining with machine learning. CIRP Journal of Manufacturing Science and Technology 35, 715–723.

[25] Männel, A., Müller, K., Knöchelmann, E., Ortmaier, T., 2020. Load Profile Cycle Recognition for Industrial DC Microgrids with Energy Storage Systems, in: 2020 IEEE 29th International Symposium on Industrial Electronics (ISIE), Delf, Netherlands. 17-19 June 2020, pp. 904–9011.

[26] Reger, A., Oette, C., Aires, A.P., Steinhilper, R., 2015. Pattern recognition in load profiles of electric drives in manufacturing plants, in: . 2015 5th International Electric Drives Production Conference (EDPC), Nuremberg, Germany. 15.09.2015 - 16.09.2015, pp. 1–10.

[27] Barreto, R., Faria, P., Vale, Z., 2020. Determination of the typical load profile of industry tasks using fuzzy C-Means. Energy Reports 6, 155–160.

[28] Duerden, C., Shark, L.-K., Hall, G., Howe, J., 2016. Prediction of granular time-series energy consumption for manufacturing jobs from analysis and learning of historical data, in: . 2016 Annual Conference on Information Science and Systems (CISS), Princeton, NJ, USA. 16.03.2016 - 18.03.2016, pp. 625–630.

[29] Dietrich, B., Walther, J., Chen, Y., Weigold, M., 2021. A Deep Learning Approach to Electric Load Forecasting of Machine Tools. MM SJ 2021 (5), 5283–5290.

[30] Efimov, A., Gorkavyy, M., Gorkavyy, A., 2020. Predicting Power Consumption of Robotic Complex Based on Neuro-Fuzzy System, in: . 2020 International Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM), Sochi, Russia. 18.05.2020 - 22.05.2020, pp. 1–5.

[31] Ellis, D., 2009. Robust Landmark-Based Audio Fingerprinting. https://www.mathworks.com/matlabcentral/fileexchange/23332-robust-landmark-based-audio-fingerprinting. Accessed 29 September 2022.

Biography

Raoul Laribi (*1992) studied sustainable electrical energy supply and received his master’s degree from the University of Stuttgart in 2017. Since then, he has been working as scientific associate at the university’s Institute for Energy Efficiency in Production (EEP). His PhD work focuses on self-tuning control of energy storage systems in industrial DC grids.

Philipp Harscher (*1990) has done research and worked in several countries like Germany, China, India and Canada. He received his bachelor's degree in renewable energies engineering and his master's degree in electromobility engineering from the University of Stuttgart in 2015 and 2022 respectively. His topics of interest include battery systems, power electronics and pattern recognition.

Jonas Knapp (*1994) studied engineering cybernetics at University of Stuttgart, Germany. Since 2021 he has been a research associate at the Institute for Energy Efficiency in Production (EEP) of the University of Stuttgart. His research focus includes modelling and simulation of industrial power grids, control design of DC microgrids, and potential analysis of electrical energy grids.

Kai Peter Birke (*1967), Prof. Dr.-Ing., studied Physics, Mathematics and Chemistry at Christian-Albrechts University, Kiel, and received his PhD at Kiel University. He is holding the Chair of Electrical Energy Strorage Systems at the University of Stuttgart and is director of the Center for Digitalized Battery Production at Fraunhofer Institute for Manufacturing Engineering and Automation (IPA) in Stuttgart.

Alexander Sauer (*1976), Prof. Dr.-Ing. Dipl.-Kfm., studied mechanical engineering and business administration at RWTH Aachen University and received his PhD at the RWTH Aachen University. He is director of the Institute for Energy Efficiency in Production (EEP) at the University of Stuttgart and head of the Fraunhofer Institute for Manufacturing Engineering and Automation (IPA) in Stuttgart.

4th Conference on Production Systems and Logistics

Is Sustainable Maintenance A Support- Or Standalone Function? A Definition

Christina Bredebach[1]
[1]*Technical University Dortmund, Dortmund, Germany*

Abstract

Sustainability is getting more and more attention in society, industry, and research. Companies are increasingly focusing on sustainable practices to meet different requirements. Industrial maintenance, which tends to be considered sustainable, is now more frequently examined in research for its actual sustainability, and various approaches to the design of maintenance are being presented. In this context, the term sustainable maintenance is not uniformly defined. There are different underlying assumptions about the term sustainability within the maintenance function itself, whether it is a support-function to enable sustainable manufacturing or a standalone function to improve sustainability in manufacturing companies by itself. For this reason, this study defines the term Sustainable Maintenance based on previous publications. For this purpose, a systematic literature review of 46 publications identified as relevant to the topic is conducted, and then a definition is derived via the Genus Proximum et Differentia Specifica by Aristotle through the distinction of sustainable maintenance from traditional maintenance.

Keywords

Sustainable Maintenance; Sustainable Manufacturing; Industry 4.0; Stakeholder Theory; Triple Bottom Line

1. Introduction

In today's world, companies face a wide variety of challenges, such as scarcity of physical resources, stricter laws and regulations, customer demand for high-quality products, and economic stagnation [1]. Challenges such as the shortage of natural resources and the growing focus on environmental concerns pose problems for companies, which can however lead to competitive survival and even competitive advantage in response to regulations [2]. Incorporating sustainability into corporate strategies is referred to as Sustainable Development when the current needs of the company and those of their stakeholders are met while focusing on protecting the environment and society [3].

Sustainability is a challenge for manufacturing companies that can lead to better product quality, increased market share, and increased profits [4]. In this context, sustainable maintenance activities have also come into focus, which, in addition to the traditional technical and economic dimensions, also consider the environmental and social ones [5].

Maintenance influences the productivity and, consequently, the profitability of companies through a direct impact on efficiency, effectiveness, and quality of actions, which are considered key elements of adequate maintenance strategies [6]. In fact, maintenance actions influence not only the technical dimensions of production systems, i.e., reliability and availability, as well as product quality, but also the three sustainability dimensions: environmental, economic, and social. [7]

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Sustainable maintenance has no clear definition but is often described as a process that achieves the condition of the objects to be maintained through technical measures [4,8] and prevents negative ecological impacts [9,8,10] the safety of employees [8,4,10] and stakeholders [9] and is economically sound [9,8] and thus also ensures the competitiveness of the company [11].

In current research, the importance of considering sustainability aspects in industrial maintenance is increasing for various reasons outlined above. The number of publications on this subject has been growing steadily in recent years. Existing definitions of the term overlap, but also complement each other and are thus not unambiguous. This paper therefore answers the following research question: **How can Sustainable Maintenance be defined?** A question that derives from the definition of Sustainable Maintenance is, whether in the existing literature it is seen as a standalone or a support function. A support function would be a support function to allow the company to design the manufacturing process sustainably, with a focus on manufacturing. As a standalone function however would itself be able to independently help the company to become more sustainable. The basis for this is provided by a systematic literature review, while the definition itself is formulated based on Aristotle's Genus Proximum et Differentia Specifica. This approach originates from [12], who developed a definition of Industry 4.0 in their paper. The methodological approach is presented in chapter 2 while the evaluation of the systematic literature research follows in chapter 3.1. Subsequently, in chapter 3.2 the definition is presented.

2. Methodology

The following section describes the methods used to develop a definition for sustainable maintenance.

2.1 Systematic Literature Review on Sustainable Maintenance

A systematic literature review differs from traditional narrative literature reviews in that it is a scientific, transparent, and reproducible process, minimizing subjective bias through extensive literature searches and detailed descriptions by researchers of their procedures, decisions, and conclusions [13]. This method enables efficient and high-quality identification and evaluation of the literature on a selected topic [13] and helps identify key questions [14].

According to [13] a systematic literature search is performed in three steps. At the beginning, the research must be planned. For this, a conceptual discussion of the research problem and a description of the significance of the problem is included in the research protocol. A specific research question is not required. The goal of the first step is to have a research protocol that does not limit the creativity of the researcher in the review process, but still limits the possibilities of subjective bias. The second step is to conduct the literature search. For this, a literature search was conducted in the Web of Science, EBSCO Host, SCOPUS, and Emerald Insights databases using a pre-developed search string. The results were sorted according to inclusion and exclusion criteria [15] which were derived from the studies of [16] and [17], categorized and expanded by forward and backward searches [15]. In the third and final step, the results of the systematic literature review are summarized. For this purpose, on the one hand, a descriptive analysis is presented, which includes metadata of the study, and on the other hand a content analysis, which enables a solution of the research problem formulated at the beginning. [13]

A total of 46 articles were identified as relevant in the systematic literature search conducted on June 1, 2022. After identifying the relevant studies to the predefined research problem, the metadata of the studies and their content were evaluated. The evaluation included the country of origin of the authors and the year of publication [13] as well as the method on which the study was based and a classification of the result. [17,18,13]. For the content analysis of the publications, the method used by [12] for the definition of Industry 4.0 was applied. For this purpose, like the development of the search string, keywords were assigned to the studies that were used to describe sustainable maintenance in the respective works. These are later used for the description of the species-forming difference.

2.2 Genus Proximum et Differentia Specifica

For the definition of the term sustainable maintenance, the genus Proximum et Differentia Specifica was chosen. A definition is a statement composed of the particular genus of the term to be defined and the difference from other terms of that genus [19]. Defining helps to identify a thing that is known by name but not by explanation [19]. According to this procedure, a thing is defined by its genus (the next higher class) and its differences from other things under the genus [20]. The definition must be unique to the thing being defined and must always be true, so definitions do not include properties that are true of both the thing being defined and other things in the genus [20].

In order to define according to the Genus Proximum et Differentia Specifica, the general generic term must first be determined. In this case the term "maintenance" was chosen according to [21]. Subsequently, a division of the generic term into more general, specific terms is chosen until the species term cannot be further divided. The decisive factor is which characteristics are chosen to distinguish the species terms. According to the description of maintenance as well as sustainability, the characteristics for differentiation refer to tasks and goals of the respective maintenance type. The type to be defined is "sustainable maintenance" while the comparison to traditional maintenance is presented.

3. Results

The following two chapters will present the results of the research process. In chapter 3.1, the results of the systematic literature review are presented, including the definition of traditional maintenance as well as identified definitions and descriptions of sustainable maintenance. Chapter 3.2 then presents the newly developed definition of Sustainable Maintenance, based on the Genus Proximum et Differentia Specifica described in chapter 2.2. The keywords assigned to sustainable maintenance that differentiate this from traditional maintenance are described more closely in chapters 3.2.1 to 3.2.5.

3.1 Systematic Literature Review

The papers identified as relevant in the systematic literature review are presented descriptively. The first study identified as relevant dates back to 2012. Overall, there is an increasing trend, although there is still a low number of publications on sustainable maintenance for the year 2022 due to the timing of the search in June 2022. With a total of seven publications on sustainable maintenance, Jasiulewicz-Kaczmarek offers the most publications, while Franciosi and Miranda have six publications on this topic. The majority of publications come from Europe, followed by Asia and Oceania.

Many of the studies analysed show the status quo of sustainable maintenance, while some also present new methods and models or theoretical frameworks. Tools for implementing sustainable maintenance have been published less frequently. Methodologically, researchers have often taken a theoretical approach, while some have also conducted research through case studies, expert interviews, or workshops. There has been no experimental research.

For the evaluation of the relevant publications, keywords were assigned to them that were used for the description of sustainable maintenance in the same. In the following, traditional maintenance is described according to the identified publications, its development in recent years and the relationship between maintenance and sustainability, to then be able to present the differences between traditional maintenance and sustainable maintenance in the sense of the genus proximum.

Traditional maintenance

Maintenance is the combination of all administrative, technical, and management actions during the life cycle of an object with the goal of maintaining or restoring the object to its functional state [22-26,5,27]. Therefore, the objectives of maintenance activities include high reliability and availability of equipment, as well as efficiency [28] and safety [26]. The implementation of maintenance activities influences product quality [1]. Nevertheless, maintenance is often perceived as a support process that has the production department as its only customer and is thus considered a cost factor [29]. The large number of machines leads to a high complexity of today's maintenance [5] which is influenced by the structure and organization of a manufacturing company [30]. Despite the perception as a cost factor in the company, maintenance is a component of most manufacturing companies, which ensures the functions of the production systems, which are necessary for an efficient production process [24].

Maintenance helps to minimize production costs and maximize equipment life corrective or preventive [31], maximize [6] thereby improving the performance [11] and profitability [24] of the entire company [4]. This includes improving the reliability of equipment, understanding the reasons for poor performance, preventing breakdowns, and reducing downtime by repairing [31]. At the same time, neglected or poorly performed maintenance leads to losses for the company [24] making it a critical function for production [11]. For example, equipment failure leads to increased repair costs, decreased quality of products, and overall shutdown of the production line [10]. Conventional decision-making approaches to maintenance strategies focus mainly on technical and monetary criteria [32].

While, as described above, maintenance as a function in manufacturing companies has been an area for outsourcing strategies and has been described as a cost driver [6], there has been an evolution in recent years together with production processes from a reactive function to a cost saving and value adding preventive, then to a green approach and is now seen as an area that should be managed sustainably [16]. Maintenance has also become critical for reliability and availability of assets due to the growing complexity resulting from the evolution of technologies, with a new task to avoid unexpected shutdowns due to digitalization [33].

The indicators described do not address the social and environmental aspects of maintenance [23]. However, it is essential to consider these aspects, as the condition of production facilities has an influence on occupational safety, the quality of the products to be produced or emissions [23]. Poorly performed maintenance leads, for example, to the emission of hazardous substances into the environment, the generation of waste due to a non-functioning system, inefficient consumption of resources and energy, and waste of stored materials [23,32].

Sustainable maintenance

A total of 190 keywords were assigned to the 46 publications. The frequency of assignment of the most frequently mentioned keywords is shown in Table 1.

Table 1: Most frequently found keywords for Sustainable Maintenance

Keyword	Frequency
Triple Bottom Line	28
Sustainable Manufacturing	26
Integrated View	11
Efficiency	10
Stakeholder	8
Quality	7
New Technology	5
Optimization	4
Availability	1

The keywords presented do not necessarily correspond to the species-forming difference, but purely to the description of sustainable maintenance. As an example, availability and downtime can be mentioned, which also belong to the objective in traditional maintenance and thus do not represent a difference.

The keywords identified and categorized here are a description of the sustainable maintenance used to derive the species-forming difference.

3.2 Definition of Sustainable Maintenance

For the definition of sustainable maintenance, the species-forming difference between sustainable and traditional maintenance is formed. This was developed from the keywords in this case. The keywords of levels two and three are specifications of the higher levels, so they are shown for clarification, but not included in the definition of sustainable maintenance. Referring to the definition of traditional maintenance, the keywords can be used to show the species-forming difference. This is shown graphically in Figure 1.

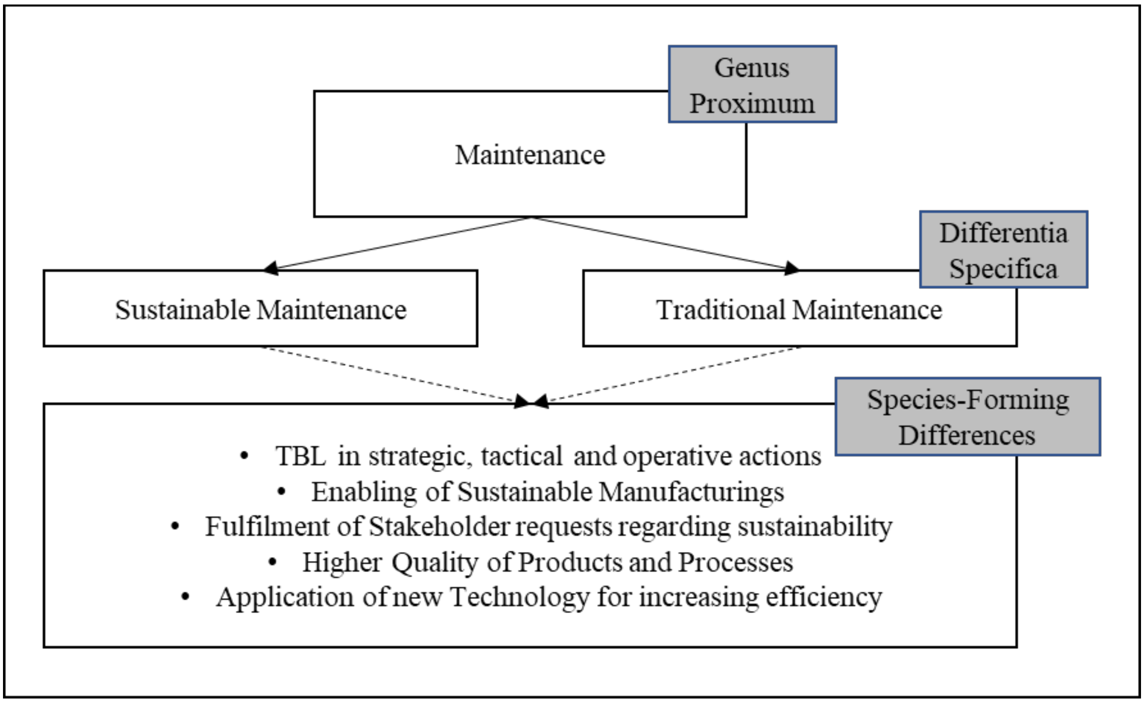

Figure 1: Genus Proximum et Differentia Specifica for Sustainable Maintenance

Thus, the definition of sustainable maintenance with the species-forming difference from traditional maintenance is as follows: Sustainable Maintenance enables the implementation of **Sustainable Manufacturing through the integrative** inclusion of the **Triple Bottom Line** in the **strategic, tactical, and operational** measures. A focus is placed on meeting **stakeholder requirements** regarding achieving **Sustainable Development.** The goals of Sustainable Maintenance include higher **quality** of the products and processes to be manufactured as well as increased **efficiency** through the application of **new technologies**.

Derived from this definition and the definitions of each keyword included, a Sustainable Maintenance Model for manufacturing companies was developed and shown in Figure 2. This model shows the possible interactions between the different keywords previously developed within a manufacturing company. In the following chapters, the keywords that were previously assigned to Sustainable Maintenance will be described based on findings in the systematic literature review. Each keyword will be described generically first and then with regard to maintenance activities.

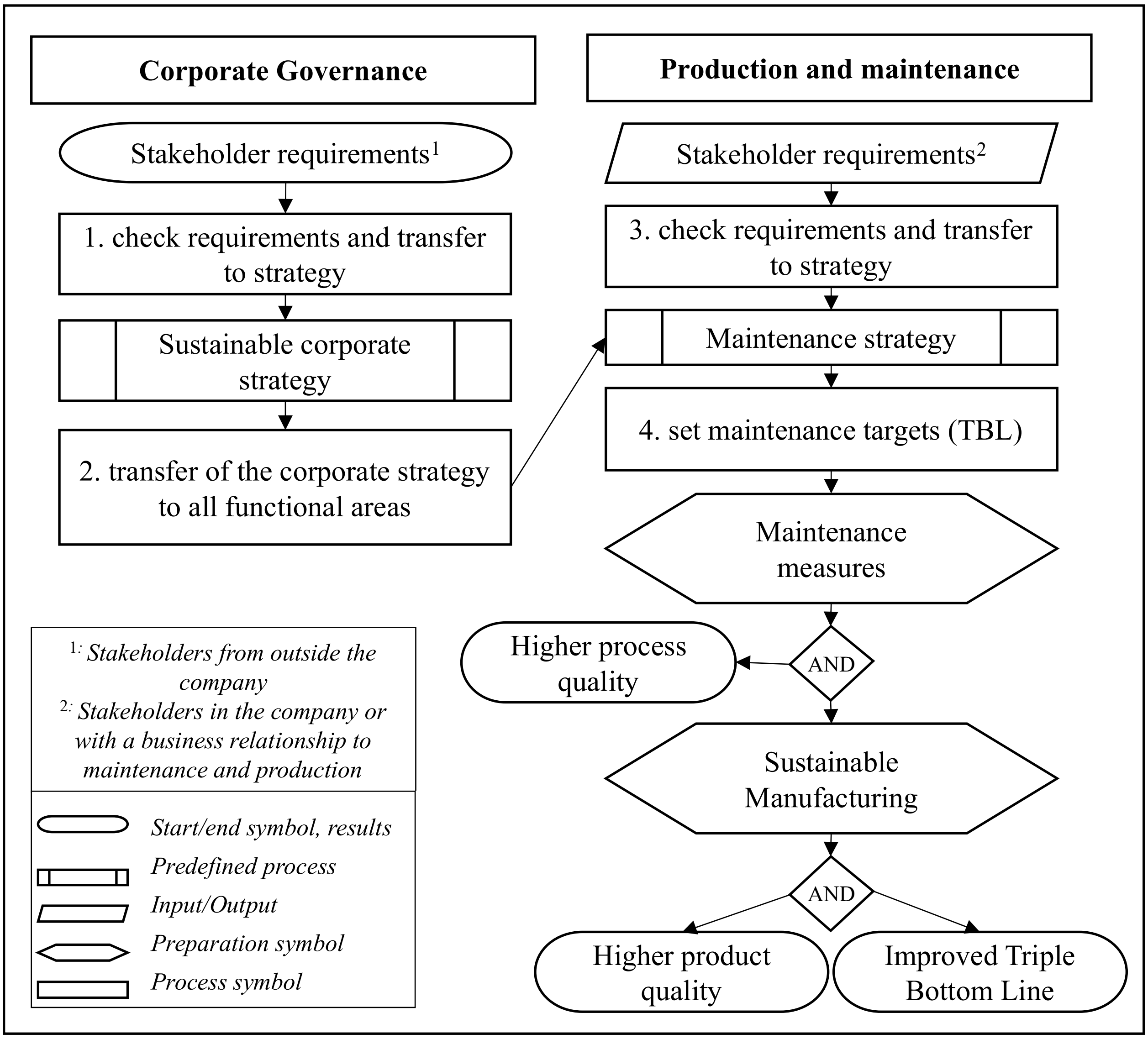

Figure 2: Sustainable Maintenance Model

3.2.1 Triple Bottom line

The Triple Bottom Line consists of three aspects: Economic, Ecological and Social [28]. The economic aspect of sustainability refers to productivity and profitability, efficiency and effective investments, the environmental aspect refers to the purchase of renewable energy, prevention of pollution and safe handling of hazardous materials, while the social aspect focuses on the health and safety of employees and good working conditions [36]. The three areas of sustainability must be considered in an integrated way, as changes in one aspect strongly influence the other two [4].

Maintenance helps to increase the economic value of a company [34] and can have an impact on all three aspects of sustainability [11]. A sustainable maintenance strategy has a great impact on reducing energy consumption, as a well-chosen maintenance strategy keeps the objects to be maintained in good condition, which contributes to energy efficiency, while digital and automated work planning in maintenance contributes to its standardization, which helps to identify the reasons for greatly increased energy consumption [37]. To integrate all three aspects of sustainability into maintenance, it is necessary to include sustainability in the maintenance strategy [10]. If sustainability aspects are not considered in maintenance, this can lead to higher repair costs, increased energy consumption and a higher number of occupational accidents [10]. Other consequences of non-executed or poorly executed maintenance include higher costs, downtime, waste, poor productivity, and product quality [18] hazardous emissions and accidents [35].

3.2.2 Stakeholder theory

Basically, there are two types of stakeholders, those with a connection to a company, for example customers, shareholders, or employees, and those that have a demand on a company, such as NGOs [38,39]. Stakeholders were originally described as a group without whose support the company could not exist, since corporate goals could not be formulated without knowledge of stakeholder demands [40]

Stakeholders of maintenance were, according to a study of [23] focused on economic factors, but rarely associate maintenance with sustainability. Possible stakeholders of maintenance that can support sustainable performance of the company are, for example, the development area of the company, as well as quality and production, where good cooperation and communication lead to a better understanding of the responsibility of the maintenance area. This can be reflected, for example, in well-maintained products that result from cooperation between maintenance personnel and the development department. [30]

3.2.3 Sustainable Manufacturing

Sustainable manufacturing is the process of manufacturing goods or services by conserving resources and using clean technologies [16] while being economically sound [41]. The overarching goal is to manufacture products that are fully recyclable and whose production process has a positive impact on the environment [42]. The entire production process from pre-manufacturing to post-use must be considered [43].

Maintenance plays an important role in enabling Sustainable Manufacturing, as it enables the company to maintain the efficiency of the production system and achieve the required quality of the products to be produced [42], is responsible for the availability and reliability as well as the safety of the equipment. [33]. Thus, the maintenance directly influences the Sustainable Manufacturing [29]. Failure to apply sustainable concepts in maintenance affects the production volume, quality, safety, and environment [5] which, as described above, form the basis of Sustainable Manufacturing.

3.2.4 Product and Process Quality

Economic, ecological, and social further development in companies can be achieved by applying management standards, such as DIN EN-ISO 9001, the quality management system [29]. Through the application of this standard, customer satisfaction can be increased by means of processes for system improvement and compliance with customer requirements [44].

Companies that integrate sustainability principles into their processes can achieve higher product and service quality, higher profits, and greater market share [10,34]. Maintenance is closely linked to production activities with the aim of producing high-quality products, and the quality of maintenance activities affects the quality of production, and thus the quality of products [33] as well as production costs and volumes, machine performance and availability [1]. Companies must become more aware that maintenance entrusts processes necessary for production processes with the least negative impact on the environment, economy, and society [30]. Product quality is an important factor for a trusting relationship with a company's stakeholders, which can be achieved through maintenance aimed at better quality without wasting resources [45].

3.2.5 New Technologies

In science, correlations between the application of new technologies and increased efficiency have been demonstrated. The implementation of automation, for example, leads to both increased product quality and improved process efficiency and customer satisfaction. These trends could be identified in particular regarding Industry 4.0. [46] Industry 4.0 is therefore seen as the key to improved productivity, enables economic growth and ensures the sustainability of manufacturing companies [47].

Sustainable maintenance cannot be achieved without considering new technologies [48]. The implementation of sustainable maintenance activities leads to an increase in production capacity and therefore an improvement in the performance of the company [5]. In addition, the competitive position of the company can be strengthened, and additional value can be added, the company may qualify for capital investment through sustainability standards [34]. Thus, new technologies are also relevant for sustainability in maintenance, especially since this business sector has a great contribution to the achievement of sustainability goals [41].

4. Conclusion

In the systematic literature review and the related content evaluation using the genus proximum, a definition of sustainable maintenance was developed based on previous publications on this topic. The differences between sustainable and traditional maintenance were elaborated upon, showing which of the characteristics of sustainable maintenance have an influence on the different areas of sustainability. Due to the focus on sustainable manufacturing in the context of sustainable maintenance, it can be stated that sustainable maintenance for achieving sustainable development is not a standalone function in the company, however, it cannot be seen as a pure support function either. It enables sustainable manufacturing in manufacturing companies and thus has a supporting function, but forms the basis for sustainable production, particularly regarding resource conservation, safety and efficiency and effectiveness. It can therefore be stated that sustainable development in companies can only be achieved through close cooperation between maintenance, production, and their stakeholders.

This work is subject to some limitations. In a systematic literature review, the incompleteness of the literature examined cannot be excluded. While the test of relevance of the studies examined was clearly defined by inclusion and exclusion criteria, it cannot be ruled out that conducting the study with two or more researchers would have yielded different results. Furthermore, the genus proximum according to Aristotle is one of many definitional theories, therefore, a different result could have possibly been obtained by using other approaches to definition as well. This work is also exclusively literature-based and therefore may not map the practical execution of maintenance. For this reason, it is recommended as future research that a study be conducted to solicit the opinions of experts in maintenance, manufacturing, and sustainability practice to test the characteristics of sustainable maintenance for feasibility and practical relevance. Additional further research should be conducted on target optimization when it comes to sustainability objectives in maintenance, as those often limit each other and tradeoffs must be made, as this paper only generically shows different parts of sustainable maintenance, but not the actual targeting of such.

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References

[1] Franciosi, C., Voisin, A., Miranda, S., Riemma, S., Iung, B., 2020. measuring maintenance impacts on sustainability of manufacturing industries: from a systematic literature review to a framework proposal. Journal of Cleaner Production 260, 121065.

[2] Sari, E., Shaharoun, A.B.M., Ma'aram, A.B., 2013. preliminary framework of sustainable maintenance performance measurement systems for automotive companies. AMR 845, 590-595.

[3] Stuchly, V., Jasiulewicz-Kaczmarek, M., 2014. maintenance in sustainable manufacturing. LogForum 10 (3), 273-284.

[4] Amrina, E., Aridharma, D., 2016. sustainable maintenance performance evaluation model for cement industry, in: 2016 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM). 2016 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), Bali, Indonesia. 04.12.2016 - 07.12.2016. IEEE, pp. 350-354.

[5] Karuppiah, K., Sankaranarayanan, B., Ali, S.M., 2021. on sustainable predictive maintenance: exploration of key barriers using an integrated approach. Sustainable Production and Consumption 27, 1537-1553.

[6] Holgado, M., Macchi, M., Evans, S., 2020. exploring the impacts and contributions of maintenance function for sustainable manufacturing. International Journal of Production Research 58 (23), 7292-7310.

[7] Dolgui, A., Bernard, A., Lemoine, D., Cieminski, G. von, Romero, D. (Eds.), 2021. advances in production management systems. Springer, Cham, 737 pp.

[8] Olugu, E.U., Wong, K.Y., Chung Ee, J.Y., Mammedov, Y.D., 2022. Incorporating Sustainability and Maintenance for Performance Assessment of Offshore Oil and Gas Platforms: A Perspective. Sustainability 14 (2), 807.

[9] Sari, E., Shaharoun, A.M., Ma'aram, A., Yazid, A.M., 2015. sustainable maintenance performance measures: A pilot survey in Malaysian automotive companies. Procedia CIRP 26, 443-448.

[10] Campos, R.S. de, Simon, A.T., 2019. insertion of sustainability concepts in the maintenance strategies to achieve sustainable manufacturing. Ind. Jour. Man. & Prod. 10 (6), 1908-1931.

[11] Ibrahim, Y.M., Hami, N., Othman, S.N., 2019. INTEGRATING SUSTAINABLE MAINTENANCE INTO SUSTAINABLE MANUFACTURING PRACTICES AND ITS RELATIONSHIP WITH SUSTAINABILITY PERFORMANCE: A CONCEPTUAL FRAMEWORK. IJEEP 9 (4), 30-39.

[12] Hermann, M., Pentek, T., Otto, B., 2015. Design Principles for Industrie 4.0 Scenarios: A Literature Review.

[13] Tranfield, D., Denyer, D., Smart, P., 2003. towards a Methodology for Developing Evidence-Informed Management Knowledge by Means of Systematic Review. Br J Management 14 (3), 207-222.

[14] Cooper, H.M., 1988. organizing knowledge syntheses: A taxonomy of literature reviews. Knowledge in Society 1 (1), 104-126.

[15] vom Brocke, J., Simons, A., Niehaves, B., Reimer, K., Plattfaut, R., Cleven, A. RECONSTRUCTING THE GIANT: ON THE IMPORTANCE OF RIGOUR IN DOCUMENTING THE LITERATURE SEARCH PROCESS.

[16] Franciosi, C., Lambiase, A., Miranda, S., 2017. sustainable maintenance: a periodic preventive maintenance model with sustainable spare parts management. IFAC PapersOnLine 50 (1), 13692-13697.

[17] Bredebach, C., 2022. What Role Does Maintenance Play in Achieving Sustainability in Manufacturing? - A Scoping Literature Review, in: . ASME 2022 17th International Manufacturing Science and Engineering Conference. American Society of Mechanical Engineers Digital Collection.

[18] Franciosi, C., Iung, B., Miranda, S., Riemma, S., 2018. maintenance for sustainability in the Industry 4.0 context: a scoping literature review. IFAC PapersOnLine 51 (11), 903-908.

[19] Westermann, H., 2001. difference, specific, in: Ritter, J., Gründer, K., Gabriel, G. (Eds.), Historisches Wörterbuch der Philosophie. Completely revised edition of Rudolf Eisler's 'Wörterbuch der Philosophischen Begriffe'. Volume 11: U-V. Schwabe & Co. AG, Basel, pp. 314-326.

[20] Aristotle. Topics: Books I and VIII (trans. Smith).

[21] DIN 31051, 2012. Grundlagen der Instandhaltung. Beuth Verlag GmbH, Berlin, 12 pp.

[22] Amrina, E., Kamil, I., Aridharma, D., 2020. fuzzy multi criteria approach for sustainable maintenance performance evaluation in cement industry. Procedia Manufacturing 43, 674-681.

[23] Franciosi, C., Di Pasquale, V., Iannone, R., Miranda, S., 2021. multi-stakeholder perspectives on indicators for sustainable maintenance performance in production contexts: an exploratory study. JQME 27 (2), 308-330.

[24] Hami, N., Shafie, S.M., Omar, S., Ibrahim, Y.M., Abdulameer, S.S., Muhamad, M.R., 2020. a review of sustainable maintenance in the manufacturing companies. International Journal of Supply Chain Management 9 (3), 935-944.

[25] Ighravwe, D.E., Ayoola Oke, S., 2017. ranking maintenance strategies for sustainable maintenance plan in manufacturing systems using fuzzy axiomatic design principle and fuzzy-TOPSIS. JMTM 28 (7), 961-992.

[26] Jasiulewicz-Kaczmarek, M., 2018. identification of maintenance factors influencing the development of sustainable production processes - a pilot study. IOP Conf. Ser.: Mater. Sci. Eng. 400, 62014.

[27] Sénéchal, O., 2017. research directions for integrating the triple bottom line in maintenance dashboards. Journal of Cleaner Production 142, 331-342.

[28] Ramiya, S., Suresh, M., 2021. factors influencing lean-sustainable maintenance using TISM approach. Int J Syst Assur Eng Manag 12 (6), 1117-1131.

[29] Jasiulewicz-Kaczmarek, M., Żywica, P., Gola, A., 2021. fuzzy set theory driven maintenance sustainability performance assessment model: a multiple criteria approach. J Intell Manuf 32 (5), 1497-1515.

[30] Jasiulewicz-Kaczmarek, M., Antosz, K., Wyczółkowski, R., Mazurkiewicz, D., Sun, B., Qian, C., Ren, Y., 2021. Application of MICMAC, Fuzzy AHP, and Fuzzy TOPSIS for Evaluation of the Maintenance Factors Affecting Sustainable Manufacturing. Energies 14 (5), 1-30.

[31] Sénéchal, O., 2016. Maintenance decision support for sustainable performance: problems and research directions at the crossroads of health management and eco-design. IFAC PapersOnLine 49 (28), 85-90.

[32] Nezami, F.G., Yildirim, M.B., 2013. a sustainability approach for selecting maintenance strategy. International Journal of Sustainable Engineering 6 (4), 332-343.

[33] Jasiulewicz-Kaczmarek, M., Legutko, S., Kluk, P., 2020. management and production engineering review, 14 pp.

[34] Aditya, P., Diego, G., 2012. achieving sustainable development through maintenance excellence. Journal of Applied Engineering Science 10 (2), 79-84.

[35] Hami, N., Munadhil, Y., Yarmin, F.M., Shafie, S.M., Abdulameer, S.S., 2019. the Moderating Role of Sustainable Maintenance on the Relationship between Sustainable Manufacturing Practices and Social Sustainability: A Conceptual Framework. IJEAT 8 (5C), 222-228.

[36] Farsi, M., Mishra, R.K., Erkoyuncu, J.A., 2021. industry 5.0 for sustainable reliability centered maintenance. SSRN Journal.

[37] Bányai, Á., 2021. energy consumption-based maintenance policy optimization. Energies 14 (18), 5674.

[38] Hillman, A.J., Keim, G.D., 2001. shareholder value, stakeholder management, and social issues: what's the bottom line? Strategic Management Journal (22), 125-139.

[39] Roloff, J., 2008. learning from multi-stakeholder networks: issue-focused stakeholder management. J Bus Ethics 82 (1), 233-250.

[40] Freeman, R.E., 2015. strategic management. Cambridge University Press.

[41] Franciosi, C., Voisin, A., Miranda, S., Iung, B., 2020. integration of I4.0 technologies with maintenance processes: what are the effects on sustainable manufacturing? IFAC PapersOnLine 53 (3), 1-6.

[42] Vrignat, P., Kratz, F., Avila, M., 2022. sustainable manufacturing, maintenance policies, prognostics and health management: a literature review. Reliability Engineering & System Safety 218, 108140.

[43] Enyoghasi, C., Badurdeen, F., 2021. industry 4.0 for sustainable manufacturing: opportunities at the product, process, and system levels. Resources, Conservation and Recycling 166, 105362.

[44] DIN. Quality management systems: Requirements (ISO 9001:2015), 71 pp.

[45] Suresh, M., Dharunanand, R., 2021. factors influencing sustainable maintenance in manufacturing industries. JQME.

[46] Fettermann, D.C., Cavalcante, C.G.S., Almeida, T.D. de, Tortorella, G.L., 2018. how does industry 4.0 contribute to operations management? Journal of Industrial and Production Engineering 35 (4), 255-268.

[47] Rosin, F., Forget, P., Lamouri, S., Pellerin, R., 2020. impacts of industry 4.0 technologies on lean principles. International Journal of Production Research 58 (6), 1644-1661.

[48] Jasiulewicz-Kaczmarek, M., Gola, A., 2019. maintenance 4.0 technologies for sustainable manufacturing - an overview. IFAC PapersOnLine 52 (10), 91-96 .

Biography

Christina Bredebach (*1994) is a PhD student at Graduate School of Logistics, Technical University Dortmund since 2021. She holds a Bachelor's and Master's degree from Duale Hochschule Baden-Württemberg. Her research focus is on Sustainable Maintenance.

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Curriculum Learning In Job Shop Scheduling Using Reinforcement Learning

Constantin Waubert de Puiseau[1], Hasan Tercan[1], Tobias Meisen[1]
[1]Chair for Technologies and Management of Digital Transformation, Wuppertal, Germany

Abstract

Solving job shop scheduling problems (JSSPs) with a fixed strategy, such as a priority dispatching rule, may yield satisfactory results for several problem instances but, nevertheless, insufficient results for others. From this single-strategy perspective finding a near optimal solution to a specific JSSP varies in difficulty even if the machine setup remains the same. A recent intensively researched and promising method to deal with difficulty variability is Deep Reinforcement Learning (DRL), which dynamically adjusts an agent's planning strategy in response to difficult instances not only during training, but also when applied to new situations. In this paper, we further improve DLR as an underlying method by actively incorporating the variability of difficulty within the same problem size into the design of the learning process. We base our approach on a state-of-the-art methodology that solves JSSP by means of DRL and graph neural network embeddings. Our work supplements the training routine of the agent by a curriculum learning strategy that ranks the problem instances shown during training by a new metric of problem instance difficulty. Our results show that certain curricula lead to significantly better performances of the DRL solutions. Agents trained on these curricula beat the top performance of those trained on randomly distributed training data, reaching 3.2% shorter average makespans.

Keywords

Job Shop Scheduling; Reinforcement Learning; Curriculum Learning; Agent Based Systems; Artificial Intelligence;

1. Introduction

Inspired by the way humans learn, deep reinforcement learning (DRL) is a machine learning paradigm in which a system, or agent, autonomously learns from gathered experience. Most famously, DRL has been successfully applied to board and video games [1,2] with superhuman performance. In recent years, DRL has also shown promising results in industrial use-cases and combinatorial optimization problems such as the job shop scheduling problem (JSSP) [3–5].

Scheduling problems deal with the allocation of resources to jobs over time to optimize criteria such as total time spent to process all jobs, called makespan [6]. The JSSP in particular is a problem formulation, where each job must visit each machine in a factory in a fixed order, and is considered NP-hard to solve optimally. In practice, scheduling problems are often solved using priority dispatching rules (PDRs) consisting of simple rules for determining the priority of jobs over a scheduling sequence [6]. The main promise of DRL for the scheduling problems compared to alternative solution approaches is that it may yield better solutions than commonly used PDRs but with much shorter computation times and less formulation effort than optimal solvers [7]. Yet, DRL for scheduling problems is only in its infancy. On the one hand, the field still neglects

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some problem conditions inherent to real-world problems [8], and on the other hand it lags behind in the application of promising DRL paradigms such as curriculum learning (CL).

CL is a recent but very active research field in DRL and is built on the premise that, as with human learning, curricula play a critical role in effective learning behaviors in DRL. More precisely, CL is concerned with generating and learning from suitable experience sequences for the DRL agent. These sequences form the curriculum, which typically progressively varies the task difficulty leading up a final goal. The transfer of CL to the JSSP domain, has only recently been attempted [3]. Such existing methods design curriculums which vary between different problem sizes, i.e. numbers of jobs and machines per problem instance. While applicable to toy-box scenarios, the number of machines is often constant in real-world scenarios and corresponding usable training data. More granular CL within one fixed problem size, however, has not been studied yet. The missing component to accomplish CL in this granularity is a common definition of a degree of difficulty of problem instances within the same problem size.

In this work, we present such a definition and propose a new CL strategy for solving the JSSP with DRL. Comparing the learning behavior with and without CL, we empirically show the superiority of our approach with respect to the achieved average makespan. Our main contributions are summarized as follows:

- The introduction of a measure for the relative difficulty of a problem instance in JSSPs of the same problem size.
- A curriculum learning strategy for JSSPs suitable to steer the learning behavior of DRL agents and to receive shorter average makespans (compare Figure 1). The observed behavior shows that starting training on the most difficult instances decreases the resulting makespans by 3%.

The remainder of this paper is structured as follows: In section 2 we summarize latest achievements in DRL-based JSSP solutions and introduce CL in this context. Section 3 details our solution method and experimental setup, followed by the presentation of the results and insights in section 4 and their discussions in section 5. Finally, section 6 provides a conclusion and outlook to future work.

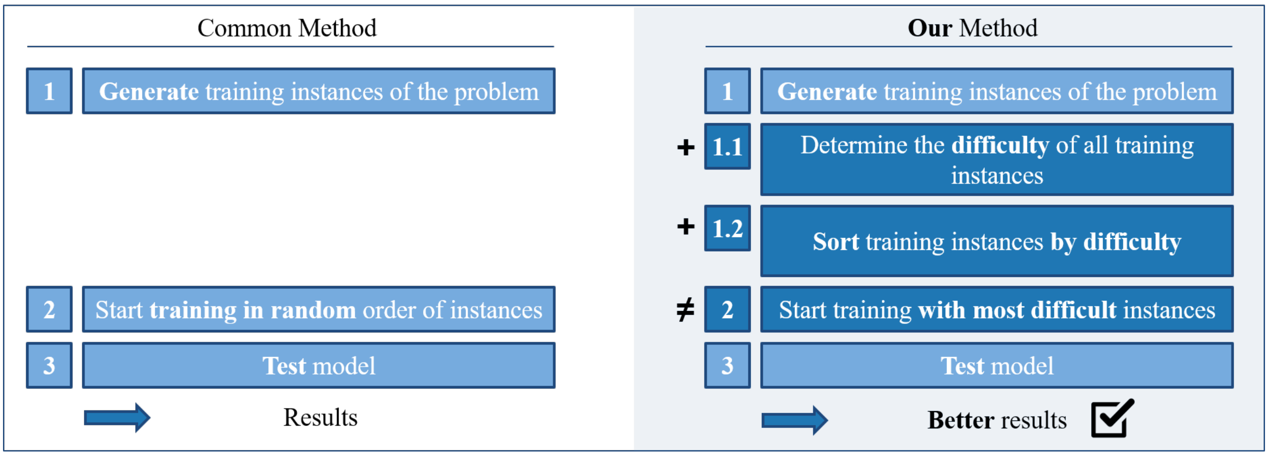

Figure 1: Comparison of the common method with our proposed method. Extension through calculations on the training instances and difference in training procedure.

2. Related Work

2.1 Deep Reinforcement Learning for Job Shop Scheduling Problems

Literature on DRL based JSSP solutions is rapidly increasing in volume and can roughly be divided into two classes: ground research and applied research. Ground research is generally concerned with new architectures [10,11,5], learning design decisions [3,4] and their comparison to existing solution methods, such as priority dispatching rules, meta heuristics and optimal solvers [12]. Here, we find continuously better performance of DRL on standard JSSP problems and benchmark datasets, matching and outperforming PDRs in recent years.

Applied research often considers an additional dimension in the problem formulation inspired by real-world use-cases, such as stochasticity [13,14], machine flexibility [15–17], dynamic job releases [18], machine failures [19] or multi-objective optimization criteria [20,21]. These studies show the general feasibility of DRL to learn, but are typically not very competitive with expert systems. Our contribution lies closer to the first class, as it methodologically extends an existing approach by means of a new learning paradigm for CL in job shop scheduling.

2.2 Curriculum Learning in Deep Reinforcement Learning based Job Shop Scheduling

According to Narvekar et al. [9], curriculum learning consists of three key elements: *task generation*, which deals with the division of the overall goal into easier sub-goals and the generation of suitable training experience; *sequencing*, dealing with the order in which to present the training experience; and *transfer learning*, comprising methods to tackle forgetting skills acquired from past experience when confronted with new experience.

CL for DRL-based JSSP is not much investigated in the current state of research. In a wider sense, CL is used in several approaches to DRL-based job shop scheduling by applying variations of experience replay [22–25,11,18], in which the gathered experience is rearranged and sampled aiming to make learning more stable. In that way, it is loosely related to the *sequencing* element of CL. However, experience replay works with the experience once it is already gathered, skipping the *task generation* element of CL. *Task generation* is less studied and a remaining challenge for solving combinatorial optimization problems with DRL [26]. In our work, we propose an own metric for the importance of experience based on the performance of priority dispatching rules, which serves as a discriminating factor for easy and hard tasks.

Iklassov et al. [3] explicitly propose CL in the JSSP domain. They define the easiness of sub-goals of JSSPs through problem sizes, as most common in combinatorial problems because of the solution space scales with the problem size [27]. By this definition, a problem instance with more jobs and machines is harder than one with less jobs and machines. Making use of a problem size agnostic neural network architecture, the authors introduce an automatic sequencing algorithm which favors collecting experiences from the currently hardest problem size. Their results indicate that models trained with CL drastically outperform those trained without CL. Our approach differs from that of Iklassov et al. [3] in that we apply CL for problem instances of the same size. Hence, we are closing an important gap that enables applying CL to those manufacturing scenarios in which the number of machines remains the same.

3. Methods

In the following, we first summarize the work by Zhang et al. [5], which serves as our methodological testbed and baseline, followed by the details of our CL extension and experimental setup.

3.1 Deep Reinforcement Learning Approach

Our approach extends the method and framework presented in Zhang et al. [5], which shows competitive results on recognized benchmark datasets of the JSSP with makespan optimization. Specifically, our method adapts the interaction logic of the DRL agent with the simulation (action-space and environment step), the action evaluation signal (reward), the input formulation (observation-space), and the network architecture.

The studied DRL agent iteratively plans tasks of a JSSP by choosing from the list of still unfinished jobs in each iteration step. The corresponding next task of this job is scheduled to start at the earliest still possible time by a mechanism called *left-shifting*: left shifting means that if the current plan, consisting of all scheduled tasks up to that point, can be optimized by switching the position of the chosen task with the previous one on the used machine, this switch is executed by the simulation. The corresponding reward signal consists of the difference of the makespan of the already scheduled tasks before and after the last step, such that the cumulative reward received throughout the planning process equals the negative makespan of the final plan. The scheduling decision is based on a size-agnostic embedding: For each task, the embedding contains the information whether it is done and what its current lower bound of the makespan is. Each task represents a node in a graph neural network in which the corresponding information is propagated from node to node and finally aggregated by summation.

In the original paper, the 40.000 training instances per agent were generated on the fly by randomly sorting processing orders on machines and drawing processing times randomly from a normal distribution. Our central extension is a different sampling procedure as part of the CL approach.

3.2 Curricular Training Procedure

Task Generation (definition of instance difficulty): In order to carry out curriculum learning, a feature to divide problem instances into subtasks that vary in difficulty is essential. Since instances of the same problem size by definition share the same computational complexity, we resort to a feature defined by how well we are already able to solve instances through an established set of rules, i.e. PDRs. We call this discriminative feature *difficulty to solve* (DTS). DTS is defined as the makespan, which the most competitive PDR achieves on any given problem instance. Accordingly, we speak of those instances on which a shorter than average makespan is realized through the best PDR as *easy* tasks and those on which a longer makespan is realized as *hard* tasks. Applied to our use case, we proceed as follows (cf. Figure 1, step 1 and 1.1 of our method): As in Zhang et al. [5], we generate 40.000 random 6x6 JSSP training instances from normal distributions with respect to machine orders and processing times. After solving the training data with six commonly used priority dispatching rules jointly with the left-shifting procedure used in Zhang et al. [5], we find that the *most tasks remaining* (MTR) prioritization rule performs best with an average of a 16% larger makespan compared to the optimal makespan (optimality gap). The results of all considered PDRs are shown in the appendix (Table A1). MTR only performed marginally better than the *least remaining processing time* (LRPT) prioritization, but much better than the most often used *shortest processing time* (SPT). Optimal solutions were generated using the CP-SAT solver by OR-Tools [25]. Figure 2a) depicts the distribution of achieved makespans through MTR, which is our used DTS metric.

Sequencing: The creation of training sequences is the next step. Often the difficulty is gradually increased over training in CL, following the intuition that an agent learns a basic strategy first and refines it later to match more difficult scenarios. To cover this sequence, but also others, we sort the training instances by

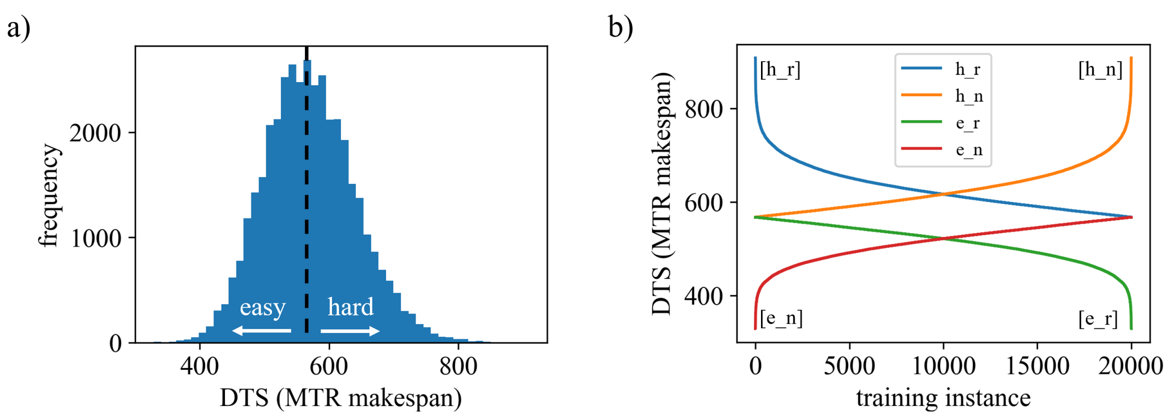

Figure 2 Training data consisting of 40.000 unique instances. a) Histogram of training instances by their DTS (makespan through the MTR dispatching rule); b) Elements of the curriculum: portions of training data sorted by DTS. (e_n = easy, normal order; e_r = easy, reversed order; h_n = hard, normal order; h_r = hard, reversed order)

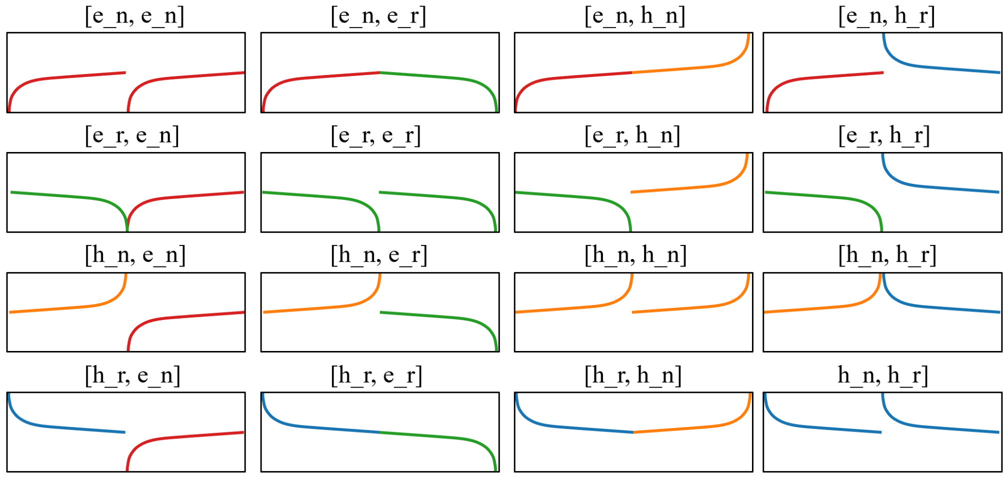

Figure 3: Schematic representation of all 16 possible curricula. As in Figure 2b), halves consist of CEs containing datapoints ordered by DTS (y-axis) along the training procedure (x-axis).

DTS, as depicted in Figure 2b), then split it into the easy and hard halves and keep the original, or normal, order (*e_n*, *h_n*) or reverse it (*e_r*, *h_r*). For example, *e_n* (red line in Figure 2b)) consists of half of the training data in normal order, i.e. starting from the lowest DTS around 300 and ending at the mean DTS of about 580. The four portions make up our ordered training *curriculum elements* (CE). One entire training curriculum consists of two concatenated CEs, e.g. [*e_n*, *e_n*] or [*e_n*, *h_r*], resulting in the 16 possible curricula, schematically depicted in Figure 3.

3.3 Experimental Setup

The experiments are designed such that differences in the agent behavior and performance may only be attributed to the training curricula. To this end, a separate RL-agent is trained for each of the 16 curricula until all training instances within the curriculum have been shown once. As baseline, we also train three RL-agents on unordered training data, where the problem instances were randomly shuffled and the agents are randomly initialized with varying random seeds. Training hyperparameters are fixed in accordance with Zhang et al. [5] for all experiments. All agents are tested on a fixed test dataset containing 1000 problem instances each time 2000 training instances have been shown. For more statistically significant results, we sampled three different training datasets with varying random seeds as described in section 3.2. The above experiments are carried out separately on all three datasets.

4. Experiment Results

Figure 4 shows the results of agents tested on the validation instances over the course of training. Agents trained on the same CE in the first half of the training period, e.g. on *e_n* in *[e_n, e_n]*, *[e_n, e_r]*, *[e_n, h_n]*, *[e_n, h_r]*, are averaged across the three datasets and depicted as solid lines. Generally, one can observe a rapid decline to a first dip of the optimality gap from the first validation point after 2.000 training instances to 6.000 training instances, followed by an increase in the optimality gap and a gradual subsequent convergence to final values towards the end of the training. Interestingly, more than 70% of the agents reach their global minimum in the first dip. This indicates that the agents develop the most successful strategy in the very beginning of training and never return to it, but converge towards a higher (worse) optimality gap instead. Moreover, the best agents 10% of all agents reached their minimum in the first dip.

A closer look at the first dip (cf. the zoom-in on the right in Figure 4) reveals that the lowest point is directly related to the easiness of the first data shown to the agent, hence the training curriculum. More precisely, the lowest point corresponds to agents trained with the *h_r* CE (blue line), meaning that they have been trained on the hardest training data. Inversely, agents trained on *e_n* (red line) remain highest among all points at

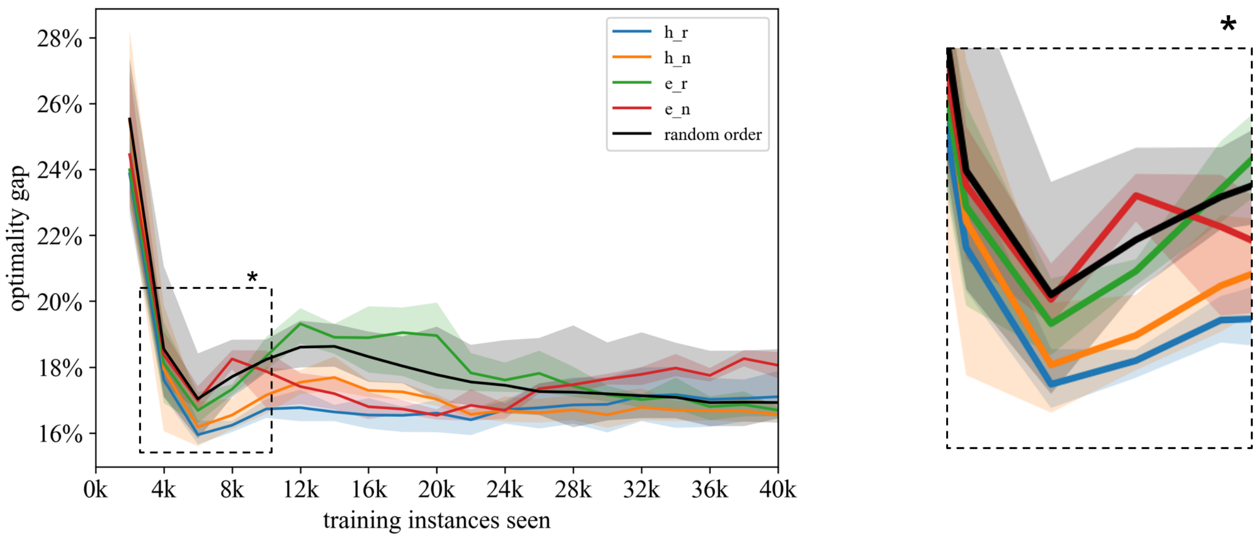

Figure 4: Performance of the agents on the test instances over training progress. Lines indicate the mean across three random seeds for the training instance generation. Shaded areas indicate the minimum and maximum values across three runs. Colored lines represent agents trained on curricula, where the first curriculum element is indicated in the legend. The second curriculum element is h_r for all depicted agents. The black line represents agents trained on randomly ordered training instances.

the first dip. Noteworthily, all agents trained on a CE perform better than those trained without a curriculum (black line) on average. This means that it is advisable to use a curriculum, specifically the *h_r* curriculum in the beginning of the training, to achieve the best results. In our case, we achieve 7% better results (1.1%p) in the first dip. Overall, we achieve 3% better results (0.5%p).

Next, we analyze the training behavior of the agents regarding the second half of training, where the second CEs are presented. Note that in some cases, such as *[e_n, e_n]*, the agent sees only one half of all instances. We study two main questions: Firstly, does the second CE have a consistent impact on the final result? Secondly, does the curriculum have a reproducible impact upon introduction in the middle of the training (difference between test after 20,000 and 22,000 training instances)? The latter may help to steer the agent away from a local minimum. Figure 5 shows the learning curves of agents trained on different curriculums composed from the same training dataset. In each plot, learning curves of four agents are displayed. The plots overlap in the first half of the training because of being trained on the same first CE, but diverge in the middle upon introduction of the second CE. Across all plots we were not able to find significant correlations between second curriculum elements and the learning curve with respect to optimal performance.

This answers the first question: the curriculum element in the second half does not have a consistent impact on the final overall result. However, we observed trends regarding the local behavior in the beginning of the second half of training. Similar to the behavior in the first half, *h_r* generally invokes the largest drop in optimality gap compared to the other CEs in three out of four cases. In some cases, this goes so far that while *h_r* invokes a drop in the optimality gap, *e_n* invokes a rise in the optimality gap.

Figure 6 visualizes the statistics of the immediate local impact of the CEs in the second half of training. Figure 6 a) shows the relative statistical impact of the CEs compared to the CEs by rank. The first bar indicates that in nine out of twelve cases, *h_r* invoked the largest immediate drop in optimality gap. Analogously, the last bar indicates that in five cases, *e_n* achieves the lowest performance. Generally, we find that *h_r* ranks highest and *e_n* lowest, whereas *h_n* and *e_r* rank in between. Similarly, in Figure 6 b), we can look at the absolute impact and count the number of times a CE caused an immediate jump towards better or worse optimality gap. Evidently *h_r* and *h_n* rather cause jumps towards better optimality gaps, whereas *e_r* is neutral and *e_n* causes jumps towards worse optimality gaps more often than not.

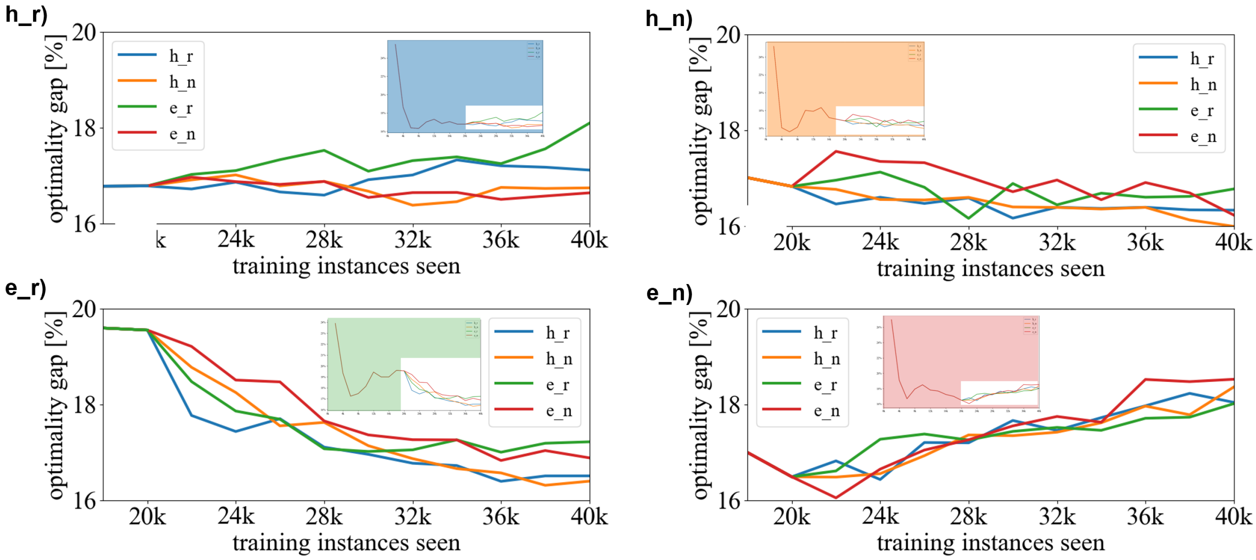

Figure 5: Zoom-ins on the second half of trainings. In each plot, training was performed on the same curriculum element in the first half (top left on [h_r], top right on [h_n], bottom left on [e_r] and bottom right on [e_n])

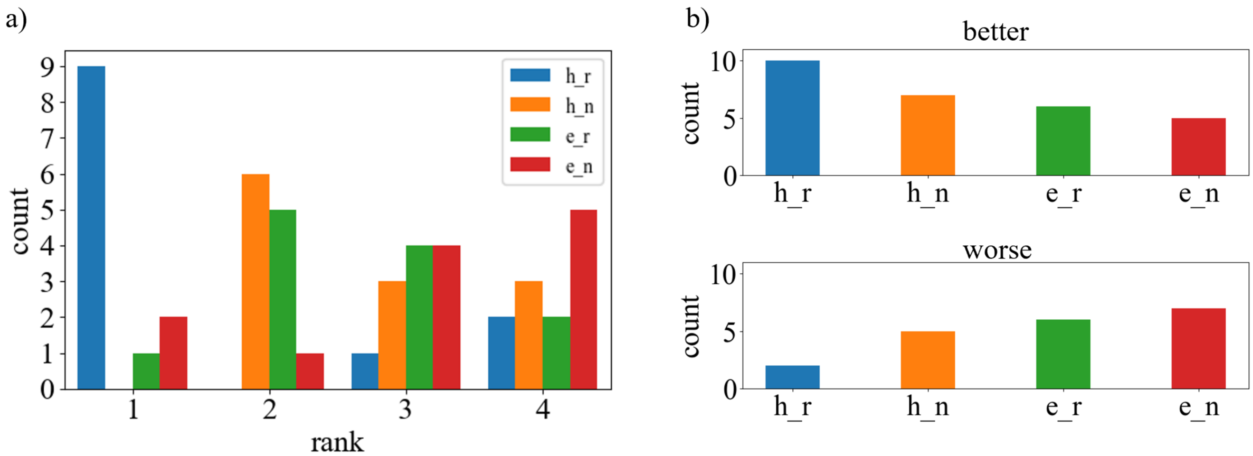

Figure 6: Statistical analysis of the local impact of training on first 2000 instances of each CE in the second half of training. a) Relative impact compared to other CEs. b) and c) Absolute immediate impact: count, how often each respective CE caused a drop (better) or rise (worse) in the optimality gap.

5. Discussion of Results

The presented results suggest that the learning behavior of the DRL agent can be positively influenced through the CEs defined in this study. As a practical consequence, we achieve better global results after a comparatively short training period. We therefore propose using CL according to our methodology, which is easily implemented and integrated into existing solution approaches. On a more fundamental level, the results suggest that the proposed DTS metric is useful to evaluate the easiness of a JSSP problem instance, a novum in this particular domain. During the experiments, we further observed the global minimum in the dip (cf. Figure 4) during training. Though useful in this particular case, in RL we much rather observe smooth, almost monotonically decreasing learning curves. An investigation for the reason behind the learning curve may be subject of future work.

Another noteworthy observation is that learning on the hardest problems first achieves the best outcomes. CL methods otherwise typically start from easier sub-problems and transfer this knowledge into the actual final problem. Our initial explanation attempt, is that the harder problems introduce a stronger negative reward signal through the larger makespan (note that our definition of DTS is related to the achieved makespan), pushing the agent more towards a certain initial strategy. Another intuitive hypothesis is that a strategy working well on harder problems, which inhibit a larger makespan, very effectively decreases the large optimality gap of these problems and leads to the strong results. To test whether a strategy that minimizes the particularly large optimality gaps may be incentivized through a curriculum, one may try using the optimality gap instead of the makespan achieved by MTR as DTS metric in the future. Note, however, that this requires solving every training instance optimally, which is much slower than our MTR-based approach especially when applying the method to larger problem instances.

6. Conclusion and Outlook

CL is a promising DRL paradigm, yet not well studied in the context of JSSP solutions. In this study we investigated the impact of a learning curriculum within a fixed problem size of the JSSP. We found that ordering training instances by how well an established priority dispatching rule, MTR, performs on these instances provides meaningful metric for forming curricula that allow us to improve the learning behavior of DRL agents and to increase the scheduling performance. By starting the training with instances sorted from worst to best performances of MTR, our approach consistently outperforms agents trained on randomly ordered training data.

Motivated by the presented results, in our future work we will investigate other metrics for the difficulty of problem instances of the same problem size. These may stem from priority dispatching rules that are combined for better performance or well suited for certain modifications of the JSSP. This is especially necessary for the successful transfer the methodology to other scheduling problems which include more challenging optimization objectives and additional constraints.

Acknowledgements

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Appendix

Table A1: Average optimality gap of priority dispatching rules on the training data.
SPT=Shortest Processing Time First (job-wise); LPT=Longest Processing Time First (job-wise); MTR=Most Tasks Remaining (job-wise); LRPT=Least Remaining Processing (job-wise); MPTLOM=Most Processing Time Left On Machine (machine-wise); RANDOM: Random Prioritization of Jobs

PDR	SPT	LPT	**MTR**	LRPT	LOUM	MPTLOM	RANDOM
opt. gap	0.40	0.32	**0.16**	0.16	0.41	0.35	0.29

References

[1] Badia, A.P., Piot, B., Kapturowski, S., Sprechmann, P., Vitvitskyi, A., Guo, D., Blundell, C., 2020. Agent57: Outperforming the Atari Human Benchmark. Proceedings of the 37th International Conference on Machine Learning 37 (119), 507–5017.

[2] Vinyals, O., Babuschkin, I., Czarnecki, W.M., Mathieu, M., Dudzik, A., Chung, J., Choi, D.H., Powell, R., Ewalds, T., Georgiev, P., Oh, J., Horgan, D., Kroiss, M., Danihelka, I., Huang, A., Sifre, L., Cai, T., Agapiou, J.P., Jaderberg, M., Vezhnevets, A.S., Leblond, R., Pohlen, T., Dalibard, V., Budden, D., Sulsky, Y., Molloy, J., Paine, T.L., Gulcehre, C., Wang, Z., Pfaff, T., Wu, Y., Ring, R., Yogatama, D., Wünsch, D., McKinney, K.,

Smith, O., Schaul, T., Lillicrap, T., Kavukcuoglu, K., Hassabis, D., Apps, C., Silver, D., 2019. Grandmaster level in StarCraft II using multi-agent reinforcement learning. Nature 575 (7782), 350–354.

[3] Iklassov, Z., Medvedev, D., Solozabal, R., Takac, M., 2020. Learning to generalize Dispatching rules on the Job Shop Scheduling. Advances in Neural Information Processing Systems (33), 1621–1632.

[4] Samsonov, V., Hicham, K.B., Meisen, T., 2022. Reinforcement Learning in Manufacturing Control: Baselines, Challenges and Ways Forward. Engineering Applications of Artificial Intelligence (112).

[5] Zhang, C., Song, W., Cao, Z., Zhang, J., Tan, P.S., Chi, X., 2020. Learning to Dispatch for Job Shop Scheduling via Deep Reinforcement Learning. Advances in Neural Information Processing Systems 33, 1621–1632.

[6] Pinedo, M., 2016. Scheduling: Theory, algorithms, and systems, Fifth edition ed. Springer International Publishing.

[7] Bello, I., Pham, H., Le V, Q., Norouzi, M., Bengio, 2016. Neural Combinatorial Optimization with Reinforcement Learning. http://arxiv.org/pdf/1611.09940v3

[8] Puiseau, C.W. de, Meyes, R., Meisen, T., 2022. On reliability of reinforcement learning based production scheduling systems: a comparative survey. Journal of Intelligent Manufacturing 33 (4), 911–927.

[9] Park, J., Chun, J., Kim, S.H., Kim, Y., Park, J., 2021. Learning to schedule job-shop problems: representation and policy learning using graph neural network and reinforcement learning. International journal of production research 59 (11), 3360–3377.

[10] R. Magalhães, M. Martins, S. Vieira, F. Santos, J. Sousa, 2021. Encoder-Decoder Neural Network Architecture for solving Job Shop Scheduling Problems using Reinforcement Learning, in: 2021 IEEE Symposium Series on Computational Intelligence (SSCI). 2021 IEEE Symposium Series on Computational Intelligence (SSCI), pp. 1–8.

[11] van Ekeris, T., Meyes, R., Meisen, T., 2021. Discovering Heuristics And Metaheuristics For Job Shop Scheduling From Scratch Via Deep Reinforcement Learning. Proceedings of the Conference on Production Systems and Logistics: CPSL 2021, 709–718.

[12] Abderrazzak, S., Hamid, A., Omar, S., 2021. Stochastic Dynamic Programming for Earliness-Tardiness Single Machine Scheduling with Maintenance Considerations. IFIP Advances in Information and Communication Technology (634), 269–276.

[13] Brammer, J., Lutz, B., Neumann, D., 2022. Stochastic mixed model sequencing with multiple stations using reinforcement learning and probability quantiles. OR Spectrum (44), 29–56.

[14] Luo, S., 2020. Dynamic scheduling for flexible job shop with new job insertions by deep reinforcement learning. Applied Soft Computing 91.

[15] S. Baer, J. Bakakeu, R. Meyes, T. Meisen, 2019. Multi-Agent Reinforcement Learning for Job Shop Scheduling in Flexible Manufacturing Systems, in: 2019 Second International Conference on Artificial Intelligence for Industries (AI4I). 2019 Second International Conference on Artificial Intelligence for Industries (AI4I), pp. 22–25.

[16] Waschneck, B., Reichstaller, A., Belzner, L., Altenmüller, T., Bauernhansl, T., Knapp, A., Kyek, A., 2018. Optimization of global production scheduling with deep reinforcement learning. Procedia CIRP 72, 1264–1269.

[17] Zeng, Y., Liao, Z., Dai, Y., Wang, R., Li, X., Yuan, B., 2022. Hybrid intelligence for dynamic job-shop scheduling with deep reinforcement learning and attention mechanism, 26 pp. https://arxiv.org/pdf/2201.00548.

[18] Kuhnle, A., Kaiser, J.-P., Theiß, F., Stricker, N., Lanza, G., 2021. Designing an adaptive production control system using reinforcement learning. Journal of Intelligent Manufacturing (44), 855–876.

[19] Luo, P.C., Xiong, H.Q., Zhang, B.W., Peng, J.Y., Xiong, Z.F., 2022. Multi-resource constrained dynamic workshop scheduling based on proximal policy optimisation. International journal of production research (60), 5937–5955.

[20] Rinciog, A., Mieth, C., Scheikl, P.M., Meyer, A., 2020. Sheet-Metal Production Scheduling Using AlphaGo Zero. Proceedings of the Conference on Production Systems and Logistics : CPSL 2020, 342–352.

[21] Narvekar, S., Peng, B., Leonetti, M., Sinapov, J., Taylor E., M., Stone, P., 2020. Curriculum Learning for Reinforcement Learning Domains: A Framework and Survey. Journal Of Machine Learning Research (21), 1–50.

[22] Gandhi, N., Mishra, S., 2021. Modelling resource allocation in uncertain system environment through deep reinforcement learning. https://arxiv.org/pdf/2106.09461.

[23] Hameed, M.S.A., Schwung, A., 2020. Reinforcement Learning on Job Shop Scheduling Problems Using Graph Networks, 8 pp. https://arxiv.org/pdf/2009.03836.

[24] Han, B.-A., Yang, J.-J., 2020. Research on Adaptive Job Shop Scheduling Problems Based on Dueling Double DQN. IEEE Access 8, 186474–186495.

[25] Liu, C.-L., Chang, C.-C., Tseng, C.-J., 2020. Actor-Critic Deep Reinforcement Learning for Solving Job Shop Scheduling Problems. IEEE Access 8, 71752–71762.

[26] Bengio, Y., Lodi, A., Prouvost, A., 2018. Machine Learning for Combinatorial Optimization: a Methodological Tour d'Horizon. https://arxiv.org/pdf/1811.06128.

Biography

Constantin Waubert de Puiseau (*1994) holds a Master's Degree from RWTH Aachen University in Mechanical Engineering. Since 2019, he works at the chair of Digital Transformation Technologies and Management at the University of Wuppertal. His research focuses on solving real-world planning and scheduling problems with reinforcement learning.

Hasan Tercan (*1988) holds a Master's Degree from TU Darmstadt in Computer Science. Since 2018, he is a scientific researcher at the chair of Technologies and Management of Digital Transformation and leader of the research group Industrial Deep Learning. In his research, he investigates the application of machine learning methods in industrial processes.

Tobias Meisen (*1981) is a Professor of Digital Transformation Technologies and Management at the University of Wuppertal since 2018. He is also the Institute Director of the In-Institute for Systems Research in Information, Communication and Media Technology, the vice-chair of the Interdisciplinary Centre for Data Analytics and Machine Learning and a co-founder of Hotsprings GmbH that is now part of Umlaut SE.

4th Conference on Production Systems and Logistics

Source Management In DC-Microgrids: An Industrial Application

Isabella Bianchini[1], Jonas Knapp[1,2], Simon Riethmüller[3], Thorben Kwiatkowski[3], Xiaotian Yang[4], Alexander Sauer [1,2]

[1] *Institute for Energy Efficiency in Production (EEP), University of Stuttgart, Germany*
[2] *Fraunhofer Institute for Manufacturing Engineering and Automation (IPA), Stuttgart, Germany*
[3] *HOMAG GmbH, Schopfloch, Germany*
4 Fraunhofer Institute for Integrated Systems and Device Technology (IISB), Erlangen, Germany

Abstract

Industrial direct current (DC) microgrids offer multiple advantages for production factories. They enable higher energy and resource efficiency not only for the production energy supply but also for integrating renewable energy resources. The basic control method of DC microgrids, namely droop control, fits the industrial application due to its decentralized and robust nature. However, in the case of droop control, the DC bus voltage deviates from the nominal value for slowly fluctuating load situations. For this reason, an additional control level for voltage restoration, called secondary control or source management, is necessary. This paper presents hierarchical control for voltage restoration in industrial DC microgrids. The control shifts the current supplied to the DC bus in case the load increases over or decreases below a defined voltage band for a certain period. In addition, the designed control is tested on a real industrial DC microgrid which includes typical industrial loads of up to 50 kW, such as robots of different sizes and CNC machine tools. The control performance with different parameters of the source management is assessed. The results show that the designed control restores the voltage level without creating instabilities in the microgrid for all tested scenarios.

Keywords

Industrial microgrid; direct current supply; droop control; hierarchical control; voltage deviation;

1. Introduction

Over the past years, the concept of direct current (DC) microgrids for integrating renewable energy sources has been proposed and studied. Renewable generation, such as photovoltaic (PV) and wind, inherently foresees the presence of a DC-DC or AC-DC conversion step for the grid connection. Due to their nature, their integration in DC grids is more efficient than in alternate current (AC) grids [1]. In addition, compared to the AC microgrids, DC microgrids overcome disadvantages such as frequency synchronisation, reactive power control, and skin effect [2]. The interest in DC microgrids and technologies has been growing in many sectors, such as residential, data centres, electricity distribution, and industry [3–5]. In the industrial sector, where the loads are increasingly being supplied by converter technologies, DC technology and microgrids have gained attention [6]. For industrial DC applications, a reduction of conversion losses of up to 3.75 % for loads and 7 % for storage systems have been estimated [7]. In addition, the DC technology enables braking energy recovery from drives and the supply of this energy into the grid instead of being converted into heat through braking resistors [8]. In the case of a Computerized Numerical Control (CNC) machine, the combination of reduced conversion losses and recuperation of braking energy resulted in an overall

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energy efficiency increase of 6.2 % [7]. In the case of industrial robots, Meike et al. estimated a recuperation potential of 15 % during operation. Resource efficiency of industrial companies can be improved by DC microgrids due to the reduced cabling requirements and the elimination of conversion steps [7]. Two phases of the German research project DC-INDUSTRIE proposed the concept of a non-proprietary DC microgrid, which aims at spreading DC microgrids in the industrial sector [9,10].

Droop control is the basic control method for DC microgrids. It is a decentralized control method based on a control loop over the converters' inner voltage and current control loops. The control uses a virtual resistance or conductance to define the target voltage (current droop control) or the target current (voltage droop control) at the device´s connection point to the DC bus [6,11]. However, it has two main limitations, the current sharing among converters and voltage deviation [1,12]. The voltage deviation is an inherent consequence of the droop control. In the case of high load, the converter with voltage droop curve compensates the load with higher current and the voltage is shifted towards lower values. In the case of low loads, the voltage is shifted towards higher voltage values. The DC bus voltage is located outside the nominal voltage band in both cases. In order to compensate for the voltage deviation, multiple approaches have been proposed in literature. These approaches are based on a higher control level, called the secondary control level [12] or source management [13], over the droop curve control. According to communication requirements, source management can be classified as decentralized, distributed and centralized [14].

This paper proposes a source management for nominal voltage restoration for industrial DC microgrids. In addition, the results of an actual application in a small-scale industrial DC microgrid are presented. The paper proves that, despite the simplicity of the approach, the control manages to restore the voltage level. The paper is structured as follows. Section 2 introduces the state of the art of secondary or source management of DC microgrids. Section 3 describes DC microgrid concept and defines the industrial system for the tests. Section 3 introduces the hierarchical control approach based on droop curves-based primary control and source management for voltage restoration. Then, section 4 applies the control approach exemplarily to the industrial system before presenting and discussing the results. Finally, section 5 offers a summary and outlook.

2. State of the art

In [15], the secondary level of the DC microgrid control proposed by Nutkani et al. aims at current sharing and voltage restoration and operates over the droop control level. It considers economic values, such as generation costs and grid tariff. The centralized second control level shifts the voltage to restore the nominal voltage level. The control does not require a high bandwidth communication, and it is tested in simulations. Zhao et al. in [16] propose a piecewise droop control strategy for improved voltage regulation. Multiple current droop curves for each converter are defined that can be changed in a decentralized manner according to the load situation. The effective switch between droop curves is tested in a laboratory-scale 30 V DC microgrid with two converters and resistive loads. In [1], Lu et al. propose a distributed hierarchical control system for voltage restoration and current sharing. A low-bandwidth communication scheme for exchanging local output current and voltage measurement between the secondary controllers is defined. The current and voltage measurement is used for the definition of voltage and current shift values, which are then combined with the results of the droop control. The control is tested in MATLAB/Simulink simulations. Nasirian et al. in [17] define a similar distributed secondary control system based on two modules, a voltage controller, and a current controller. Here, the voltage controller is based on a cooperative voltage observer for the global voltage estimation. The current control compares local currents and neighbouring currents to adjust the virtual droop resistance. The control system is tested on a DC microgrid prototype with a rated voltage of 48 V. A real-time control for voltage restoration and current sharing in DC microgrids is proposed by Olives-Camps et al. in [18]. The control can solve optimization problems without requiring a precise model. Control performances are assessed in simulations, testing both centralized and distributed control implementation. It

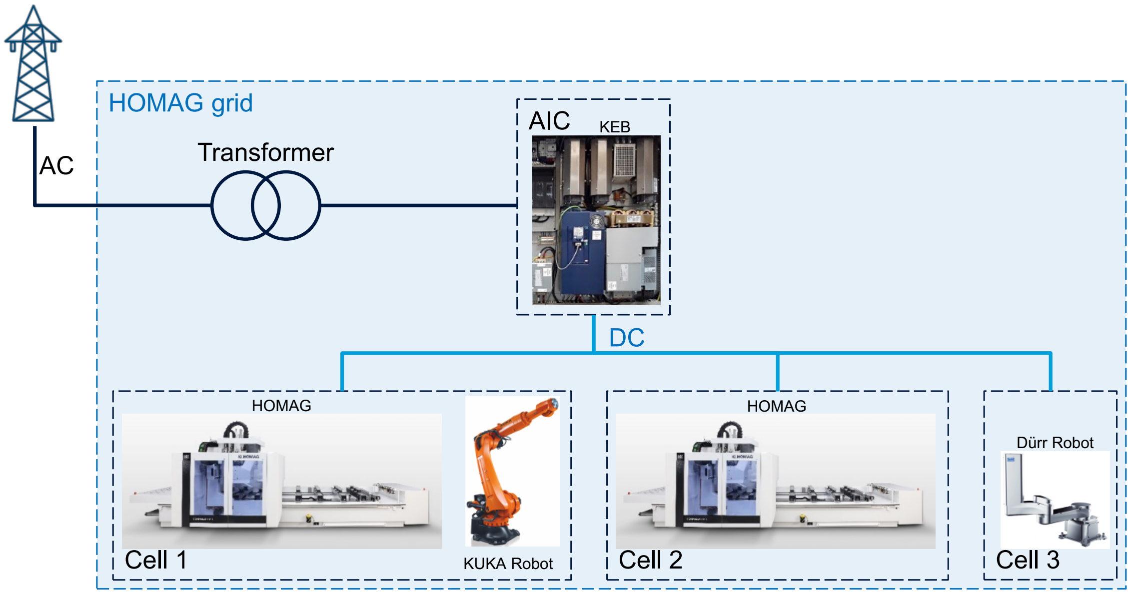

Figure 1: Structural diagram of the electrical DC microgrid at HOMAG plant. An active infeed converter (AIC) is the interconnection point between the AC grid and DC microgrid and supplies the consumers in three cells.

is shown that the control is robust, the distributed implementation has good dynamic performances, and reduces communication requirements.

The proposed control approaches can restore the voltage level and improve the DC microgrid performance. However, some of the proposed control strategies are highly complex and require communication between converters. The design of the hierarchical control for industrial microgrids should guarantee simplicity and reliability [13]. Moreover, in industry the attractiveness of effective but simple and reliable control systems increases when the approaches have been successfully tested in an actual industrial system. However, here mostly simulation and laboratory-scale microgrids are tested.

3. Description of the industrial DC microgrid

Figure 1 shows the typical structure of a DC grid, here using the HOMAG DC microgrid as an example. All devices are connected to a DC bus consisting of a power rail distributing power within the devices. An active infeed converter (AIC) feeds the bus system. The AIC is the interconnection point between the AC and the DC grid and transforms the voltage to the appropriate level [10]. In addition, there was an energy storage system, a lithium ion battery with a capacity of 200 Ah (two battery cells with 100 Ah and 50 V each). However, it was not used in the test and thus is not shown in Figure 1. The consumers of the DC grid comprise three cells. The first cell includes a HOMAG woodworking machine and a robot. The robot in cell 1 loads the machine with workpieces. The second cell uses another woodworking machine similar to the one in the first cell, but without robot. The third cell is the smallest in terms of power, as only a small robot is integrated.

For the following sections, it is necessary to define active devices and to distinguish them from passive ones. Each active device receives a predefined droop curve and adjusts its supply and/or consumption according to the DC bus status. Therefore, the active device is actively involved in the control of the DC microgrid. For the DC grid used in this paper, the AIC is the only active device and the three consumer cells are passive devices.

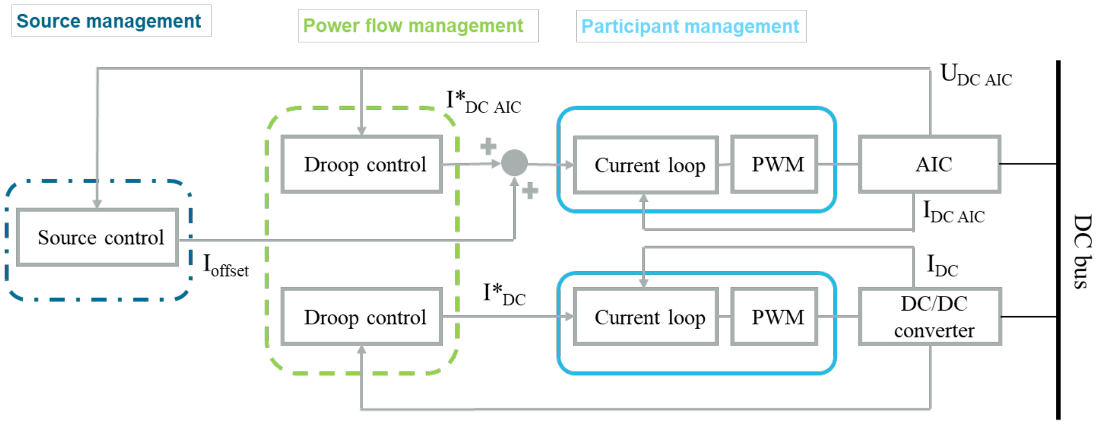

Figure 2: Schematic representation of the hierarchical control for the industrial DC microgrid used in this paper. The control includes power flow management (primary droop control) and source management (secondary control). Participant management is out of the scope of the paper.

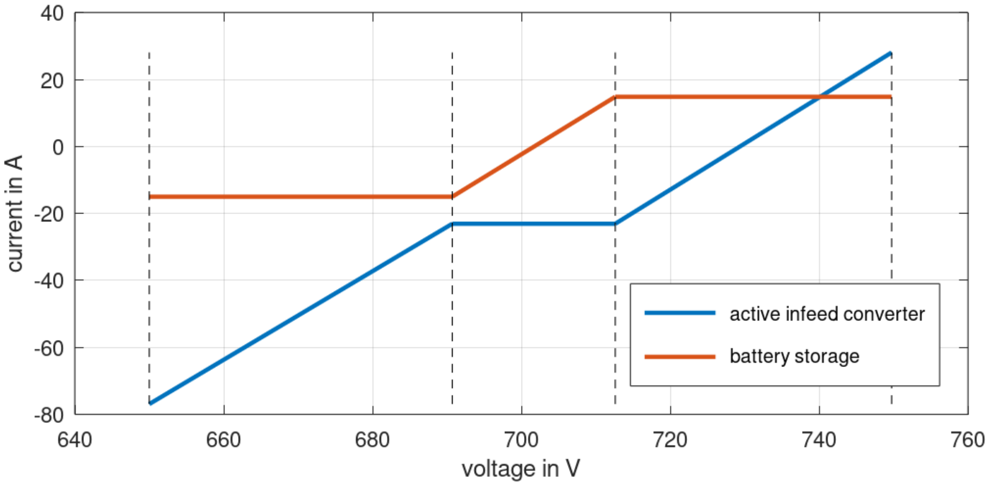

Figure 3: Example of droop curves including an AIC and battery storage system.

4. Control design

The DC microgrid control presented in this paper is a hierarchical control. The lower level is based on the on droop curves and the higher level is managed by a secondary control, the source management (Figure 2). The droop control is designed for all the active participants of the microgrids [13]. The source management operates in a centralized way, delivering a current offset that is added to the current defined by the active participants' droop control. Only the active devices included in the source management receive the current offset. The following paragraph describes both control levels. The lowest control level, also referred to as participant management, is out of the scope of this paper.

4.1 Droop curve control design

To control voltage and balance power within the DC grid, every active device measures its voltage and adapts its power infeed proportionally to the voltage deviation. The droop curve-based approach does not depend on digital communication and has the smallest possible response time, only limited by converter dynamics. **Error! Reference source not found.** shows an example of droop curves of the AIC and the battery storage. Devices supply the DC microgrid if the current is negative, while they absorb power from the grid if the current is positive. The vertical dotted lines divide three areas in which only one device actively adjusts its power infeed to the voltage variations. In this case, the respective droop curve has a positive power

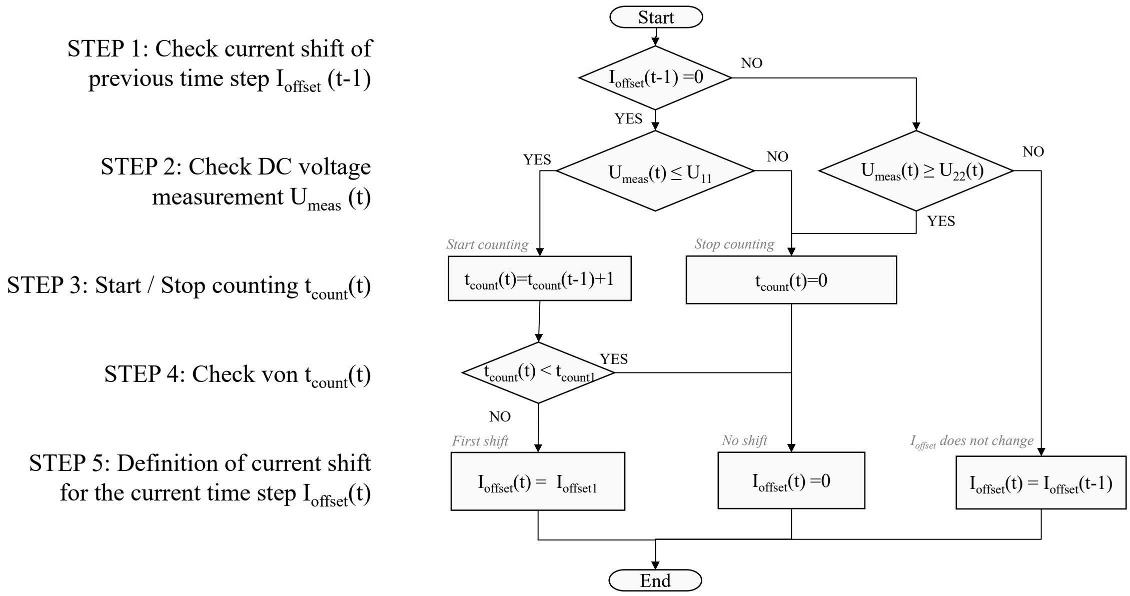

Figure 4: Flowchart of the source management implemented on the PLC of the active infeed converter (AIC) for voltage restoration. Considered case: high load.

gradient. At the same time, the other device supplies a constant power, which does not depend on the voltage, and its droop curve gradient is equal to zero. More details about droop curves and the relevant parameters can be found in literature [6,10].

Depending on the design of the droop curve, certain functions, such as peak shaving, are implemented. The operating point in normal mode is between the inner two dotted lines [690 V; 716 V]. In this area, the AIC constantly feeds around 23 A into the DC grid while the battery storage compensates for power deviations and thus operates peak shaving. Other functions that can be implemented are: charge/ discharge storage, feed into DC grid, feed back into AC grid, or uninterruptible power supply.

As previously described, the AIC is the only active device in the HOMAG microgrid and, thus, the only device with a droop curve. Its droop curve corresponds to the one in Figure 3.

4.2 Source management design

If the loads are higher than the nominal ones, the voltage level in a DC microgrid is reduced. If this higher load stagnates for a longer time, an undesirable operating point closer to the stability limit will be used. The aim of the source management designed in this paper is to restore the voltage level at the nominal value. The control is centralized and operated by the AIC’s programmable logic controller (PLC). Figure 4 shows the flowchart of the source control as implemented in the AIC’s PLC.

In order to restore the nominal voltage, the control activates a current shift that is added to the droop curve target current and increases the current delivered by the AIC. The negative shift (more current supplied to the microgrid) is activated if the measured DC bus voltage is lower than a certain voltage threshold U_{11} for more than a predefined time limit t_{count}. This way, the source management is activated only when the loads are higher than nominal power for longer periods. To avoid frequent activation and deactivation, the I_{offset} is set back to zero in case the voltage overcomes a second threshold U_{12} higher than U_{11}.

The same can be defined for low loads and high voltage levels. In this case, the shift will be positive (less current supplied to the microgrid) and the voltage thresholds will be higher than the nominal voltage, with $U_{22} < U_{21}$. This part of the control is not tested and is out of the scope of this paper.

5. Results

This paragraph describes the results of applying the proposed control design (section 4) in the industrial system described in section 2. To test the designed control, different scenarios were defined (see Table 1). In the first scenario, only the droop curve-based control is considered, and the source management is deactivated. The scenarios SM1, SM2, and SM3 differ due to the value of U_{12}. Scenario SM4 is an extreme scenario differing from SM1 because of doubled current offset and longer counter time.

Figure 6 shows the results of the first two scenarios, where voltage and current profiles are compared. The effect of the control is apparent. When the voltage at the AIC's DC side remains longer than 0.5 seconds under 695 V, then the secondary control is activated, and the I_{offset} is added on the droop curve, causing the shift in the current (examples: 38.19 s, 40.77 s, and 41.54 s). On the other hand, the secondary control is deactivated, and the I_{offset} is set back to zero when the voltage overcomes the second voltage limit U_{12} of 700 V (examples: 40.05 s, 40.98 s, and 41.82 s). When activated, the secondary control causes a small voltage overshoot during the settling time. In this scenario, the voltage step is not sufficient to reach an inflection point of the droop curve, as it happens after the first shift in the figure (38.19 s): even if the voltage exceeds

Table 1: Test scenarios description and parameter definition.

Scenario	Description	U_{11} [V]	U_{12} [V]	I_{offset} [A]	t_{count} [s]
Droop	Droop-curve control only	0	0	0	0
SM1	Droop-curve & source management 1	695	700	-5	0.5
SM2	Droop-curve & source management 2	695	702	-5	0.5
SM3	Droop-curve & source management 3	695	705	-5	0.5
SM4	Droop-curve & source management 4	695	700	-10	0.8

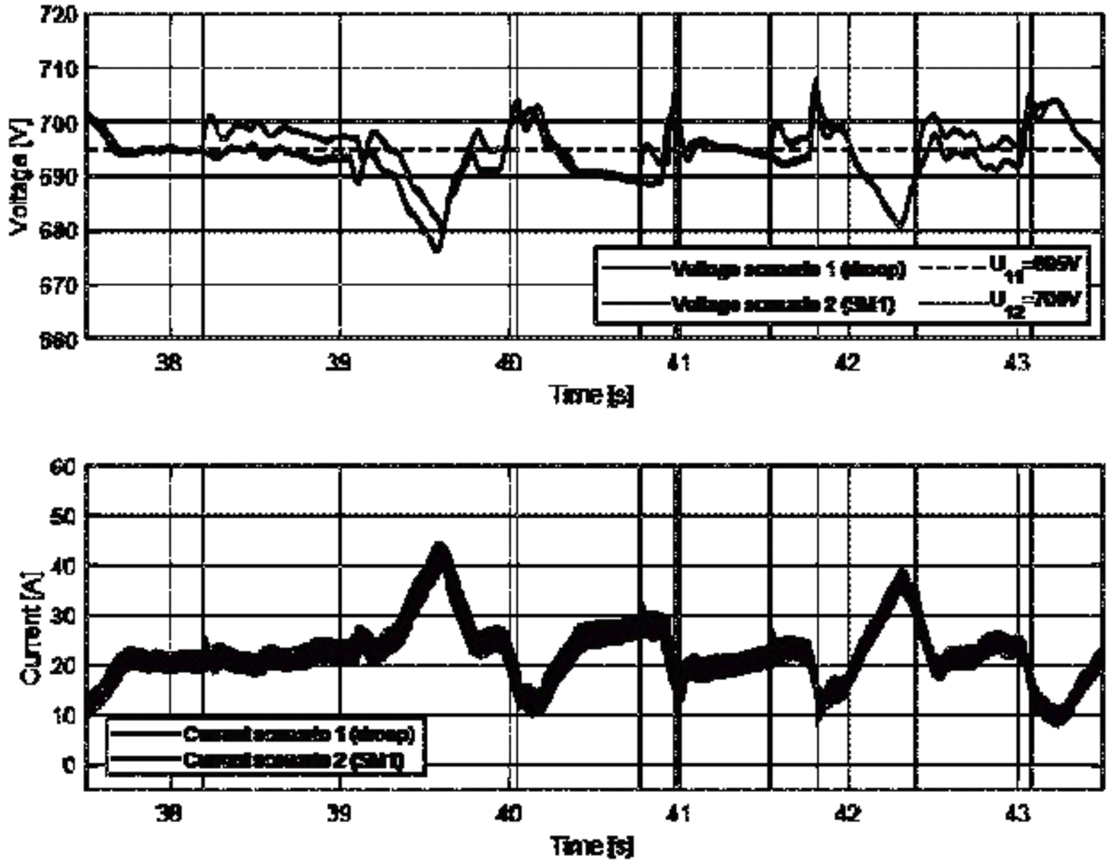

Figure 5: Results from scenario 1 (droop) and 2 (SM1), voltage measurements top, current measurement bottom.

the limit voltage of 700 V, the control is not deactivated until 40.77 s. Since the control operates on the current, the shift is almost instantaneous (current step). However, after circa 100 ms, the dynamics end and the supplied current of scenario SM1 follows the current of scenario "droop". In both scenarios, the system remains stable. Similar voltage and current profiles are measured in scenarios SM2 and SM3 but with later deactivation times of the control. Different are the profiles obtained in scenario SM4. Figure 7 presents the results of the last scenario. The activation is followed by a deactivation after less than 100 ms. This is due to the high current step caused by the control and the fast voltage increase over 700 V, which deactivates the shift. This happens in all the cases showed in Figure 7 except for the activation at 39.48 s. In this case, the load has a peak and shift in current is not enough to overcome the threshold of 700 V. Also in this scenario, the system remains stable.

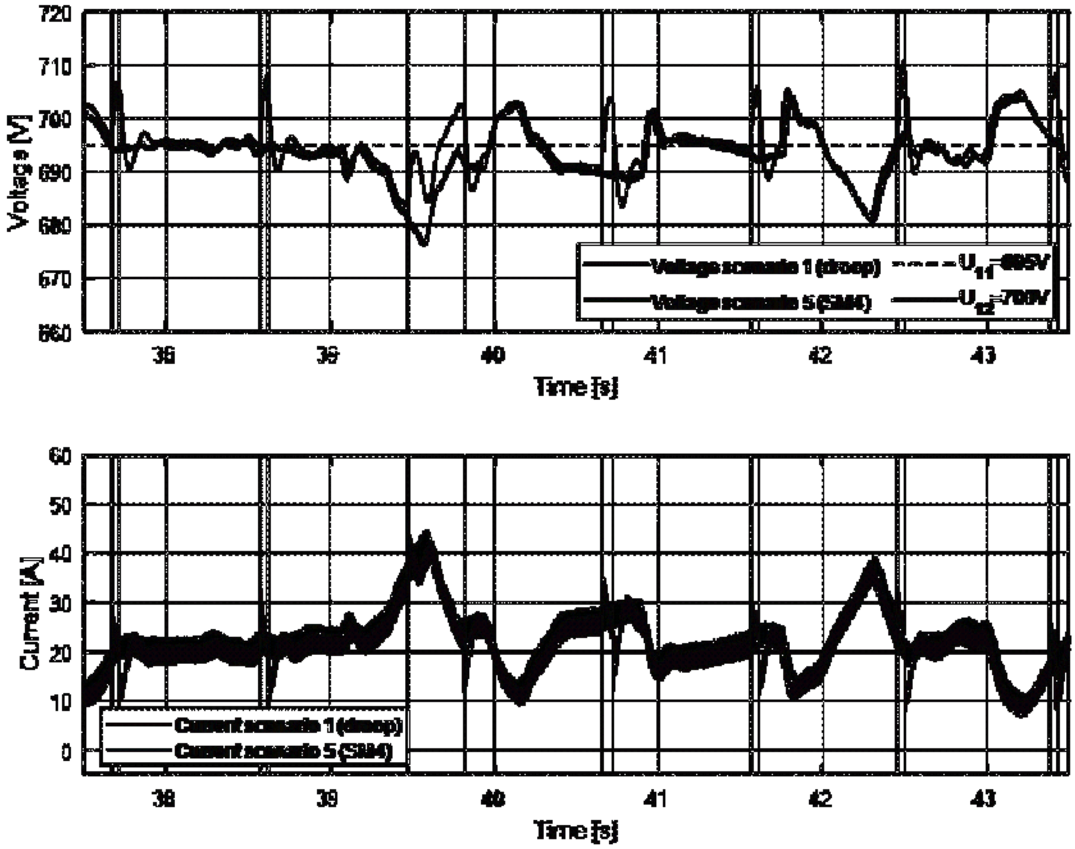

Figure 6: Results from scenario 1 (droop) and 5 (SM4), voltage measurements top and current measurement bottom.

Table 2: Performance parameters for the results assessment. *Active control time for scenario SM2 could not be measured during the test.

Scenario	Active control time	Min. voltage [V]	Max. voltage [V]	Mean voltage [V]	Median voltage [V]	Standard deviation voltage [V]
Droop	0%	667.0	711.1	693.3	694.1	6.0
SM1	45%	667.8	712.3	695.3	696.1	5.5
SM2	-*	667.6	713.8	695.6	696.3	5.6
SM3	83%	670.8	715.6	697.3	698.1	5.5
SM4	9%	668.9	717.9	694.5	694.9	5.9

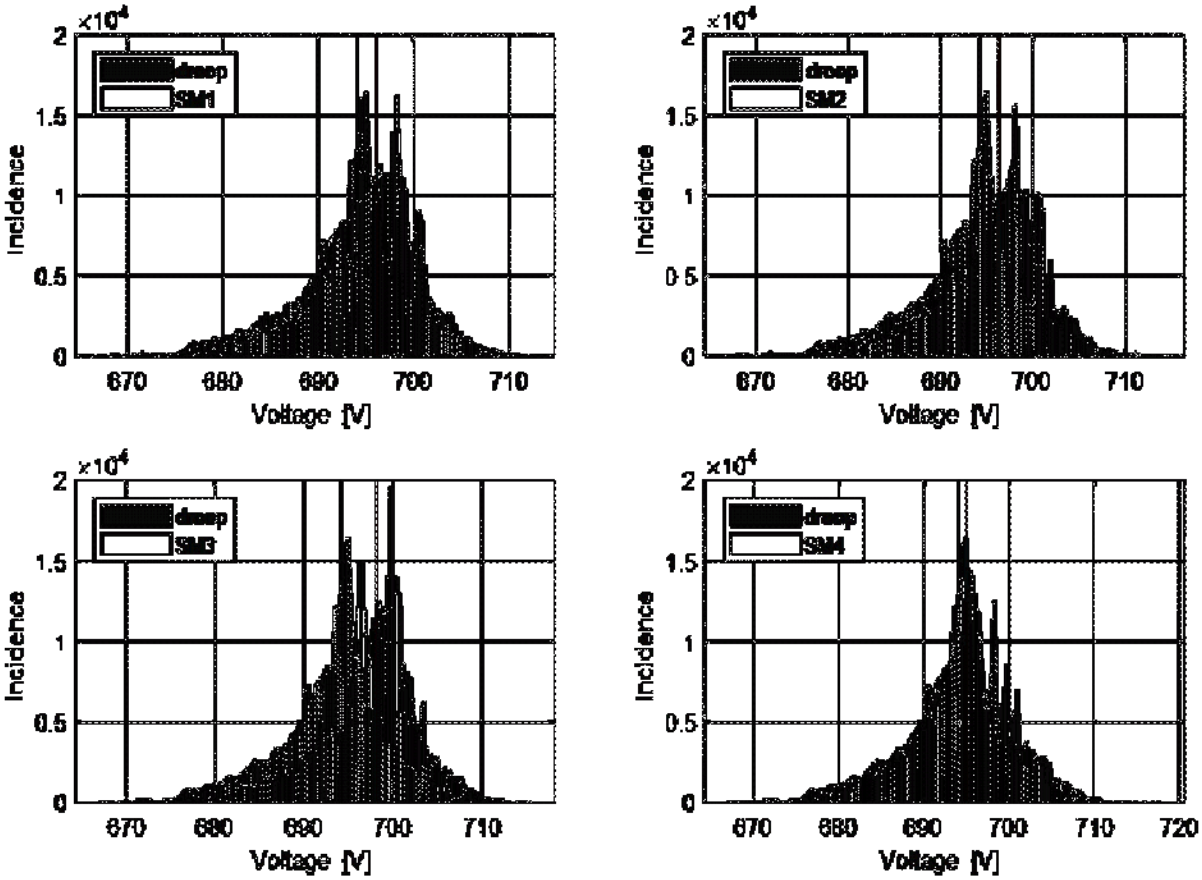

Figure 7: Histograms of measured voltage incidence. Each scenario with source management is compared to the droop curve only scenario.

To systematically assess the results, performance parameters were defined (Table 2). Active control time is when the source management is active, and the current shift is equal to I_{offset}. Increasing U_{12} has the effect of a longer maintained droop curve shift. Differently, in SM4, the active time is only 9 % of the test time. This is due to the voltage overshoot after activation and the almost direct deactivation of the control. Even if the parameter could not be calculated for scenario SM2 due to measurement problems, it is possible to assume that the active control time increases with the voltage limit U_{12}.

The control in all scenarios SM1-4 increases both the minimum and maximum DC voltage. The minimum voltage variation compared to scenario droop is not remarkable in scenarios SM1, SM2, and SM4 and increases up to 3.8 V for scenario SM3. The maximum voltage variation compared to scenario droop increases consistently with the increased voltage limit *U12*. The same effect has the high current shift in scenario SM4, in which the voltage reaches a peak of 717.9 V.

Mean and median voltages consistently increase with the voltage limit *U12*, from 2.0 V to 4.0 V difference with scenario droop. However, in scenario SM4, the mean and median variation from scenario droop is limited to 1.2 V and 0.8 V. This is due to the limited active time of the control: even if minimum and maximum voltages are higher, the control does not affect the average voltage.

Regarding the voltage standard deviation, a decrease can be observed. In particular, for scenario SM1-3, the voltage values are more concentrated around the mean values. In Figure 8, the incidence of voltage levels is presented in histograms. The median is shifted right, thanks to the source management (SM1-3). In case of SM4, the difference is barely visible due to the limited control active time.

6. Conclusion

This paper presents the concept of a hierarchical DC microgrid control for voltage restoration. Source management operates over the droop curve control level to restore the voltage at the nominal level through a current shift. The control concept is implemented and tested on an actual application, a real industrial DC microgrid, including different robots and woodworking machines for a load of up to 50 kW. The results show that this simple control concept can shift the voltage to higher values in all test scenarios. In addition, no instability occurs. Therefore, this control concept is promising for the installation in industrial DC microgrids. Further research should include the definition of a method for computing the source management parameters based on the load profile and the formal investigation of the control stability. Future applications should test the low load case, i.e., the voltage shift towards lower voltage levels in case of low load, and test other DC microgrids with different devices and load.

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References

[1] Lu, X., Guerrero, J.M., Sun, K., Vasquez, J.C., 2014. An Improved Droop Control Method for DC Microgrids Based on Low Bandwidth Communication With DC Bus Voltage Restoration and Enhanced Current Sharing Accuracy. IEEE Trans. Power Electron. 29 (4), 1800–1812.

[2] Liu, Q., Tao, Y., Liu, X., Deng, Y., He, X., 2014. Voltage unbalance and harmonics compensation for islanded microgrid inverters. IET Power Electronics 7 (5), 1055–1063.

[3] Chen, S.-M., Liang, T.-J., Hu, K.-R., 2013. Design, Analysis, and Implementation of Solar Power Optimizer for DC Distribution System. IEEE Trans. Power Electron. 28 (4), 1764–1772.

[4] Dong, D., Cvetkovic, I., Boroyevich, D., Zhang, W., Wang, R., Mattavelli, P., 2013. Grid-Interface Bidirectional Converter for Residential DC Distribution Systems—Part One: High-Density Two-Stage Topology. IEEE Trans. Power Electron. 28 (4), 1655–1666.

[5] Schaab, D.A., Weckmann, S., Kuhlmann, T., Sauer, A., 2018. Simulative Analysis of a Flexible, Robust and Sustainable Energy Supply through Industrial Smart-DC-Grid with Distributed Grid Management. Procedia CIRP 69, 366–370.

[6] Schaab, D.A., Sauer, A. DC-Microgrids will change Electric Power Supply in German Industry, in: , World Sustainable Energy Days 2020, 4 - 6 March 2020, Wels / Austria.

[7] Kuhlmann, T., Bianchini, I., Sauer, A., 2020. Resource and energy efficiency assessment of an industrial DC Smart Grid. Procedia CIRP 90, 672–676.

[8] Meike, D., 2013. Increasing Energy Efficiency of Robotized Production Systems in Automobile Manufacturing. PhD Thesis. Riga, 1–214.

[9] Borcherding, H., Austermann, J., Kuhlmann, T., Weis, B., Leonide, A. Concepts for a DC network in industrial production. 2017 IEEE Second International Conference on DC Microgrids (ICDCM), 227–234.

[10] ZVEI & consortium DC-INDUSTRIE2, 2022. System concept DC-INDUSTRIE2. https://dc-industrie.zvei.org/en/publications/system-concept-for-dc-industrie2. Accessed date: 15.11.2022.

[11] Shuai, Z., Fang, J., Ning, F., Shen, Z.J., 2018. Hierarchical structure and bus voltage control of DC microgrid. Renewable and Sustainable Energy Reviews 82, 3670–3682.

[12] Meng, L., Dragicevic, T., Vasquez, J.C., Guerrero, J.M., 2015. Tertiary and Secondary Control Levels for Efficiency Optimization and System Damping in Droop Controlled DC–DC Converters. IEEE Trans. Smart Grid 6 (6), 2615–2626.

[13] Bianchini, I., Kuhlmann, T., Wunder, B., Unru, A., Sauer, A., 2021. Hierarchical Network Management of Industrial DC-Microgrids. 2021 IEEE Second International Conference on DC Microgrids (ICDCM), 1–6.

[14] Dragicevic, T., Lu, X., Vasquez, J., Guerrero, J., 2015. DC Microgrids–Part I: A Review of Control Strategies and Stabilization Techniques. IEEE Transactions on Power Electronics 7 (31), 4876–4891.

[15] Nutkani, I.U., Peng, W., Loh, P.C., Blaabjerg, F., 2014. Autonomous economic operation of grid connected DC microgrid. 2014 IEEE 5th International Symposium on Power Electronics for Distributed Generation Systems (PEDG), 1–5.

[16] Zhao, P., Liu, Z., Zhao, Y., Wang, Q., Liu, J., 2021. An Adaptive Piecewise Droop Control Strategy for DC Microgrids. 2021 IEEE Fourth International Conference on DC Microgrids (ICDCM), 1–6.

[17] Nasirian, V., Davoudi, A., Lewis, F., Guerrero, J., 2016. Distributed adaptive droop control for DC distribution systems. 2016 IEEE Power and Energy Society General Meeting (PESGM), 1–13.

[18] Olives-Camps, J.C., Del Rodríguez Nozal, Á., Mauricio, J.M., Maza-Ortega, J.M., 2022. A model-less control algorithm of DC microgrids based on feedback optimization. International Journal of Electrical Power & Energy Systems 141, 108087.

Biography

Isabella Bianchini (*1990) studied electrical engineering at Pavia University, Italy. Since 2019 she has been a research associate at the Institute for Energy Efficiency in Production (EEP) of the University of Stuttgart. Her research focus includes industrial energy flexibility, demand response, and control of DC microgrids.

Jonas Knapp (*1994) studied engineering cybernetics at University of Stuttgart, Germany. Since 2021 he has been a research associate at the Institute for Energy Efficiency in Production (EEP) of the University of Stuttgart. His research focus includes modelling and simulation of industrial power grids, control design of DC microgrids, and potential analysis of electrical energy grids.

Simon Riethmüller (*1993) studied mechatronics engineering at Baden-Wuerttemberg Cooperative State University Stuttgart campus Horb, Germany. Since 2021 he has been project manager for the research project DC-INDUSTRIE 2 at HOMAG GmbH Schopfloch, Germany. His focus in the project includes the coordination of build up and start up the model plant provided by HOMAG for the research project and the coordination of tests at the plant.

Thorben Kwiatkowski (*1994) studied mechatronics engineering at Baden-Wuerttemberg Cooperative State University Stuttgart campus Horb, Germany. Since 2020, he has been an automation developer in the product development department at HOMAG GmbH. His main areas of expertise include PLC programming, virtual modelling, and the development of project and ramp-up tools.

Xiaotian Yang (*1993) studied electrical engineering at RWTH Aachen University, in Germany. Since 2020 he has been a research associate at the Fraunhofer Institute for Integrated Systems and Device Technology IISB. His research focus includes modelling and control of power electronic converters in the context of DC microgrids.

Alexander Sauer (*1976), Prof. Dr.-Ing. Dipl.-Kfm., studied mechanical engineering and business administration at RWTH Aachen University and received his PhD at the RWTH Aachen University. He is head of the Institute for Energy Efficiency in Production (EEP) at the University of Stuttgart and head of the Fraunhofer Institute for Manufacturing Engineering and Automation IPA in Stuttgart.

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Deriving Digital Energy Platform Archetypes for Manufacturing – A Data-Driven Clustering Approach

Sebastian Duda[1,2], Lukas Fabri[1, 3], Can Kaymakci[4,5],Simon Wenninger[1,3], Alexander Sauer[4,5],

[1] Branch Business & Information Systems Engineering of the Fraunhofer FIT, Augsburg-Bayreuth, Germany
[2] FIM Research Center, University of Bayreuth, Germany
[3] FIM Research Center, University of Applied Sciences Augsburg, Germany
[4] Fraunhofer Institute for Manufacturing Engineering and Automation IPA, Stuttgart, Germany
[5] Institute for Energy Efficiency in Production (EEP),University of Stuttgart, Stuttgart, Germany

Abstract

External factors such as climate change and the current energy crisis due to global conflicts are leading to the increasing relevance of energy consumption and energy procurement in the manufacturing industry. In addition to the growing call for sustainability, companies are increasingly struggling with rising energy costs and the power grid's reliability, which endangers the competitiveness of companies and regions affected by high energy prices. Appropriate measures for energy-efficient and, not least, energy-flexible production are necessary. In addition to innovations and optimizations of plants and processes, digital energy platforms for the visualization, analysis, optimization, and control of energy flows are becoming essential. Over time, several digital energy platforms emerged on the market. The number and the different functionalities of the platforms make it challenging for classic manufacturing companies to keep track of and select the right digital energy platform. The characteristics and functionalities of digital energy platforms have already been identified and structured in literature. However, classifying existing platforms into archetypes makes it easier for companies to select the platforms providing the missing functionality. To tackle this issue, we conducted an explorative and data-driven cluster analysis based on 47 existing digital energy platforms to identify digital energy platform archetypes and derive implications for research and practice. The results show four different archetypes that primarily differ in terms of energy market integration functionalities: Research-Driven Energy Platforms, Energy Flexibility Platforms, SaaS-Aggregators / Virtual Power Plants, and (Manufacturing) IoT-Platforms. Decision makers in manufacturing companies will benefit from the archetypes in future analyses as decision support in procurement processes and modifications of digital energy platforms.

Keywords

Digital Energy Platform; Demand Side Management; Energy Flexibility; Clustering

1. Introduction

The negative consequences of climate change, global crises, and local energy shortages require targeted and effective measures to achieve the climate targets in the international climate agreements [1]. The German government has adopted the phase-out of coal and nuclear power generation as a critical measure [2]. To ensure a sufficient power supply, the share of electricity generation from renewable energy sources should already increase to 80% of electricity consumption by 2030 [3]. However, the output of renewable energy

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sources is highly dependent on external circumstances such as the sun and wind [4]. Therefore, an increase in storage capacities and synergy effects (e.g., in sector coupling) is necessary for transforming towards clean electricity generation. Demand side management (DSM) offers a competitive solution to meet the expected challenges by increasing energy flexibility (EF) on the demand side [5]. The industrial sector offers significant potential for savings. This sector accounts for 44 percent of electricity consumption in Germany [6]. At the same time, this sector offers considerable potential for balancing fluctuations in the power grid by adjusting power consumption to the available power [7]. Energy-intensive industrial companies typically can shut down, shift, or regulate their (production) processes and equipment to adjust their electricity demand [8]. Exploiting EF helps companies to benefit from reduced energy procurement costs by responding to volatile electricity prices or reducing their grid charges by avoiding peak loads while contributing to the stabilization of the power grid [9]. Despite these advantages, the exploitation of EF in manufacturing companies is low [10]. For companies that intend to exploit EF and need to select suitable platform solutions, it is often unclear which aspects and functions of a platform are relevant to them [11]. Evaluating available platforms is time-consuming, and tools and assistance such as a pre-classification of platforms and their characteristics do not exist. Besides platform selection obstacles, Leinauer et al. [12] identify technical obstacles such as high IT requirements, high effort, and complexity within IT systems, IT security and data security, lack of IT prerequisites in companies, lack of standardization of IT systems, and the lack of interoperability of IT systems that refrain companies from exploiting EF. Additionally, Honkapuro et al. [13] found the "lack of economic benefits, lack of motivation among the customers, [and] missing standards in data system interfaces" as major obstacles to exploiting available EF. DEPs tackle all said obstacles by providing economic benefits, simplifying exploitation, and proposing standards. As a first step to shedding light on the perceived black box and support companies, Duda et al. [11] developed a multi-layer taxonomy of digital energy platforms (DEPs) for DSM applications in the industry that includes a general and a more specific data-centric and transaction-centric perspective. While the taxonomy creates a solid foundation for understanding and analyzing DEPs in detail, structuring the market and landscape of existing platforms to simplify the selection process is still arduous. To identify, conceptualize, and define typical setups of platforms, deriving archetypes, such as done by Arnold et al. [14] for the case of IIoT platforms, has established a solid approach in literature. To address this vacuum of missing archetypes of DEPs, we formulate our guiding research question as follows:

Which archetypes of digital energy platforms exist in the manufacturing domain?

To adequately address our research question, we follow an explorative, data-driven clustering approach embedded in an adapted process of the well-established Cross Industry Standard Process for Data Mining (CRISP-DM). Moreover, we derive four archetypes of DEPs, illustrating which roles digital energy platforms can play. The remainder of this paper is structured as follows: Section 2 provides the theoretical background of DEPs before we detail the methodological approach in Section 3. Section 4 presents our cluster analysis and the derived archetypes. Section 5 gives implications for research and practice before it concludes with limitations and prospects for further research.

2. Literature

Digital platforms are emerging in almost all industries [15]. To enable the industry to use DSM and exploit their EF in their production processes, DEPs provide innovative services [16] and connect the industry with providers for control parameters (e.g., contemporary energy procurement costs [17]) or marketplaces (e.g., for trading EF) [18]. Zhong et al. [19] show that integrating DEPs into the existing production planning and controlling is key for the practical usage of DSM and exploiting the EF. A platform architecture has advantages since platforms can connect a company's heterogeneous components, planning systems, and machines [18]. In recent years, many DEPs have been developed (see Table 1). Yet, the DEPs provide different functionality and are based on various architectures and business models. Taxonomies can help to classify and compare DEPs.

Taxonomies aid in classifying entities into their dimensions. Depending on whether one can choose one or multiple characteristics of a dimension, the dimension is exclusive (E) or non-exclusive (NE). This allows decision-makers and researchers to distinguish between and compare different manifestations of the entities. Based on the taxonomy, real-world examples can be classified by creating groups of entities - archetypes. Decision-makers can use a taxonomy and respective archetypes to select the appropriate entity for their needs. There is an active research stream that develops taxonomies for platforms. Blaschke et al. [20] developed a taxonomy to categorize digital platforms according to four dimensions (infrastructure, core, ecosystem, and service dimensions). Blaschke et al. [20] used the method to build taxonomies proposed by Nickerson et al. [21]. In addition, they derived three archetypes of digital platforms. Moreover, there are taxonomies for platforms in multiple domains. Bouadjenek et al. [22] developed a taxonomy that classifies social information retrieval platforms. A taxonomy of mobility platforms was developed by Harri et al. [23]. Arnold et al. [14] developed a taxonomy and derived archetypes of industrial internet of things platforms. Also, in the domain of energy management, there are taxonomies. Khan et al. [24] developed a smart meter data taxonomy, Behrens et al. [25] proposed a taxonomy on constraints in DSM methods, and Karlin et al. [26] derived a taxonomy of energy feedback systems. However, the academic discourse lacks a more detailed look at DEPs. Duda et al. [11] propose a taxonomy to categorize DEPs but to better understand these platforms, the derivation of respective archetypes is critical. This paper builds on their taxonomy (see Figure 1) to derive archetypes.

	Dimensions	Characteristics				Exclusivity
General dimensions	Platform operator	Company	Consortium	Aggregator		E
	Access	Web-App	Native-App	Specific interface		NE
	Operational concept	On-Premise	Cloud	Hybrid		NE
	Access requirements	Free Access	Certain criteria to fulfill	Certain devices necessary		NE
	Platform structure	Fixed structure	Modular structure without external interfaces	Modular structure with external interfaces		E
Data-centric dimensions	Platform type	SaaS	PaaS			E
	Communication	One-to-Many	Many-to-Many			E
	Data flow	Unidirectional	Bidirectional			E
	Data processing	Transactional	Visual analysis	Data-driven analysis		NE
	Data source	Device	Cloud			NE
Transaction-centric dimensions	Main function	Electricity trading	Energy flexibility trading	Virtual power plant		E
	Trading venue	Stock Exchange	Markets for system services	OTC		NE
	Flexibility type	Market flexibility	System flexibility	Grid flexibility		NE
	Market design	Open	Closed			E
	Pricing	Free	Regulated	Free with regulating elements	No pricing	NE

Figure 1: The multi-layer taxonomy for DEPs of Duda et al. [11]

3. Methodological Approach

In this paper, we used the CRISP-DM process to address the paper's research question adequately. We follow a CRISP-DM-based data-driven clustering approach to derive the archetypes of DEPs based on selected real-world entities. CRISP-DM is a standardized process that aims to increase business understanding and gain insights by applying data mining methods [27]. Figure 2 displays our process. In the first step of "Business

Understanding", we focus on understanding the field of DEPs (see Section 2), and setting the objective of deriving archetypes of DEPs. In the second step of "Data Understanding", we review the data necessary for subsequently applying clustering techniques. Here, we build on data from Duda et al. [11], who developed a taxonomy for DEPs using real-world examples (cf. Figure 1). In doing so, we dispose of the data of 47 real-world DEPs with information about their nature in the 15 dimensions depicted in Duda et al.'s taxonomy [11]. Each platform considered in this work (cf. Table 1) was characterized/labeled in the taxonomy's dimensions based on information available in project reports, data sheets, or interviews conducted in Duda et al.'s work [11] to the best of the authors' knowledge.

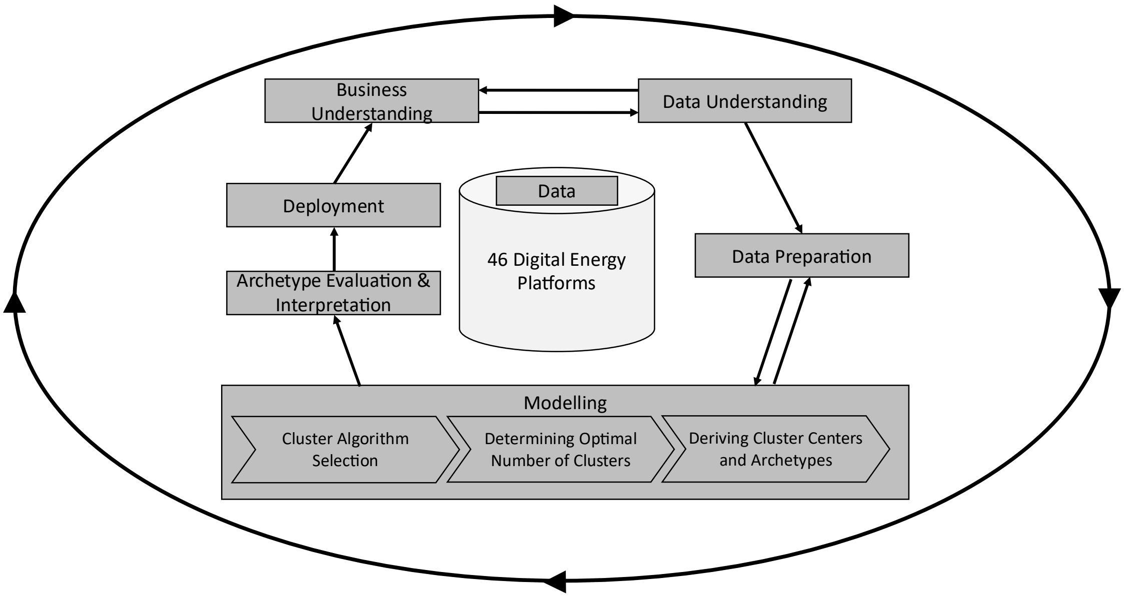

Figure 2: Adapted CRISP-DM process to derive DEP archetypes using a data-driven clustering approach (own illustration adapted from [27])

Table 1: DEPs considered in this work

Cordinet Project, Cornwall Local Energy Market, Electron Platform, ETPA, Flexible Power, FutureFlow, GoFlex, Nextra, Nodes Market, Piclo Flexibility Marketplace, wepower, AWS IoT Core, Bosch IoT Suite, CELOS, Cloud der Dinge, Connected Factories, Connected Factories 2, Enterprise IoT Platform, FIWARE, Google IoT Core, IBM Watson, ITAC.MES.Suite, LITMUS, OpenIoTFog, Productive 4.0, PTC Thingworx, Siemens Mindsphere, tapio, Virtual FortKnox, Bosch Energy Platform, DEXMA Platform, EMPURON EVE, EnCoMOS, ennex OS, ITC Power Commerce EnMS, KMUPlus - Energy Intelligence, opti.node, PHI-Factory, SIMATIC Energy Suite, Smart Energy Hub, ENIT, Balance Power, BayWa r.e. CLENS, Centrica Business Solutions, e2m, Entelios, Next-Kraftwerke, ENIT Systems

After reviewing the available data, we ensure high data quality and modify the data in the "Data Preparation" step for the following modeling step, checking for missing characteristics – if we cannot extract platform information, we set the respective value to zero, indicating missing information. The fourth step of "Modelling" consists of three sub-steps to correctly and replicable derive archetypes. First, we select cluster algorithms that can handle the hierarchically structured platform data. Considering several algorithms allows us to avoid algorithm-biased results on the number and composition of archetypes. We apply the commonly used clustering algorithms k-modes, k-means, k-means minibatch, spectral clustering, agglomerative clustering, and Birch. All steps of data preparation and modeling are implemented in Python using the algorithms available in the open-source "scikit-learn" [28] and "scipy" [29] library that provides tools for data analysis. Second, to determine the number of clusters k, i.e., the number of archetypes, we use the elbow method with a specific metric called distortion score for each algorithm [30]. The elbow method is typically used in cluster analysis and can be applied to different metrics. The distortion score measures and calculates the sum of square distances from each point to its assigned center [31]. We subsequently compare the results of k_{opt} for each algorithm and determine the optimal global number of clusters $\overline{K}_{opt}$ with Equation 1 where N is the number of clustering algorithms:

$$\overline{K}_{opt} = \left\lfloor \frac{\sum_{i=0}^{N} k_{opt}(i)}{N} \right\rfloor \tag{1}$$

$$Alg_{opt} = \underset{dist\_score}{argmin}\left(\sum_{i=0}^{N_{\overline{K}_{opt}}} dist\_score(i, \overline{K}_{opt}) \right) \tag{2}$$

Third, we derive the cluster centers, i.e., the characteristics of each archetype, by applying the clustering algorithm Alg_{Opt} exhibiting the lowest distortion score by comparing the clustering algorithms with K_{opt}, thus, the best separated and tightest clusters on the data (see Equation 2). The clusters represent DEPs with similar characteristics identified based on the taxonomy. Using typical characteristics based on recurring patterns, knowledge can be synthesized in a cumulative form of archetypes [32]. The results then serve as a basis for the step "Archetype Evaluation & Interpretation", where we graphically present the cluster analysis results transforming the information on cluster centers into interpretable archetypes with individual characteristics. Section 4 reports the clustering analysis results before Section 5 discusses the findings. The results' discussion and the publication within this piece of research present the last step, "Deployment" and contribute to the initial "Business Understanding" step. Further iterative analysis loops are possible, i.e., for future analysis of novel platform data.

4. **Results**

4.1 **Clustering Results**

The applied data-driven clustering approach led to the following results. For all algorithms except k-modes, the optimal number of clusters was 4, in line with Equation 1, which is why we continued with four archetypes for further analysis. The distortion scores of the different algorithms were at a relatively similar level, with the Birch algorithm having the lowest score of 169.003 and thus being used to determine the exact archetypes. Table 2 reports the detailed results.

Table 2: Optimal Number of Clusters and Distortion Scores for each Algorithm tested

Cluster Algorithm	Optimal Number of Clusters	Distortion Score
k-modes	5	159.569
k-means	4	172.833
k-means mini batch	4	178.765
spectral clustering	4	169.100
agglomerative clustering	4	169.940
Birch	4	169.003

For better visualization, we calculated the two principal components of the data and visualized it as depicted in Figure 3. Figure 3 reports the two principal components on the x and y-axis. Each of the four clusters is colored differently to distinguish the archetypes we present in subsection 4.2 in detail. The archetypes

“Energy Flexibility Platform” (blue) and “SaaS-Aggregators” (orange) differ quite strongly from the two remaining archetypes, “Research-based Platform” and “Manufacturing IoT Platform”. Both last-named archetypes seem to be more similar to each other. Nevertheless, the two-dimensional depiction may not be capable of distinguishing between the multiple dimensions resulting from the input data. We further analyze the archetypes in the following.

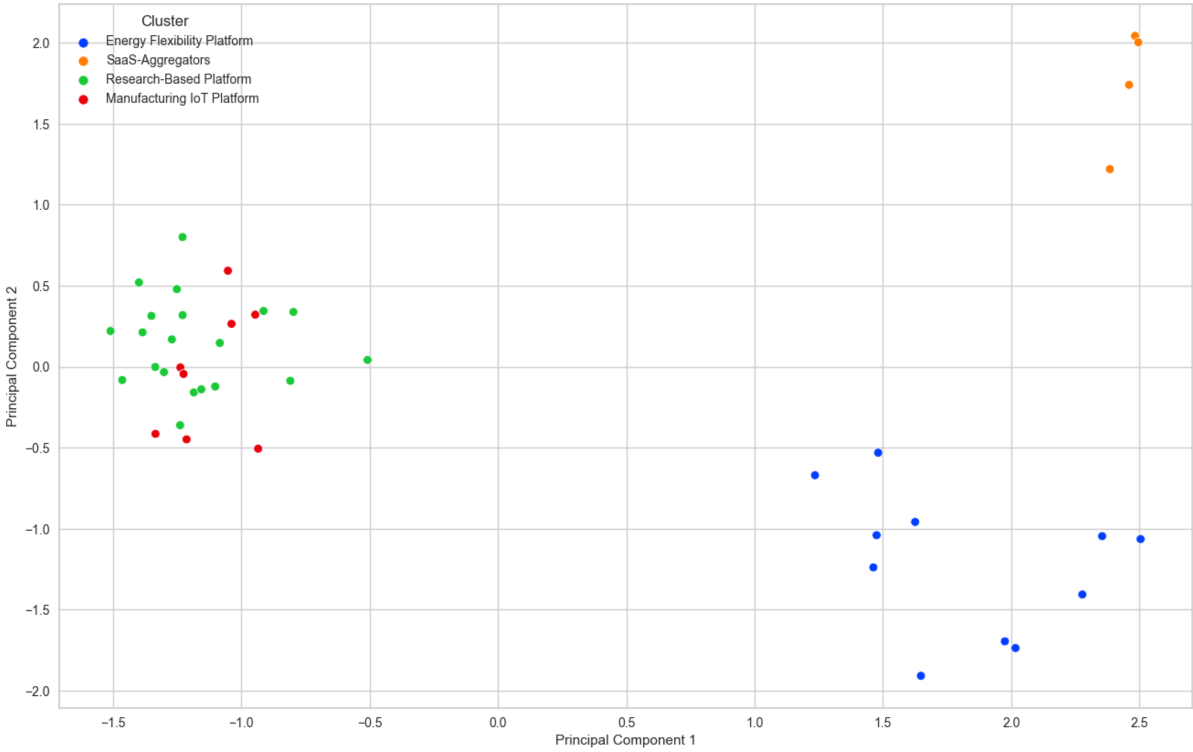

Figure 3: Simplified graphical representation of the derived archetypes after principal component analysis

4.2 **Digital Energy Platform Archetypes**

This section presents and analyses the DEP archetypes in detail. Table 3 provides an overview of each archetype with its central attributes and characteristics, exemplary platforms, and the number of platforms associated with the specific archetype. We observe a relatively high share of research-driven energy platforms followed by energy flexibility and manufacturing IoT platforms. The smallest share holds for the SaaS-Aggregators/Virtual Power Plant archetype.

Research-driven Energy Platforms are developed by research institutes, universities, and companies. These are sometimes organized in larger research projects financed by several ministries (e.g., the German Ministry of Education and Research) or the European Union. Nevertheless, the platforms in this cluster are not only platform concepts or prototypes but also fully functional platforms with international customers in the manufacturing field. The energy platforms offered are primarily open and web-based. Furthermore, the platforms use statistical tools and methods to analyze and especially visualize the energy consumption of manufacturing plants.

Energy Flexibility Platforms implement a new concept and connect energy suppliers and commercial energy consumers – e.g., typically found as local energy markets. The platform’s objective is to enable the flexibilization of power consumption to allow a flexibility marketing for specific use cases such as electricity grid congestion management. The development of these platforms is mostly research-driven. Compared to the research-driven energy platforms, we could not identify any development toward the commercialization of the flexibility platforms. Thus, research projects and consortiums mainly dominate this cluster instead of company-only solutions or products.

SaaS-Aggregators / Virtual Power Plants are company-based, well-established aggregators that offer SaaS products for their customers in energy-intensive industries. The provided software offered participation in virtual power plans to optimize energy procurement for energy-intensive industries. Most of the platforms in this cluster have highly restricted access possibilities. Therefore, companies that want to participate in virtual power plants must fulfill the criteria. The platforms are also used for trading flexibilities on the spot markets (e.g., Intraday). Furthermore, the platforms offer to trade the given flexibilities from manufacturing companies in the energy markets.

(Manufacturing) IoT-Platforms offer the broadest functionality of all platforms and, thus, focus least on the energy domain. The platforms are mainly responsible for acquiring, aggregating, visualizing, and analyzing data streams out of the manufacturing processes, as well as controlling these processes. The platforms are offered by well-established companies and are cloud-based platforms. They also give free and unrestricted access to the resources and services they offer in their ecosystems. Platforms in this cluster are typically generic platforms without a focus on energy management. However, some of the platforms in this cluster also develop native applications, e.g., for industrial PCs, to simplify the platform's integration with the machines and components.

Table 3: Overview of the Determined Archetypes

Archetype	Central Attributes and Characteristics	Platform Examples	Number of Platforms in sample
Research-driven Energy Platforms	Web-App, Research-driven Company, Open, Data-driven	Virtual Fort Knox, ENIT Systems, Smart Energy Hub	22
Energy Flexibility Platforms	Research, Many-to-Many-Platforms, Energy Flexibility Trading, OTC	WePower, GoFlex, Nextra, ETPA	11
SaaS-Aggregators / Virtual Power Plants	Aggregator, Interfaces, Cloud, Closed Access, Transactional, Trading,	NextKraftwerke, BalancePower, Entelios, e2m	6
(Manufacturing) IoT-Platforms	Company, Cloud, Free-Access, One-to-Many, Native-App	Siemens Mindsphere, Bosch IoT Suite, ITAC.MES.Suite	8

5. **Implications and Conclusion**

This paper addressed the lack for archetypes characterizing DEPs that make it easier for companies to select the platforms providing the missing functionality. Following an explorative data-driven clustering approach building on the well-established CRISP-DM process, we identified four DEP archetypes: Research-driven Energy Platforms, Energy Flexibility Platforms, SaaS-Aggregators / Virtual Power Plants, and (Manufacturing) IoT-Platforms. Our results and findings have several implications for practice and research. First, the archetypes structure DEPs in their functionality and services provided, which may serve as a first market overview. Market gaps can be identified, highlighting technological needs or opportunities for novel platforms, e.g., platforms that combine functionalities of two or more archetypes or business models beneficial for providers. Second, and in line with the first implication, the archetypes may represent a decision support system for the early stages of digital platform selection. Comparing a company's existing IT infrastructure with the identified archetypes can lead to a particular archetype that fills current gaps in automation or additional services. Third, with the goal of (entirely) automated energy flexibility marketing from the shop floor to the energy/flexibility markets, the archetypes clearly show that typical production and IoT issues should be thought of in line with energy supply and demand. Compared with Figure 3, we see that no overarching archetype covers the full range of functionalities provided for each archetype. Transferring this finding to practice, companies may consider several platforms in their enterprise architecture for automated flexibility marketing. This leads to implication number four: interfaces and standardized communication are crucial for the automation of flexibility marketing, which is in line with findings from Schott et al. [33]. Thus, selecting and implementing platforms requires expertise in requirements engineering and defining interfaces between different platforms. Alternatively, developing a "holistic" platform that covers every functionality needed from the shop floor to energy/flexibility markets would be a costly approach, as proposed by Bauer et al. [7]. Fifth, the archetypes "Research-Driven Energy Platforms" and "IoT Platforms" are comparatively most comparable (cf. Figure 3). It appears that the majority originate or were developed in the production domain and less in the energy domain. The focus of "Research-driven Energy Platforms" is on optimizing energy consumption (efficiency instead of flexibility), emphasizing data management and less on the marketing of flexibility and its economic potential. It may make sense to establish research consortia with additional specialists from the energy sector to further develop these platforms in flexibility marketing. In contrast, the "SaaS Aggregators / Virtual Power Plants" archetype differs significantly from the "Research-Driven Energy Platforms" and "IoT Platforms" archetypes. This indicates historically grown structures and proprietary solutions in a highly regulated energy sector [34], which aggregators have tapped in recent years [35]. The need for end-to-end communication and interfaces can also be derived here, which should be considered in practical implementation.

As with any research endeavor, our work has some limitations but spurs future research. First, our study is limited in data about existing DEPs focusing on Germany. Broadening the scope might distort the results and strengthen the validity of the derived archetypes. We leave this and the research's transferability to other countries for future studies. Second, the derived archetypes represent the status quo regarding existing DEPs. Ongoing development, market, and customer requirements (e.g., changing regulations) may lead to changes in archetypes. Thus, we recommend applying our methodological approach cyclically to obtain insights into trends from a market and functionality perspective. Third, there is room for improvement regarding our methodological approach next to limitations in data. There are several other clustering algorithms and metrics to derive the optimal number of clusters and evaluate the clusters' composition [36].In summary, despite these limitations, we contribute relevant archetypes of DEPs for production companies and researchers.

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References

[1] S. Wenninger, "Data-driven support and risk modeling for a successful heat transition in the building sector," University of Bayreuth, 2022, doi: 10.15495/EPub_UBT_00006488.

[2] Bundesministerium für Wirtschaft und Energie, "Kommission "Wachstum, Strukturwandel und Beschäftigung" Abschlussbericht," Berlin, 2019.

[3] Bundesministerium für Wirtschaft und Klimaschutz, Erneuerbare Energien im Stromsektor erstmals konsequent auf 1,5-Grad-Klimapfad. [Online]. Available: https://www.bmwk.de/Redaktion/DE/Dossier/erneuerbare-energien.html (accessed: Oct. 18 2022).

[4] P. Schott, "Demand-Side Flexibility – Enabled and Enhanced by Information Technologies in Current and Future Electricity Systems," University of Bayreuth, 2021, doi: 10.15495/EPub_UBT_00005794.

[5] M. Paulus and F. Borggrefe, "The potential of demand-side management in energy-intensive industries for electricity markets in Germany," Applied Energy, vol. 88, no. 2, pp. 432–441, 2011, doi: 10.1016/j.apenergy.2010.03.017.

[6] BDEW Bundesverband der Energie- und Wasserwirtschaft e.V., Nettostromverbrauch nach Verbrauchergruppen. [Online]. Available: https://www.bdew.de/service/daten-und-grafiken/nettostromverbrauch-nach-verbrauchergruppen/ (accessed: Oct. 18 2022).

[7] D. Bauer et al., "Wie IT die Energieflexibilitätsvermarktung von Industrieunternehmen ermöglicht und die Energiewende unterstützt," HMD, 2020, doi: 10.1365/s40702-020-00679-8.

[8] M. Lindner, S. Wenninger, G. Fridgen, and M. Weigold, "Aggregating Energy Flexibility for Demand-Side Management in Manufacturing Companies – A Two-Step Method," in Lecture Notes in Production Engineering, Production at the Leading Edge of Technology, B.-A. Behrens, A. Brosius, W.-G. Drossel, W. Hintze, S. Ihlenfeldt, and P. Nyhuis, Eds., Cham: Springer International Publishing, 2022, pp. 631–638.

[9] L. Haupt, M.-F. Körner, M. Schöpf, P. Schott, and G. Fridgen, "Strukturierte Analyse von Nachfrageflexibilität im Stromsystem und Ableitung eines generischen Geschäftsmodells für (stromintensive) Unternehmen," Z Energiewirtsch, vol. 44, no. 2, pp. 141–160, 2020, doi: 10.1007/s12398-020-00279-5.

[10] E. Unterberger et al., "The regional and social impact of energy flexible factories," Procedia Manufacturing, vol. 21, pp. 468–475, 2018, doi: 10.1016/j.promfg.2018.02.146.

[11] S. Duda et al., Structuring the Digital Energy Platform Jungle: Development of a Multi-Layer Taxonomy and Implications for Practice: Hannover : publish-Ing, 2022.

[12] C. Leinauer, P. Schott, G. Fridgen, R. Keller, P. Ollig, and M. Weibelzahl, "Obstacles to demand response: Why industrial companies do not adapt their power consumption to volatile power generation," Energy Policy, vol. 165, p. 112876, 2022, doi: 10.1016/j.enpol.2022.112876.

[13] S. Honkapuro, P. Valtonen, J. Tuunanen, J. Partanen, and P. Jarventausta, "Demand side management in open electricity markets from retailer viewpoint," in 2015 12th International Conference on the European Energy Market (EEM), Lisbon, Portugal, May. 2015 - May. 2015, pp. 1–5.

[14] L. Arnold, J. Jöhnk, F. Vogt, and N. Urbach, "IIoT platforms' architectural features – a taxonomy and five prevalent archetypes," Electron Markets, vol. 32, no. 2, pp. 927–944, 2022, doi: 10.1007/s12525-021-00520-0.

[15] M. de Reuver, C. Sørensen, and R. C. Basole, "The Digital Platform: A Research Agenda," Journal of Information Technology, vol. 33, no. 2, pp. 124–135, 2018, doi: 10.1057/s41265-016-0033-3.

[16] D. Lee and C.-C. Cheng, "Energy savings by energy management systems: A review," Renewable and Sustainable Energy Reviews, vol. 56, pp. 760–777, 2016, doi: 10.1016/j.rser.2015.11.067.

[17] P. Siano, "Demand response and smart grids—A survey," Renewable and Sustainable Energy Reviews, vol. 30, no. 3, pp. 461–478, 2014, doi: 10.1016/j.rser.2013.10.022.

[18] M. Roesch et al., "Harnessing the Full Potential of Industrial Demand-Side Flexibility: An End-to-End Approach Connecting Machines with Markets through Service-Oriented IT Platforms," Applied Sciences, vol. 9, no. 18, p. 3796, 2019, doi: 10.3390/app9183796.

[19] R. Y. Zhong, X. Xu, E. Klotz, and S. T. Newman, "Intelligent Manufacturing in the Context of Industry 4.0: A Review," Engineering, vol. 3, no. 5, pp. 616–630, 2017, doi: 10.1016/J.ENG.2017.05.015.

[20] M. Blaschke, K. Haki, S. Aier, and R. Winter, Taxonomy of Digital Platforms: A Platform Architecture Perspective. [Online]. Available: https://aisel.aisnet.org/cgi/viewcontent.cgi?article=1220&context=wi2019 (accessed: Oct. 18 2022).

[21] R. C. Nickerson, U. Varshney, and J. Muntermann, "A method for taxonomy development and its application in information systems," European Journal of Information Systems, vol. 22, no. 3, pp. 336–359, 2013, doi: 10.1057/ejis.2012.26.

[22] M. R. Bouadjenek, H. Hacid, and M. Bouzeghoub, "Social networks and information retrieval, how are they converging? A survey, a taxonomy and an analysis of social information retrieval approaches and platforms," Information Systems, vol. 56, pp. 1–18, 2016, doi: 10.1016/j.is.2015.07.008.

[23] J. Harri, F. Filali, and C. Bonnet, "Mobility models for vehicular ad hoc networks: a survey and taxonomy," IEEE Commun. Surv. Tutorials, vol. 11, no. 4, pp. 19–41, 2009, doi: 10.1109/SURV.2009.090403.

[24] Z. A. Khan, D. Jayaweera, and H. Gunduz, "Smart meter data taxonomy for demand side management in smart grids," in 2016 International Conference on Probabilistic Methods Applied to Power Systems (PMAPS), Beijing, Oct. 2016 - Oct. 2016, pp. 1–8.

[25] D. Behrens, T. Schoormann, and R. Knackstedt, "Towards a Taxonomy of Constraints in Demand-Side-Management-Methods for a Residential Context," in Lecture Notes in Business Information Processing, Business Information Systems, W. Abramowicz, Ed., Cham: Springer International Publishing, 2017, pp. 283–295.

[26] B. Karlin, R. Ford, and C. Squiers, "Energy feedback technology: a review and taxonomy of products and platforms," Energy Efficiency, vol. 7, no. 3, pp. 377–399, 2014, doi: 10.1007/s12053-013-9227-5.

[27] R. Wirth and J. Hipp, "CRISP-DM: Towards a Standard Process Model for Data Mining," Proceedings of the 4th International Conference on the Practical Applications of Knowledge Discovery and Data Mining, 2000. [Online]. Available: https://pdfs.semanticscholar.org/48b9/293cfd4297f855867ca278f7069abc6a9c24.pdf?_ga=2.178440930.712398945.1585210432-406106918.1585080227

[28] F. e. a. Pedregosa, Scikit-learn: Machine Learning in Python. [Online]. Available: https://scikit-learn.org/stable/index.html (accessed: Oct. 14 2022).

[29] P. Virtanen et al., "SciPy 1.0: fundamental algorithms for scientific computing in Python," Nature methods, vol. 17, no. 3, pp. 261–272, 2020, doi: 10.1038/s41592-019-0686-2.

[30] R. L. Thorndike, "Who belongs in the family?," Psychometrika, vol. 18, no. 4, pp. 267–276, 1953, doi: 10.1007/BF02289263.

[31] M. Shibasaki, A. Witayangkurn, and M. M. Rahman, "Comparison of life patterns from mobile data in Bangladesh," in 2019 First International Conference on Smart Technology & Urban Development (STUD), Chiang Mai, Thailand, Dec. 2019 - Dec. 2019, pp. 1–7.

[32] J. Wanner, C. Wissuchek, G. Welsch, and C. Janiesch, "A Taxonomy and Archetypes of Business Analytics in Smart Manufacturing," 2021.

[33] P. Schott, J. Sedlmeir, N. Strobel, T. Weber, G. Fridgen, and E. Abele, "A Generic Data Model for Describing Flexibility in Power Markets," Energies, vol. 12, no. 10, p. 1893, 2019, doi: 10.3390/en12101893.

[34] M. Mulder, Regulation of Energy Markets. Cham: Springer International Publishing, 2021.

[35] J. Stede, K. Arnold, C. Dufter, G. Holtz, S. von Roon, and J. C. Richstein, "The role of aggregators in facilitating industrial demand response: Evidence from Germany," Energy Policy, vol. 147, p. 111893, 2020, doi: 10.1016/j.enpol.2020.111893.

[36] S. Emmons, S. Kobourov, M. Gallant, and K. Börner, "Analysis of Network Clustering Algorithms and Cluster Quality Metrics at Scale," PloS one, vol. 11, no. 7, e0159161, 2016, doi: 10.1371/journal.pone.0159161.

Biography

Sebastian Duda is working at the FIM Research Center of the University of Bayreuth and the Project Group Business & Information Systems Engineering of the Fraunhofer FIT. He focuses on research in the field of convergence of digital technologies.

Lukas Fabri is working at the FIM Research Center of the University of Applied Sciences Augsburg and the Project Group Business & Information Systems Engineering of the Fraunhofer FIT. He focuses on research in data analytics solutions for the industrial and energy context.

Can Kaymakci has been working as a research associate in the Industrial Energy Systems Department at Fraunhofer IPA since January 2020. In the group Energy Flexible Production and Energy Data Analysis, he is involved in research and industrial projects using AI and Machine Learning for energy data.

Dr. Simon Wenninger, MBA & Eng. is working at the FIM Research Center of the University of Applied Sciences Augsburg and the Project Group Business & Information Systems Engineering of the Fraunhofer FIT. He focuses on research in data analytics in an industrial and energy context.

Prof. Dr.-Ing. Alexander Sauer is the Head of the Institute for Energy Efficiency in Production (EEP) at the University of Stuttgart and director of the Fraunhofer Institute for Manufacturing Engineering and Automation IPA.

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Towards Robustness Of Production Planning And Control Against Supply Chain Disruptions

Tobias Wittmeir[1], Michael Heider[2], André Schweiger[2], Michaela Krä[1], Jörg Hähner[2], Johannes Schilp[1], Joachim Berlak[3]

[1]*Digital Manufacturing Group, Institute of Computer Science, University of Augsburg, Germany*
[2]*Organic Computing Group, Institute of Computer Science, University of Augsburg, Germany*
[3]*Institute for Automation & Industrial Management (IAIM), FOM University, Munich, Germany*

Abstract

Just-in-time supply chains have become increasingly popular in past decades. However, these are particularly vulnerable when logistic routes are blocked, manufacturing capacities are limited or customs are under strain, as has been seen in the last few years. The principle of just-in-time delivery requires a coordinated production and material flow along the entire supply chain. Challenges in the supply chain can lead to various disruptions, so that certain manufacturing jobs must be changed, postponed or cancelled, which will then impact supply down the line up to the consumer. Nowadays, many planning and control processes in the event of a disturbance are based on the procedural knowledge of employees and undertaken manually by those. The procedures to mitigate the negative effects of disturbances are often quite complex and time-critical, making disturbance management highly challenging.

In this paper, we introduce a real-world use case where we automate the–currently manual–reschedule of a production plan containing unavailable jobs. First, we analyse existing literature regarding the classification of disturbances encountered in similar use cases. We show how we automate existing manual disturbance management and argue that employing stochastic optimization allows us to not only promote future jobs but to on-the-fly create entirely new plans that are optimized regarding throughput, energy consumption, material waste and operator productivity. Building on this routine, we propose to create a Bayesian estimator to determine the probabilities of delivery times whose predictions we can then reintegrate into our optimizer to create less fragile schedules. Overall, the goals of this approach are to increase robustness in production planning and control.

Keywords

Production Disturbances; Disturbance Management; Production Planning and Control; Automated Production Planning; Supply Chain Management; Robustness

1. Introduction

Over the last decades, companies have been faced with challenges in a competitive environment characterised by globalisation, increasing product variety and growing market dynamics [1]. These new market requirements force them to focus on their essential core competences and to outsource other activities. In this context, the management of logistic processes in particular has become considerably more important in recent years [2]. Logistic objectives such as delivery times, on-time delivery, service level, throughput times, inventories, capacity utilisation and delay costs are critical to the success of an enterprise [3]. Due to the increasing inter-company cooperations e.g. as a result of outsourcing, logistics have to deal more and more with cross-company delivery problems, leading to new challenges and the discipline of supply chain management.

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Changing customer demands, a dynamic environment and quality problems are requiring companies to adapt themselves and their business and manufacturing processes faster to new boundary conditions leading to reschedules in supply as well as to turbulences along the entire value chain and supplier networks [4]. This leads to disturbances on various levels, not least due to the high complexity of such systems [2]. Disturbances occur both at the management level and at the level of production and assembly processes [5].

To counter disturbances at production level, it is necessary to optimally synchronize production planning and control. The main task of production planning and control is the coordination of all production and assembly processes to achieve the logistical targets [6]. In production planning, the current production plan is established for a certain planning time fence. All material and resource requirements are derived from that. Production control regulates the execution of the planned schedule, accounting for all unavoidable disturbances such as employee absences, machine disruptions, delivery delays or quality issues and production losses [7–9]. A detailed overview of several classification systems for production disturbances is presented in section 2.1. In section 3, we give an overview over various approaches in literature towards handling disturbances automatically.

In this paper, we present a real-world use case of a large multinational company (cf. section 4), in which a production plan, which covers a fixed horizon of ten days, is devaluated by material flow disturbances. The disturbance makes the production of one or more jobs within the fixed planning horizon impossible, so the production plan has to be changed. The main causes of these disturbances are short-term delivery problems or failures, material discrepancies in the enterprise resource planning (ERP) system or breakdowns in the company's own preproduction. The potential reasons for these are manifold and less relevant for this work as we focus on resolving the effect rather than preventing disturbances. Nor could the disturbance be solved at the logistical level, since e.g. a larger warehouse is not a realistic option for modern cost-sensitive operations. Given the existing options, in this case disturbances can only be reacted to at the level of production planning and control.

Recent studies show that, especially in production planning and control, many activities are based on the experience and process knowledge of the responsible employees [10]. Part of these manual steps are e.g. rescheduling in the event of a malfunction as well as the identification and selection of suitable strategies to resolve the situation [11]. In our use case, the production plan was fixed completely manually so far.

Manual disturbance management is often quite complex, time-consuming and relies on the procedural knowledge of employees. In this paper, we present our own approach for automating and subsequently improving this process with various techniques from the wider field of artificial intelligence (cf. section 5). We start by replicating the existing manual processes in software, albeit substantially faster. We discuss that–with the help of stochastic optimisation–we are able to solve the problem more effectively by foregoing a mere repositioning of scheduled jobs to on-the-fly create completely new production plans for the fixed horizon that are optimized in terms of throughput, energy consumption, material waste, and operator productivity. In a next step (cf. section 6), we propose to not only react to disturbances that have already occurred, but also to predict or prevent them by generating new alternative solutions (e.g. finding new suppliers, readjusting slightly different parts or simply fulfilling different orders first). For this, we discuss the use of Bayesian Neural Networks.

2. Production disturbances and robustness

In this section, based on a detailed literature review, several classification systems of production disturbances are provided. We then introduce the term "robustness" both in general and in the context of production systems, as this is a formalisation of the properties of systems that can deal with such disturbances.

2.1. Production disturbances

Production disturbances are unexpected and undesirable events that cause a production system not to function as planned. Equipment or software failures, media errors, waiting times for materials, subsequent interruptions in the production flow of stations/machines, lack of personnel, loss of speed, scrap or quality problems, planning errors and adjustments are factors that are often classified as disturbances by manufacturing companies. The occurrence of disturbances directly affects the productivity of production systems, as more time and resources than planned are required to produce the same outcome. Reducing production disturbances contributes to stable and more reliable production systems and is critical to maintaining the competitiveness of manufacturing companies [12]. Literature offers a wide range of disturbance classifications. The main classification systems are summarised in Table 1.

Table 1: An overview of classification systems for disturbances found in literature

Classification basis	References	Categories	Explanation and/or examples
Manner of occurrence	[13]	Unpredictable	Unexpected, appears suddenly during execution of production processes, abrupt changes in the expected and planned production specifications, e.g. urgent order, modification of order, machine breakdown
		Predictable	Can be predicted during execution of production processes due to undesirable situations caused by deviations from expected and planned requirements or deviations from equipment specifications, e.g. equipment breakdown
Origin of disturbances	[14,15]	Internal	Undesirable events triggered by resources and/or operations of production systems, e.g. machine breakdown, unavailability of labour, quality inspection, layout re-configuration
		External	Undesirable events caused by the environment in which the production system is evolving, e.g. disturbances due to the company's relationship with its customers or suppliers (e.g. delivery difficulties of raw materials in terms of time, quality and price, delay, cancellation, introduction of rush orders)
Type of affected entities	[16]	Resources	Machine breakdowns, change or lack of resources (raw materials or tools)
		Operations or work order	Overflow and change request (increase/decrease in operating times)
	[17]	Production	Each class is divided into inventory, capacity, and dual/multiple suppliers' issues
		Supply	
		Transportation	
	[18,19]	Supply	Delays, quality problems
		Resources	Machine breakdown, tool breakage, labour problems
		Production	Scraps management, quality problems, production time, product reject
		Customers	Rush orders, order modification, order cancelation
Nature of effect caused to aggressed production system entities	[20]	Unavailability of aggressed entity/relation	Sudden (unpredictable) event that disables an entity in production system, entity switches from Normal functioning mode to the Stop mode, or disturbance that has attacked an interentities relation causes the impossibility of interaction or communication between the two entities
		Degradation of aggressed entity/relation	Corresponds to an event that causes the alteration or non-satisfaction of one or more properties/requirements of a production system entity, aggressed entity becomes unable to perform its function according to pre-set objectives
Causes of disturbances	[21]	Component failures	Breakdowns in sensors and mechanical limit switches
		Design	Disturbances which would have been avoided had the design been conceived differently, e.g. flaws in software design, mechanical blocking due to software design, collisions because of poor coordination of system component functions, materials inadequately chosen given a robot's loading capacity, and errors caused by assembling system parts
		Human error	Includes those errors committed by the operators who run the system
		External Factors	Likely to interfere with organization performance, e.g. delays in deliveries, delays in testing machinery and equipment, and mistakes in installation of machinery and equipment

As shown in Table 1, the individual categories always depend on different characteristics of the disturbances. Furthermore, some classification systems map disturbances along the entire supply chain, while others only focus on the disturbances within a production system.

In addition, disturbances that have occurred can be differentiated according to their temporal impact, which can range from hours to weeks. Short-term disturbances are abrupt, suddenly occurring and lead to strong deviations between planning and realisation. Examples are machine breakdowns or order modifications. Medium-term disturbances are consequential errors from disturbances in the short-term range or due to inaccurate representations of the real plant and order data. The modification of the production plan or the use of non-adapted control strategies usually cause long-term disturbances [22].

According to [23], disturbances can be divided into deterministic and stochastic disturbances. Deterministic disturbances interrupt the production process in a planned manner, such as preventive and planned maintenance. Stochastic disturbances cause unanticipated interruptions in production systems.

Along with these, other disturbance categories can be found, such as primary and secondary disturbances [24]. In [15,21,25–31] further classification systems can be found. Some of these are along the lines of those shown in Table 1, some are an extension by adding new classes, some aim at specific levels of production or are sector-specific. Furthermore, our research has shown that there is no existing disturbance classification based on the impact on production planning or production control.

2.2. Robustness

Different meanings of the term "robustness" exist in literature depending on the context. In general, robustness describes the ability of a system to maintain its functionality in reference to changes of internal or external variables. Robustness is reflected in the degree to which a system is insensitive to effects that were not explicitly considered in its design [32]. Tomforde et al. [32] distinguish between active and passive robustness and present a quantification method to measure robustness. The term "robust" usually refers to a fundamental design concept that allows the system to work correctly under a wide range of disturbances. In the context of production, robustness refers to manufacturing tolerances, scheduling systems or production processes. The robustness of a production plan describes its ability to be executable and achieve satisfactory results despite changing environmental conditions and disturbances typical in production systems. A production process is robust if it is insensitive to undesirable influencing variables, if production takes place on schedule and if quality is met while maintaining the planned economic effort [33,34].

3. Disturbance management in literature

Production planning and control has gradually shifted from low level internal decision making to incorporating the entire supply chain [35]. Combined with JIT production this raises the need of supply chain risk management [36]. Existing research in this area can be split into two main sectors, reactive, where disturbances are handled after they occurred (cf. section 5), and proactive, where potential future risks are identified (cf. section 6).

Li et al. [37] proposed a framework which employs machine learning techniques to identify when rescheduling is needed before performing optimization and tested the approach on simulated use cases. Starting from an existing schedule with unavailable jobs Wang et al. [38] use a branch-and-price algorithm to find an alternative to the original schedule while allowing to fully reject single jobs. Bierwirth and Mattfeld [39] employed genetic algorithms for a similar non-deterministic and dynamic job shop problem, where –instead of disturbances removing existing jobs–newly arriving jobs require a rescheduling.

On the proactive side, the possibility of using higher statistics to predict possible supply risks has been explored by several authors, such as Wang et al. [40] or He et al. [41]. Brintrup et al. [42] performed an analysis of which features prove useful to predict supply disturbances while highlighting the importance of domain knowledge for this process. They also built a point estimate prediction system for estimating delivery probabilities. Baryannis et al. [43] explored the performance trade-offs necessary to use more explainable models like decision trees. Recently, Hosseini and Ivanov [44] employed Bayesian Neural Networks to model supply chain disruptions caused by a pandemic.

4. Case study

In this paper, we present a real-world case study from a multinational manufacturing company. Our use case involves large-scale production using several parallel assembly lines. A few variants of a basic product are produced on one assembly line with a constant cycle time each. This is ensured by the number of employees per assembly line: If a product has more features, i.e. more assembly steps, more employees are used and vice versa. In assembly, work is done in two-shift operation. The number of employees is highest at the beginning of each shift and decreases over the course of the shift. This means that at the beginning of each shift, the product variants with the most features are processed and the less complex variants are assembled at the end of the shift. This is the strictest form of flow production called continuous flow production, which is bound both spatially and temporally. It is characterised by a continuous transport flow on a conveyor belt [45].

For this case study, we only consider disturbances linked to material availability. The procurement of raw and auxiliary materials or semifinished products is synchronized with the production plan by using the just-in-time principle (JIT). There is a fixed production plan for the next ten days, which is determined with the help of a scheduling optimizer. On each new day, the plan is extended by one day through another scheduling run (rolling horizon production planning). We consider a disturbance in material availability that results in a planned job that cannot be produced and lies within the fixed planning horizon. Following [14], this kind of disturbance can have both internal and external triggers. It can occur at short notice if, e.g. during the setup of one or more workstations on the assembly line, it is discovered that a material is missing for which there should be stock according to the ERP system (internal disturbance). The discrepancy in material availability can also become apparent in the medium term due to delivery problems by the supplier (external disturbance) or due to a breakdown in the company's own preproduction (internal disturbance). However, both can also occur at short notice.

As described above, disturbance management regarding an occurred and not prevented disturbance is carried out completely manually by a production planner. Depending on the point of occurrence of the disturbance, the production plan must be adjusted in the short term or changed in the medium term. The planner executes the following process.

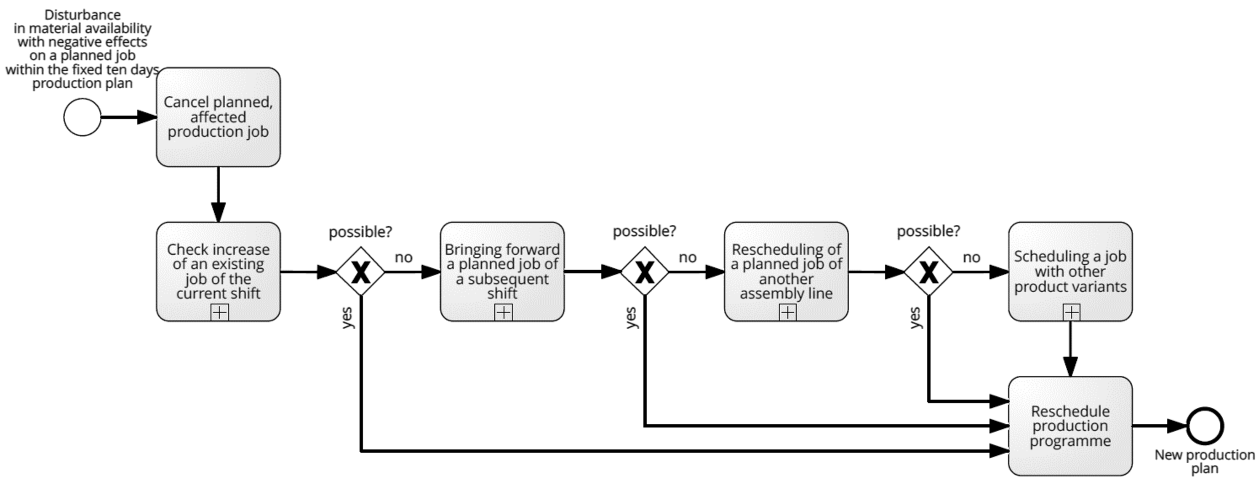

Figure 1: Process of manual fixing of a production plan in case of a disturbance in material availability

As shown in Figure 1, the rescheduling of the production plan is a step-by-step approach. Each step has further sub-processes in which the planner checks the availability of a sufficient number of employees, of critical parts of the bill of materials, of short range, design and finishing parts as well as preproduction capacities. If there is more than one possible solution, then the option with the earliest demand in the market is selected. The aim of rescheduling is to optimally close gaps in the production plan in order to maintain adherence to schedules and to prevent or minimise production losses. Another crucial factor is to avoid that workers are not busy or have to be sent home.

5. Improving reactive disturbance handling

The current disturbance handling process of the case study, described in section 4, is primarily carried out manually. Due to the time and staff required to execute certain production jobs and some strict requirements, as not to cause a break in production, only very few alternative viable production plans exist. These might not be optimal and currently primarily selected because they fulfil the constraints and do not lose out on production capacity. Typically, the number of viable solutions is in the low hundreds. However, highly trained and experienced planners know which jobs are likely suited from their grasp at the overall picture and therefore do not need to evaluate too many solutions following the time-intensive process of Figure 1.

In a first step, we thus automate important parts of the process to speed up and improve disturbance handling. Using data about each product, such as material requirements, the number of employees needed and current market demand, all of which is readily available in the existing ERP systems, we can find the best alternative for replacing the disturbed job in the original production plan. Additionally, instead of simply using the first possible solution like in the manual step-by-step process, we can perform an exhaustive search evaluating all viable solutions, therefore, achieving human-competitive or better results. A description of the cost function used to evaluate an individual solution can be found in section 5.1. The algorithm can perform all the previously manual work, although we allow the expert user to choose between equally good or similar plans in the hope, they have a better grasp at the big picture and select even more smartly from the possible options. However, currently the available options only allow the swap of two jobs or the expanse of one. We often encounter that other operations or a different order might provide a better overall plan. Section 5.2 describes how stochastic optimization can be used to create entirely new schedules for the fixed planning horizon while still fulfilling the known demand and utilizing the existing and expected parts. With the described capabilities of automatically fixing disturbances, we can consider this scheduling/control mechanism to be weakly robust, returning the system into an acceptance state.

5.1. Comparing production plan costs

To evaluate and compare different alternatives a sensible cost function is needed:

$$c(p) = \sum_i^n w(p_i) + m(p_i) + s(p_i) + d(p_i) \tag{1}$$

where $p \in \mathbb{R}^{n,3}$ is a production plan, $c: \mathbb{R}^{n,3} \to \mathbb{R}$ and $w, m, s, d: \mathbb{R}^3 \to \mathbb{R}$. The cost function considers workers (w), material (m), setup (s) and demand (d), all of which individually inflict costs on a job. We optimize under the constraint that jobs in a plan have a decreasing demand in the number of workers over the course of a shift due to the fixed cycle times discussed in section 4. If a job would require more workers than a previous one or less workers than the next one, we assume that it should inflict a higher cost due to idling some workers for the duration of this job. Similarly, a job's usage of material that would be needed for another, later job within the fixed horizon (as not enough material is available to perform both despite expected deliveries arriving on time) should be punished. Switching between jobs causes setup costs due to changes in the machine configurations, transporting parts to stations etc. This is typically constant for a type of job, however, the less setup, the more production can take place overall. Lastly, we should always account for the actual demand. Some products might be needed earlier or later, in larger quantities or requested by higher priority customers. The parameters of those functions are largely application-specific and in our current implementation they are guided by expert knowledge.

Fully automated and unexplained decisions can often lead to distrust of computerized system by the employees using them, especially when they disagree with the final decision [46,47]. In the current setup, we involve the responsible stakeholders in the decision making by presenting the top solutions together with their itemized cost and allowing them to make their favourite pick. Together with historical information and expert statements about the parametrizations of those cost functions, this increases stakeholder’s trust in the solution quality.

5.2. Optimizing the production plan

As a next step, we expand the algorithmic capabilities to not only fix the plan but create a new optimal schedule: Instead of simply filling the timeslot of a single job that has become impossible due to a disturbance, we propose to reoptimize (while accounting for schedule nervousness) the entire production plan within the fixed horizon, allowing the reordering of jobs, expansion of jobs, as well as the addition of new jobs or the removal of jobs not affected by the disturbance. In addition to these new options in the assembly line, adjusting the company's preproduction plan as well as utilizing options for short-term deliveries could make further jobs available. While the current approach allows for evaluating all constraint-satisfying solutions in less than a second, optimizing the entire plan gives a vastly increased number of options for which an exhaustive search is no longer feasible for realistic real-world scenarios. For this reason, we deploy stochastic optimization methods such as the well-known genetic algorithm (GA), including specialised operators as in [48], utilizing the previously defined single-objective cost function. However, treating the costs multi-objectively or adding additional factors such as energy usage, material waste or operator idling is straight forward. With these powerful black-box optimizers, the production plan can not only be (hot-)fixed but improved. As a result, the production planning process will make another step towards stronger robustness and self-optimization. New solutions will likely exhibit more differences between the original and optimized production plan which could lead to distrust. However, with the explanations based on cost functions and expert information, stakeholders are deeply informed about the inner workings of the decision-making process. We plan to further explore explainability requirements and user needs in the future. Additionally, this optimizer could be expanded with additional data sources pertaining to uncertainties, i.e. of scheduled deliveries, in order to increase the robustness of the production plan by creating schedules that include jobs less likely to fail.

6. Estimating delivery uncertainties

While the fast handling of a disturbance is an important aspect of production planning and control, the actual goal is to avoid as many of these disturbances as possible. Each disturbance and fixing of the plan necessarily mean that a specific product is not manufactured. This might in turn lead to customer orders not to be fulfilled on time, or down-the-line production seeing further disturbances. We propose that our reactive approach at increasing the robustness of the production should be combined with a proactive component. If the likely occurrence of a disturbance was known in advance there could be two possible actions to prevent it from disrupting the production plan. Firstly, if it is known early enough, the initial scheduling could create a plan that is not affected by it. A second option would be to try to counteract the disturbance, e.g. by procuring parts from another supplier. The increased time available to react or proactively respond would improve overall planning agility.

One major source of disturbances we identified in section 2.1 is the unavailability of parts or raw materials, often caused by late or cancelled deliveries. In JIT production simply reacting once such a disturbance has already occurred leaves very little time for fixing the out-dated production plan. Even when using the system described in section 5 an earlier notice can help at creating more robust alternatives as the fitness landscape can be explored better or human intervention might make other parts in the fixed planning horizon available. For this reason, we propose to use statistical methods for estimating the probability distributions of delivery dates. With these models the probability of the delivery occurring between now and the desired date equals the integral under the distribution. This presents a great advantage over traditional point estimate methods that only tell us whether a delivery might occur at a specific time and date without any information about other points in time.

If a delivery would be predicted as likely to be late some manual actions could be performed. This includes simply checking back with the supplier, looking for alternative suppliers that can provide the required components on short notice, or using different, but compatible, materials/parts among other possible actions. While these actions can help at stabilising or saving a schedule, our focus for this paper lies on utilizing this information within our scheduling process, providing both alternative schedules as well as scheduling jobs in an order where they are more likely to be executable, i.e. by placing them at a time where they are likely to be available.

We plan to employ Bayesian Neural Networks, or other similar and potentially less complex methods providing useful posterior distributions, to estimate these delivery uncertainties or more specifically, their probabilities over time. For this we are collecting data of past deliveries, including ones that were on time, late or cancelled completely. As the usefulness of such data is highly dependent on the meaningfulness of its features, we are currently in the process of analysing which features contain useful information. One avenue we pursue is to probe scheduling and purchasing experts into how they determine a likely missed delivery in their own day-to-day work. Additionally, we analyse all available data with statistical methods such as feature importance analysis and variance inflation scoring.

7. Conclusion

The organisation in production networks and the increased use of JIT are forcing companies to coordinate their material flows along their supply chain. As shown, such complex production systems are vulnerable to a variety of disturbances. A key factor in dealing with production disturbances is a more robust production planning and control. In this paper, we have provided a comprehensive literature review on production disturbances and how they can be classified. We also found that there is currently no classification that distinguishes disturbances in terms of their impact on production planning and control. Thus, we plan on combining the presented classification approaches and develop a new concept to classify disturbances on planning and control level in future work.

We also presented a case study where the production plan of a multinational company becomes impossible due to disturbance in material availability. To automate the rescheduling of such plans we developed an algorithmic approach with several expansion stages. In the first stage, we automated the rescheduling steps, which are currently carried out completely manually, by optimising a weighted cost function. For the next stage, we discussed the usefulness of genetic algorithms, with the help of which it is possible not only to close gaps in production plans by simple measures, but also to create completely new production plans for the fixed planning horizon that are optimized with regard to further criteria. Most importantly, this scheduling solution allows more degrees of freedom than the automated user approach. As we described, this is a form of reactive disturbance management leading to more robust production systems. In a further expansion stage, we want to proactively handle disturbances in material availability or, at least, better identify potential future risks. To this end, we proposed the use of Bayesian machine learning to estimate the probability distributions of a delivery over time. This knowledge, in turn, can be integrated into our scheduling optimizer, which would lead to resilient and less vulnerable production plans and thus to an increased robustness of the whole production system.

To summarize, we found that despite a large variety of existing classification systems the case of production planning and control can still not be fully mapped. Furthermore, we were able to implement an artificial intelligence–based algorithmic automation achieving human competitive results in reactive handling of disturbances and proposed a proactive disturbance handling approach based on machine learned predictions.

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References

[1] Nyhuis, P., Mayer, J., Pielmeier, J., Berger, C., Engehausen, F., Hempel, T., Hünnekes, P. (Eds.), 2016. Aktuellen Herausforderungen der Produktionsplanung und -steuerung mittels Industrie 4.0 begegnen: Studienergebnisse. PZH Verlag, Garbsen.

[2] Berlak, J., Berg, J., Stangl, M., Baumgart, L., 2020. Real-Time IoT-Based Production Planning and Control of Industrial Robots in an Automated Cyber-Physical Production System Under Dynamic Conditions: Lessons Learned from a Make-to-Order Usage Case, in: Moreno-Díaz, R., Pichler, F., Quesada-Arencibia, A. (Eds.), Computer Aided Systems Theory – EUROCAST 2019. Springer International Publishing, Cham.

[3] Lödding, H., 2012. A manufacturing control model. International Journal of Production Research 50 (22).

[4] Permin, E., Bertelsmeier, F., Blum, M., Bützler, J., Haag, S., Kuz, S., Özdemir, D., Stemmler, S., Thombansen, U., Schmitt, R., Brecher, C., Schlick, C., Abel, D., Poprawe, R., Loosen, P., Schulz, W., Schuh, G., 2016. Self-optimizing Production Systems. Procedia CIRP 41.

[5] Bokrantz, J., Skoogh, A., Ylipää, T., Stahre, J., 2016. Handling of production disturbances in the manufacturing industry. Journal of Manufacturing Technology Management 27 (8).

[6] Berlak, J., Hafner, S., Kuppelwieser, V.G., 2020. Digitalization's impacts on productivity: a model-based approach and evaluation in Germany's building construction industry. Production Planning & Control 32 (4).

[7] Wiendahl, H.-P., Wiendahl, H.-H., 2020. Betriebsorganisation für Ingenieure, 9th ed. Hanser, München.

[8] Eversheim, W., 1998. Organisation in der Produktionstechnik: Konstruktion, 3rd ed. Springer Berlin Heidelberg.

[9] Schuh, G., Stich, V., 2012. Produktionsplanung und -steuerung, 4th ed. Springer Berlin Heidelberg.

[10] Berger, C., Berlak, J., Reinhart, G., 2016. Service-based production planning and control of cyber-physical production systems. BLED 2016 Proceedings.

[11] Lödding, H. (Ed.), 2020. PPS-Report 2019: Studienergebnisse, 1st ed. TEWISS, Garbsen.

[12] Ito, A., Ylipää, T., Gullander, P., Bokrantz, J., Centerholt, V., Skoogh, A., 2021. Dealing with resistance to the use of Industry 4.0 technologies in production disturbance management. Journal of Manufacturing Technology Management 32 (9).

[13] Mirdamadi, S., 2009. Modélisation du processus de pilotage d'un atelier en temps réel à l'aide de la simulation en ligne couplée à l'exécution.

[14] Hopkin, P., 2018. Fundamentals of risk management: Understanding, evaluating and implementing effective risk management, 5th ed. Koganpage.

[15] Leitão, P., Restivo, F., 2004. Predictive disturbance management in manufacturing control systems. Proceedings of the IMS International Forum.

[16] M'Halla, A., 2010. Contribution à la gestion des perturbations dans les systèmes manufacturiers à contraintes de temps. Ecole Centrale de Lille; Ecole nationale d'ingénieurs de Tunis (Tunisie).

[17] Ivanov, D., Dolgui, A., Sokolov, B., Ivanova, M., 2016. Disruptions in supply chains and recovery policies: state-of-the art review. IFAC-PapersOnLine 49 (12).

[18] Vargas, A., Day, S., Boza, A., Ortiz, A., Ludäscher, B., Sacala, I.S., Moisescu, M.A., 2016. Decision-Making System and Operational Risk Framework for Hierarchical Production Planning. Journal of Control Engineering and Applied Informatics 18.

[19] Darmoul, S., Pierreval, H., Hajri–Gabouj, S., 2013. Handling disruptions in manufacturing systems: An immune perspective. Engineering Applications of Artificial Intelligence 26 (1).

[20] Bayar, N., Hajri-Gabouj, S., Darmoul, S., 2018. Knowledge-based disturbance propagation in manufacturing systems: A case study. International Conference on Advanced Systems and Electric Technologies.

[21] Cowling, P., Johansson, M., 2002. Using real time information for effective dynamic scheduling. European Journal of Operational Research 139 (2).

[22] Simon, D., 1995. Störungsmanagement, in: Reinhart, G., Milberg, J., Simon, D. (Eds.), Fertigungsregelung durch zielgrößenorientierte Planung und logistisches Störungsmanagement. Springer Berlin Heidelberg.

[23] van Brackel, T., 2009. Adaptive Steuerung flexibler Werkstattfertigungssysteme. Dissertation.

[24] Schwartz, F., 2004. Störungsmanagement in Produktionssystemen. Dissertation, Aachen: Shaker.

[25] Katragjini, K., Vallada, E., Ruiz, R., 2013. Flow shop rescheduling under different types of disruption. International Journal of Production Research 51 (3).

[26] Bayar, N., Darmoul, S., Hajri-Gabouj, S., Pierreval, H., 2016. Using immune designed ontologies to monitor disruptions in manufacturing systems. Computers in Industry 81.

[27] Vieira, G.E., Herrmann, J.W., Lin, E., 2003. Rescheduling Manufacturing Systems: A Framework of Strategies, Policies, and Methods. Journal of Scheduling 6 (1).

[28] Paz Barroso, M., Wilson, J.R., 1999. HEDOMS - Human Error and Disturbance Occurrence in Manufacturing Systems: Toward the development of an analytical framework. Human Factors and Ergonomics in Manufacturing.

[29] Frizelle, G., McFarlane, D., Bongaerts, L., 1998. Disturbance measurement in manufacturing production systems. In: Proceedings of ASI '98, Bremen, Germany.

[30] Wandt, R., Friedewald, A., Lödding, H. Simulation aided disturbance management in one-of-a-kind production on the assembly site. IEEE International Conference on Industrial Engineering and Engineering Management 2012.

[31] Saadat, M., Tan, M., Owliya, M., 2008. Changes and disturbances in manufacturing systems: A comparison of emerging concepts. 2008 World Automation Congress.

[32] Tomforde, S., Kantert, J., Müller-Schloer, C., Bödelt, S., Sick, B., 2018. Comparing the effects of disturbances in self-adaptive systems-A generalised approach for the quantification of robustness. Transactions on Computational Collective Intelligence.

[33] Müller-Schloer, C., Schmeck, H., Ungerer, T. (Eds.), 2011. Organic Computing—A Paradigm Shift for Complex Systems. Springer, Basel.

[34] Scholl, A., 2001. Robuste Planung und Optimierung: Grundlagen-Konzepte und Methoden-experimentelle Untersuchungen.

[35] Olhager, J., 2013. Evolution of operations planning and control: from production to supply chains. International Journal of Production Research 51 (23-24).

[36] Jüttner, U., Peck, H., Christopher, M., 2003. Supply chain risk management: outlining an agenda for future research. International Journal of Logistics Research and Applications 6 (4).

[37] Li, Y., Carabelli, S., Fadda, E., Manerba, D., Tadei, R., Terzo, O., 2020. Machine learning and optimization for production rescheduling in Industry 4.0. The International Journal of Advanced Manufacturing Technology 110.

[38] Wang, D., Yin, Y., Cheng, T., 2018. Parallel-machine rescheduling with job unavailability and rejection. Omega.

[39] Bierwirth, C., Mattfeld, D.C., 1999. Production scheduling and rescheduling with genetic algorithms. Evolutionary computation 7 (1).

[40] Wang, G., Gunasekaran, A., Ngai, E.W., Papadopoulos, T., 2016. Big data analytics in logistics and supply chain management: Certain investigations for research and applications. International Journal of Production Economics.

[41] He, M., Ji, H., Wang, Q., Ren, C., Lougee, R., 2014. Big data fueled process management of supply risks: Sensing, prediction, evaluation and mitigation. Proceedings of the Winter Simulation.

[42] Brintrup, A., Pak, J., Ratiney, D., Pearce, T., Wichmann, P., Woodall, P., McFarlane, D., 2020. Supply chain data analytics for predicting supplier disruptions: a case study in complex asset manufacturing. International Journal of Production Research 58 (11).

[43] Baryannis, G., Dani, S., Antoniou, G., 2019. Predicting supply chain risks using machine learning: The trade-off between performance and interpretability. Future Generation Computer Systems 101.

[44] Hosseini, S., Ivanov, D., 2022. A multi-layer Bayesian network method for supply chain disruption modelling in the wake of the COVID-19 pandemic. International Journal of Production Research 60 (17).

[45] Fandel, G., Fistek, A., Stütz, S., 2011. Produktionsmanagement, 2nd ed. Springer Berlin Heidelberg.

[46] Muir, B.M., Moray, N., 1996. Trust in automation. Part II. Experimental studies of trust and human intervention in a process control simulation. Ergonomics 39 (3).

[47] Hoff, K.A., Bashir, M., 2015. Trust in automation: integrating empirical evidence on factors that influence trust. Human factors 57 (3).

[48] Viana, M.S., Morandin Junior, O., Contreras, R.C., 2020. A Modified Genetic Algorithm with Local Search Strategies and Multi-Crossover Operator for Job Shop Scheduling Problem. Sensors Basel 20 (18).

Biography

Tobias Wittmeir (*1996) is a research assistant at the Digital Manufacturing Group at the University of Augsburg since 2020. From 2014 to 2019 he studied Industrial Engineering. His main research focuses on the identification and handling of disturbances and their effects on production planning and control.

Michael Heider (*1993) is a member of the Organic Computing Group at the University of Augsburg since 2019. His main research interests lie within explainable machine learning techniques and evolutionary optimisation. He organized multiple workshops on evolutionary rule-based learning systems.

André Schweiger (*1996) is a research assistant at the Organic Computing Group since 2022. From 2015 to 2021 he studied Computer Science and Multimedia at the University of Augsburg.

Michaela Krä (*1990) has been working at the Digital Manufacturing Group since 2016. In 2015, she completed her bilingual studies in Production and Automation in Munich and Paris. Her main research focuses on the integration of autonomous transport systems in production planning and control.

Jörg Hähner (*1974) holds the Chair of Organic Computing since 2012. His group focusses on bio-inspired algorithms, optimization, machine learning and large-scale systems engineering. They frequently collaborate with industry partners to disseminate state-of-the-art research.

Johannes Schilp (*1976) has been Chair of Digital Manufacturing since 2015. He is also head of the processing department at the Fraunhofer Research Institution for Casting, Composite and Processing Technology and member of scientific networks like WG MHI and automation research groups (VDMA).

Joachim Berlak (*1973) has been full professor at the Institute for Automation & Industrial Management (IAIM) of FOM University in Munich. He is member of the editorial board of the International Journal for Digital Manufacturing Technology (DMT) and CEO of software4production GmbH.

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Optimizing Investment Planning For District Heating Coupling Of Industrial Energy Systems Using MILP

Thomas Kohne[1], Daniel Piendl[1], Matthias Weigold[1]

[1]Institute of Production Management, Technology and Machine Tools (PTW), TU Darmstadt, Otto-Berndt Str. 2, 64287 Darmstadt, Germany

Abstract

Industrial energy systems are being transformed to decrease energy costs, reduce emissions, and ensure security of supply. The increasing integration of renewable energies and industrial waste heat leads to complex and interconnected industrial energy systems. At the same time, the decarbonization of the heating sector is still in its infancy and possibilities are discussed to make excess heat from industrial companies available for building supply via district heating networks or to use district heating for thermal energy supply in the industrial sector. In this paper, we present an optimization-based investment planning approach to calculate the optimal dimensioning of a potential heat transfer station connecting industrial sites to district heating systems. The approach is based on a model library that includes typical components of industrial energy systems. Moreover, it integrates different energy demands such as heating, cooling, or electricity of production systems and sites as well as waste heat of production processes depending on predominant temperature levels. The approach manages to include transformation strategies of the industrial energy system by integrating different scenarios using regret optimization, giving decision makers a better overview of the impact of the investment in a heat transfer station on the overall factory planning. The approach is applied to the planning process of an industrial company. In the use case, a positive net present value shows the benefits of an investment in a heat transfer station. Moreover, energy costs and carbon dioxide emissions can be reduced over the planning horizon and through the higher utilization of waste heat as well as the more efficient use of energy systems.

Keywords

Industrial energy system; waste heat; heat transfer station; transformation strategies; regret optimization

1. Introduction

Increasing energy costs as well as the socio-ecological goal of reducing greenhouse gas emissions and achieving climate neutrality pose major challenges for industrial companies. To align with the goals of the Paris agreement [1], industrial companies must invest in a transformation of their on-site energy system [2,3], hereinafter referred to as industrial energy systems (IES). The industry's share of the global energy demand is about one third [4] within which the energy demand for heating appliances accounts for up to 70 % [5]. Thus, focusing on the transformation of industrial heat supply is a key element for climate neutrality [6]. Besides transforming IES, industrial companies must adapt to new energy markets for the cost- and emission-efficient as well as secure provision and use of energy [7]. Due to the goal of integrating

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renewable energies and waste heat into the overarching energy system, energy-related products such as electricity flexibility [8] or the sale of surplus heat [9,10] become more and more available. While the former takes place via national and international energy markets, the marketing of surplus heat often must be negotiated with the operator of the local district heating system (DHS) [10,11]. Due to technical and organizational barriers within the planning phase of such projects, only 7 % of the German DHS heat demand is supplied with waste heat [12] although a potential of up to 127 PJ (over 25 %) is estimated [13,14]. Whether an integration is economically suitable for the industrial company strongly depends on the investment costs, but also on the available heat quantity and its temperature level, the heat pricing and finally, the transformation of the IES at the site. To support companies in their investment decision and thereby help exploiting the shown potentials, we address the investment planning to couple IES with DHS using mathematical optimization. After laying out the fundamentals in section 2, the approach for an optimal investment planning of coupling IES and DHS is presented in section 3. The underlying modeling is outlined in section 4, which is applied to a use case in section 5. The paper closes with a summary in section 6.

2. Fundamentals

In the following, the fundamentals of investment planning in IES with a focus on thermal energy systems and transformation strategies, coupling to DHS as well as mathematical optimization are further introduced.

2.1 Transformation of industrial energy systems

IES are used to meet the various energy requirements of industrial production systems and sites and supply different forms of energy such as electricity, gas, process heating and cooling, space heating, and air conditioning or compressed air [15]. Moreover, increasing integration of renewable energies and industrial waste heat leads to complex and interconnected IES, especially within their thermal energy supply [16,17], which often consists of central heating and cooling networks (see Table 1).

Table 1: Typical industrial thermal networks with flow and return temperatures as well as applications [16]

	Flow / °C	Return / °C	Typical applications
Steam	120-240	80-160	Process heat for chemical processes, drying application
High temperature	90-120	70-90	Metal washing, space heating, domestic hot water
Medium and low temperature	50-70	30-50	Space heating, cleaning processes, potential for waste heat uptake
Cooling	10-30	15-40	Cooling of industrial equipment, air conditioning
Cold water	1-6	6-12	Cooling of industrial equipment / chemicals, air conditioning

The supply for process and space heating is still mainly based on fossil fuels such as combined heat and power (CHP) units or gas-fired boilers [15]. To achieve climate neutrality, transformation strategies are developed and applied to these systems. For planning heat integration with DHS, these potential strategies must be included since future surplus heat might be dependent on the transformation of the IES. Main transformation strategies for industrial thermal networks can be summarized as follows [18–22]:

- Efficiency: Reducing heating and cooling demand, installing more efficient energy converters,
- Waste heat integration:
    - Direct integration without substituting cooling, e. g. from heat treatment furnaces,
    - Direct integration with substituting cooling, e. g. from compressors for pressured air,
    - Indirect integration via heat pumps, e. g. from cooling networks,

- Electrification: Use of electric boilers or heat pumps instead of fossil fuel-based boilers or CHP,
- Low carbon fuels: Construction of a hydrogen infrastructure, switch to biogas,
- Additional: use of renewable energy sources (photovoltaic, solar thermal, geothermal), interconnection of thermal grids via heat exchangers and heat pumps.

2.2 Heat integration in district heating systems

DHS are a climate-friendly and cost-effective way of distributing heat due to economies of scale and the potential to integrate renewables and waste heat over longer distances [10]. The potential for heat integration is dependent on the topology and parameters of the DHS, which can be classified into four generations with decreasing flow temperatures and increasing integration of decentral energy sources [23]. For third party heat integration, the temperature levels within the IES and the DHS determine the possible structure of a heat transfer station (HTS). If the temperature of industrial surplus heat does not meet required temperatures, heat pump technology can be integrated [24]. Moreover, the fluctuating energy demand in DHS, which is highly dependent on the season, outdoor temperature, and time of the day, must be considered for a potential feed-in. The temporal difference between heat demand and surplus heat can partly be solved by using heat storage [25]. The DHS operator must guarantee the security of supply. Thus, irregular heat sources must be secured by backup capacities [26]. Considering these technical requirements in combination with the complexity of IES, HTS between IES and DHS must be planned and operated comprehensively [27].

For third-party feed-in and its investment decisions, potential revenues and costs are important. The costs of heat supplied in DHS consists of the three components: costs for heat generation, costs for distribution and costs for connecting customers. These are passed on to the customers as a connection fee, fixed costs for network maintenance, and variable costs per unit of heat purchased [28]. The marginal costs of the DHS determine the maximum profit of the IES. These can change over time depending on the utilized energy converters and primary energy prices [29,11]. If the IES can supply a base load an additional compensation is provided [10]. Investment costs include the costs for energy converters and heat exchangers as well as costs for pumps, pipes, valves, etc. Missing transparency in analyzing potential heat sources in IES and technical requirements as well as missing knowledge about potential revenues and costs in the investment planning are major barriers for industrial energy management to initiate such investment projects [11].

2.3 Optimal investment planning for heat transfer stations in industrial energy systems

Mathematical programming is a broad approach to optimize IES from component to system level regarding design and operational strategies [30]. At the system level, optimization can support investment decisions, taking multiple types of energy demands and technologies into account and evaluating economic and ecological goals [31]. An analysis of several approaches shows that the formulation as mixed integer linear programming (MILP) is most common for IES on the system level as it is a good compromise between model detail and computation time [32]. In investment planning there are several criteria to evaluate investment decisions. For optimizing IES, the net present value (NPV) method as goal function is considered the most appropriate [33]. The economic criterion can also include ecological terms by economizing ecological factors, e. g. as with carbon pricing. The uncertainty during the investment planning about the development of energy prices and demands or changes in the IES are considered in mathematical programming through stochastic, robust or regret optimization and can be used next to parameter and scenario studies [34]. In this work, regret optimization is used to integrate transformation strategies. The minimization of regret focuses on decision makers who want to undergo the least amount of opportunity costs in the worst-case scenario [35]. The mathematical formulation is presented in [36] as a minimax rule.

Mathematical optimization is often used in research for planning and operating DHS [37] and include industrial waste heat for reducing costs and emissions. Within these models, such as in [38,39], industrial waste heat is just one parameter that neglects the complexity of IES. Moreover, the decision making of industrial sites is often excluded in the modelling. Approaches such as [40,41] minimize the joint costs of both parties, not individual goals of industry and energy supplier. Research on optimizing IES [32] and waste heat integration [42] mostly focuses on the internal use of waste heat. Therefore, research on investment planning which focuses on the connection to DHS and the integration of the complexity of IES, the goals of industrial companies and transformation strategies is necessary. Thus, after researching operational strategies [27,43] we now extend the approaches to the overarching investment planning.

3. Approach

In the following, we present an optimization-based investment planning approach to calculate the optimal dimensioning of a HTS connecting IES to DHS. The approach aims to support decision makers of industrial companies. It integrates a modelling approach for IES with different forms of energy demands as well as waste heat of production processes depending on predominant temperature levels. Moreover, the approach manages to include transformation strategies of the industrial site by integrating different scenarios.

3.1 Contextualization within factory planning

The investment planning of a DHS connection is part of the IES planning, in general following the goal of an economical supply and use of energy to fulfill the corporate purpose. The industrial energy management must meet the goals for quality, time, cost, and socio-ecological effects. Thus, investing in a HTS between DHS and IES should ensure the supply of the industrial site in quality (temperature levels and energy amount) and time (fluctuating energy demands) [44]. Moreover, the investment aims to reduce energy costs, e. g. by economizing surplus heat. In former work, we showed that these goals can be met in operation [43], but for investment planning in the context of the factory planning process (Figure 1) [45], tools must evaluate long payback periods as well as consider risks [46,11]. Mathematical optimization models especially support the concept phase, using information of the basic evaluation and giving a structure for detailed planning. The investment planning of an DHS connection can be seen as one planning phase within a broader transformation strategy including several single investment planning cycles. During the planning cycle of the DHS connection there is an uncertainty about subsequent planning cycles which might affect the IES or the overall industrial site and, thus, the profitability of the DHS connection. This influence and its uncertainty must be considered early on during the DHS connection investment planning cycle.

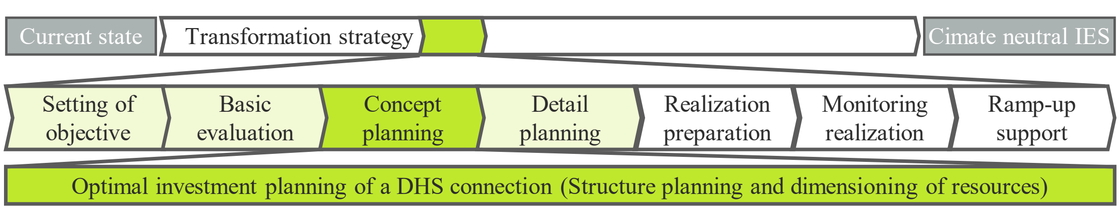

Figure 1: Optimal investment planning of IES in the context of factory planning [45] and transformation strategies.

3.2 System boundary of the modeling approach

In Figure 2 the overall system boundary of the optimization modeling approach is depicted based on the fundamentals in section 2. The industrial site is modeled with a focus on the IES. The IES is divided into several components: energy converters, waste heat sources, energy storages and supply networks. Thermal networks for heating and cooling on different temperature levels depending on the demand requirements in the IES and DHS (see Table 1) define the possible heat flows and the energy converters are connected to different energy grids. The energy demands of the industrial site with their temperature requirements are integrated as parameters. The IES modelling is built up in a modular model library. Thus, different kinds of IES can be modelled within the generic modelling approach. To address transformation strategies, the IES can be adapted by instantiating new versions of the IES with different energy converters. The DHS site models the necessary requirements such as heat pricing models, temperature levels and maximum feed-in energy. The HTS can be connected to different grids via heat exchangers and heat pumps as explained in [27]. Moreover, heat storage sizing as well as costs for pumps and pipes are modelled. The overall optimization problem is then to minimize the NPV in combination with regret optimization.

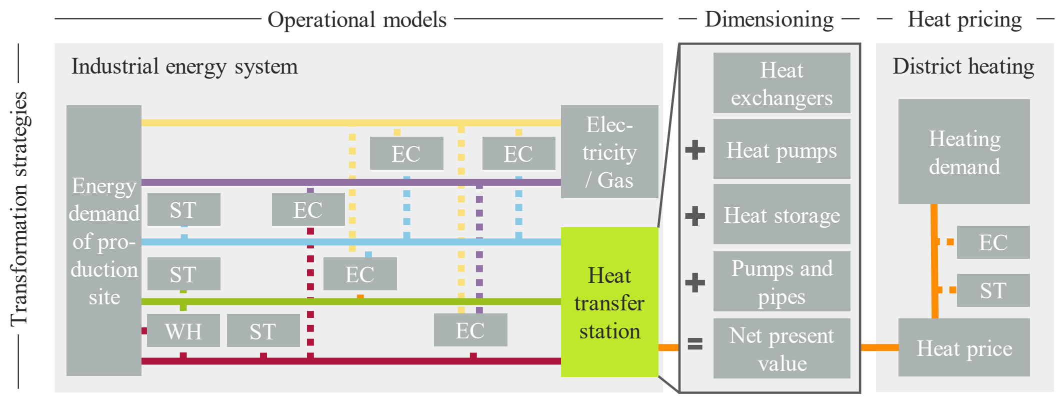

Figure 2: System boundary for investment planning approach, colored lines display energy networks (yellow: electricity; violet: gas; blue: cooling; green, orange, red: heating on different temperature levels); EC: energy converter; WH: waste heat; ST: storage.

3.3 Modelling

The approach uses a MILP model for the different parts of the system boundary formerly explained. To address the appropriate model detail, some basic assumptions are made:

- The operational models of the energy systems are modelled as energy balances considering temperature levels, energy demands and, energy pricing as parameters [43].
- To address the non-linearity of technical systems and parameters, piecewise linearization for part load behavior and investment costs is used (not included in the following equations) [32].
- The annual operational strategy is based on design days by using time series aggregation based on the methodology presented in [47]. These scenarios contain time-varying model parameters such as energy demands or temperature-dependent efficiencies.
- The DHS is modelled in this work as a linear programming model.

For the operation of the IES, energy converters are modeled as defined in Equation (*1*). The converted energy $P_{d,t,i}^{\mathrm{out}}$ for each design day in D and time step in T is calculated by the input energy $P_{d,t,i}^{\mathrm{in}}$ and an efficiency parameter $\eta_{d,t,i}$. Moreover, it is restricted to minimum $\mathrm{P}_i^{\mathrm{min}}$ and nominal $\mathrm{P}_i^{\mathrm{nom}}$ power by the operating decision variable $\delta_{d,t,i}^{\mathrm{on}}$. The specific models for energy converters are further explained in [32,43].

$$\mathrm{P}_i^{\mathrm{min}} \cdot \delta_{d,t,i}^{\mathrm{on}} \leq P_{d,t,i}^{\mathrm{out}} = P_{d,t,i}^{\mathrm{in}} \cdot \eta_{d,t,i} \leq \mathrm{P}_i^{\mathrm{nom}} \cdot \delta_{d,t,i}^{\mathrm{on}} \quad \forall d \in \mathrm{D}, \forall t \in \mathrm{T}, \forall i \in \mathrm{I} \qquad (1)$$

Energy converters are connected to the supply networks N. The energy balances of thermal networks consist of the input $P_{d,t,i}^{\mathrm{in}}$ and output $P_{d,t,i}^{\mathrm{out}}$ power of energy converters $\mathrm{I}_n^{\mathrm{out}}$, $\mathrm{I}_n^{\mathrm{in}}$ and waste heat sources J_n with power

$P_{d,t,j}^{\mathrm{WH}}$ (Equation (*2*)) of network n. These energy sources must supply the energy demands of the network $\mathrm{P}_{d,t,n}^{\mathrm{dem}}$. Moreover, energy storage $P_{d,t,n}^{\mathrm{ST}}$ can be used.

$$\sum_{i\in \mathrm{I}_n^{\mathrm{out}}} P_{d,t,i}^{\mathrm{out}} + \sum_{j\in \mathrm{J}_n} P_{d,t,j}^{\mathrm{WH}} = \mathrm{P}_{d,t,n}^{\mathrm{dem}} + P_{d,t,n}^{\mathrm{ST}} + \sum_{i\in \mathrm{I}_n^{\mathrm{in}}} P_{d,t,i}^{\mathrm{in}} \quad \forall d \in \mathrm{D}, \forall t \in \mathrm{T}, \forall n \in \mathrm{N} \tag{2}$$

The HTS is connected to the thermal networks of the IES. The possible connections must be defined before the optimization. For the dimensioning of the components K of the HTS, a binary decision variable x_k^{buy} is integrated (Equation (*3*)). The variable P_k^{nom} defines the optimal nominal power of components within the HTS which is constrained to $\mathrm{P}_k^{\mathrm{nom,max}}$. The operational models and investment cost curves of dimensioned components within the HTS are further explained in [32].

$$P_{d,t,k}^{\mathrm{out}} \leq P_k^{\mathrm{nom}} \leq x_k^{\mathrm{buy}} \cdot \mathrm{P}_k^{\mathrm{nom,max}} \quad \forall d \in \mathrm{D}, \forall t \in \mathrm{T}, \forall k \in K \tag{3}$$

The system is optimized by maximizing the NPV (Equation (*4*)-(*6*)) considering design days for every year Y with a weighting factor $\omega_{y,d}$. The NPV includes the investment costs I, the operating costs C_y in year y as well as a discount factor with the interest rate i. The operating costs are compared to those in case no HTS is bought $\mathrm{C}_y^{\mathrm{base}}$. The investment costs include costs for the components of the HTS $\mathrm{c}_k^{\mathrm{fix/var}}$. Moreover, costs for pumps and pipes $\mathrm{c}^{\mathrm{p,fix/var}}$ can be integrated. The operating costs include energy costs $\mathrm{c}_y^{\mathrm{el/gas/th}}$ as well as revenues for the sold thermal energy $\mathrm{r}_y^{\mathrm{th}}$. Also, a base load factor $\mathrm{r}_{y,d}^{\mathrm{th,base}}$ can be integrated.

$$\max NPV = -I + \sum_{y\in \mathrm{Y}} \frac{C_y - \mathrm{C}_y^{\mathrm{base}}}{(1+\mathrm{i})^y} \tag{4}$$

$$I = \mathrm{c}^{\mathrm{p,fix}} + P^{\mathrm{th,max}} \cdot \mathrm{c}^{\mathrm{p,var}} + \sum_{k\in \mathrm{K}} x_k^{\mathrm{buy}} \cdot \mathrm{c}_k^{\mathrm{fix}} + P_k^{\mathrm{max}} \cdot \mathrm{c}_k^{\mathrm{var}} \tag{5}$$

$$C_y = \sum_{d\in \mathrm{D}} \omega_{y,d} \cdot \left(P_{y,d}^{\mathrm{th,base}} \cdot \mathrm{r}_{y,d}^{\mathrm{th,base}} + \sum_{t\in \mathrm{T}} P_{y,d,t}^{\mathrm{th,sell}} \cdot \mathrm{r}_y^{\mathrm{th}} - P_{y,d,t}^{\mathrm{th,buy}} \cdot \mathrm{c}_y^{\mathrm{th}} - P_{y,d,t}^{\mathrm{el}} \cdot \mathrm{c}_y^{\mathrm{el}} - P_{y,d,t}^{\mathrm{gas}} \cdot \mathrm{c}_y^{\mathrm{gas}} \right) \quad \forall y \in Y \tag{6}$$

If several transformation strategies and pricing or demand scenarios α are to be evaluated, the goal function is adapted to a regret minimization (Equation (*7*)). Here, instances for each scenario are created. Then, each single scenario is optimized, resulting in its NPV_α^*, after which the overall regret optimization is conducted. The solution of regret minimization leads to the investment NPV_α that would be least regretted by the decision maker in the worst case scenario [35].

$$\min_{I,C_y} \max_{\alpha} (\mathrm{NPV}_\alpha^* - NPV_\alpha) \tag{7}$$

4. Evaluation

In this section, the modelling approach is applied to the IES of an industrial company for a first concept and dimensioning of a HTS to the local DHS. The industrial site of the use case is planning a transformation to climate neutrality of the IES. Within a research project, the coupling to the local DHS is under consideration.

4.1 Use Case

The IES of the industrial company consists of five different thermal networks as depicted in Table 1. The networks are supplied by gas-fired CHP and boilers as well as compression chillers and cooling towers.

Moreover, it is planned that the networks are connected via heat pumps and heat exchangers and that waste heat from compressors for pressurized air can be used. The potential HTS can only be connected to the low temperature network due to spatial issues. Thus, the IES can supply heat to the DHS via heat pump or receive heat via heat exchanger. An additional storage can be connected to the HTS. The parameters for the existing components were supplied by the industrial company. For a theoretical evaluation of the approach within this paper, parameters, and investment costs for the components of the HTS were taken from [32]. In the application within the project, data on specific components from suppliers are used. Eight design days containing the energy demand for each network, the availability of waste heat as well as the ambient temperature and solar irradiance are derived from measurement data spanning one year. The heat price was set to the marginal heat cost of the DHS. To adapt the optimization to potential developments of the IES, two transformation strategies besides the conventional IES supply are considered for implementation in four years: electrification with heat pumps, electric boilers, photovoltaic and battery storage on the one hand and a built up of a hydrogen infrastructure with electrolysis, hydrogen fired CHP and electric boilers on the other hand. Besides the conventional, electrification and hydrogen strategies, three projections of gas and electricity prices are assumed based on [48]. Thus, nine scenarios for a future development of the IES and prices are integrated in the optimization.

4.2 Results

The overall model is built up in the python based optimization modeling language Pyomo and solved by the commercial solver CPLEX for a time horizon of ten years and an interest rate of 4.5 % [35]. The theoretical optimization for each scenario is depicted in Table 2. It shows the NPV for the optimal HTS for each single scenario, the NPV for each single scenario with the optimal investment for the conventional and average pricing scenario as well as the NPV with the investment determined by the regret optimization. By utilizing the regret optimization, the maximum regret for any scenario can be reduced from 7.87 to 0.19 M€. The investment in the regret optimal HTS yields savings between 1.6 and 10.1 M€ over the time horizon of ten years compared to the NPV without a HTS. A total emissions reduction of the IES and the DHS of up to 3.9 % can be reached. However, one scenario results in higher total emissions of 0.5 %. In all scenarios heat is supplied to the DHS, but in some scenarios no heat is received. Furthermore, the optimal investment decisions for each single scenario are shown. For each scenario a heat pump is bought. However, for only some scenarios the investment in a heat exchanger and storage is optimal. The regret optimal HTS consists of a heat pump with 5.9 MW and a heat exchanger with 4.9 MW nominal power for a total of 0.65 M€. With these results, further detail planning of the HTS is conducted with the industrial company.

5. Summary and Discussion

In this paper, we present an optimization-based investment planning approach to calculate the optimal dimensioning of a potential HTS connecting IES to DHS. The approach is contextualized in the factory planning supporting the concept phase within investment projects. The MILP model of the IES integrates energy demands of production systems and sites as well as waste heat of production processes depending on predominant temperature levels with models of energy converters, storages, and thermal networks. Transformation processes for climate neutrality of the IES are integrated by applying regret optimization for comparing different transformation strategies and price scenarios. The approach is applied to the planning process of an industrial company which is currently in the concept phase of planning an HTS to the local DHS. Results indicate that the investment in the regret optimal HTS yields substantial savings over the time horizon of ten years compared to the NPV without a HTS. Moreover, by utilizing the regret optimization, the maximum regret for any scenario can be reduced substantially. However, the results must be validated in further steps (detail planning) of the project, e. g. with simulation models for detailed components, as well as at the end of the project.

The presented approach mainly focuses on the dimensioning of the components of the HTS considering techno-economical aspects. Regulatory and contractual aspects such as limitation on emissions or heat feed-in, restrictions on groundwork within residential areas as well as specific pricing regulation must be discussed with local administration as well as the energy supplier upfront or integrated in the model in a second iteration. Thus, generated results by using the approach can be seen as a first indication for concept planning which must be validated and concretized in detail planning. In detail planning also the hydraulic connection between the IES and the DHS must be considered, e. g. by integrating simulation models. As the approach can be used iteratively in the concept planning and integrates complex modelling such as regret optimization, expert knowledge is necessary. In future work, the usability for a broader use could be improved. Moreover, in future research the approach can be extended by integrating different possible variants of the HTS in form of a structure optimization or apply different pricing schemes of DHS.

Table 2: Results of the use case. Transformation strategies: conventional (C), electrified (E) and hydrogen (H2). Electricity and gas price projections: average prices (A), high electricity and low gas price (H) and low electricity and high gas price (L).

Scenario α	C&A	C&H	C&L	E&A	E&H	E&L	H2&A	H2&H	H2&L
NPV_{α}^{*} in M€	1.8	5.4	6.6	2.8	9.7	6.2	1.4	10.3	3.7
NPV_{α} (C/A HTS) in M€	1.8	2.5	6.2	2.5	3.0	6.0	1.1	2.4	3.5
Regret to NPV_{α}^{*} in M€	0.0	2.84	0.39	0.34	6.69	0.26	0.29	7.87	0.21
NPV_{α} (regret opt.) in M€	1.6	5.2	6.4	2.6	9.5	6.0	1.2	10.1	3.5
Regret to NPV_{α}^{*} in M€	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19
Emissions (no HTS) in Mt CO_2	2.18	2.18	2.08	1.82	1.78	1.86	2.36	2.29	2.43
Emission reduction in %	2.1	0.0	3.6	2.2	0.0	3.9	1.0	-0.5	2.7
Heat supplied in GWh/a	16.1	9.7	38.7	16.3	10.1	35.0	9.7	7.5	32.1
Heat received in GWh/a	0.7	19.6	0.0	7.5	23.8	0.0	9.3	26.4	0.0
Heat pump in MW	4.3	3.4	6.9	4.3	3.1	5.7	4.3	3.4	5.7
Heat exchanger in MW	0.3	5.0	0.0	4.3	4.5	0.0	4.3	5.0	0.0
Heat storage in MWh	0.0	0.0	0.0	24.7	10.2	5.0	0.0	0.0	0.0

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References

[1] United Nations, 2015. Paris Agreement. http://unfccc.int/files/meetings/paris_nov_2015/application/pdf/paris_agreement_english_.pdf. Accessed 26 September 2022.

[2] IRENA, IEA, REN21, 2020. Renewable Energy Policies in a Time of Transition: Heating and Cooling. IRENA, OECD/IEA and REN21.

[3] IRENA Coalition for Action, 2021. Companies in transition towards 100% renewables: Focus on heating and cooling. International Renewable Energy Agency, Abu Dhabi.

[4] REN21, 2022. Renewables 2022 Global Status Report, Paris.

[5] Arbeitsgemeinschaft Energiebilanzen e.V. (AGEB), 2020. Anwendungsbilanzen zur Energiebilanz Deutschland: Endenergieverbrauch nach Energieträgern und Anwendungszwecken.

[6] Thiel, G.P., Stark, A.K., 2021. To decarbonize industry, we must decarbonize heat. Joule 5 (3), 531–550.

[7] Matzen, F.J., Tesch, R. (Eds.), 2017. Industrielle Energiestrategie: Praxishandbuch für Entscheider des produzierenden Gewerbes. Springer Gabler, Wiesbaden.

[8] Richstein, J.C., Hosseinioun, S.S., 2020. Industrial demand response: How network tariffs and regulation (do not) impact flexibility provision in electricity markets and reserves. Applied Energy 278, 1–23.

[9] Bühler, F., Petrović, S., Karlsson, K., Elmegaard, B., 2017. Industrial excess heat for district heating in Denmark. Applied Energy 205, 991–1001.

[10] Li, H., Sun, Q., Zhang, Q., Wallin, F., 2015. A review of the pricing mechanisms for district heating systems. Renewable and Sustainable Energy Reviews 42, 56–65.

[11] Moser, S., Puschnigg, S., Rodin, V., 2020. Designing the Heat Merit Order to determine the value of industrial waste heat for district heating systems. Energy 200, 1–9.

[12] IEA, 2020. Germany 2020: Energy Policy Review, Paris.

[13] BDEW, 2021. Fernwärme: 126 Milliarden Kilowattstunden Wärme für die leitungsgebundene Wärmeversorgung wurden in Deutschland im Jahr 2020 erzeugt. Bundesamt der Energie- und Wasserwirtschaft e. V. https://www.bdew.de/presse/presseinformationen/zdw-fernwaerme-126-milliarden-kilowattstunden/. Accessed 12 August 2022.

[14] Brueckner, S., Arbter, R., Pehnt, M., Laevemann, E., 2017. Industrial waste heat potential in Germany—a bottom-up analysis. Energy Efficiency 10 (2), 513–525.

[15] Blesl, M., Kessler, A., 2021. Energy Efficiency in Industry. Springer Berlin Heidelberg, Berlin, Heidelberg.

[16] Kleinertz, B., Gruber, A., Veitengruber, F., Kolb, M., Roon, S., 2019. Flexibility potential of industrial thermal networks through hybridization, in: Technische Universität Wien (Ed.), 11. Internationale Energiewirtschaftstagung (IEWT), pp. 1–31.

[17] Thiede, S., 2012. Energy Efficiency in Manufacturing Systems, 1st ed. ed. Springer Berlin / Heidelberg, Berlin, Heidelberg.

[18] Bardy, S., Seyfried, S., Metternich, J., Weigold, M., 2022. Supporting the Transformation to Climate Neutral Production with Shop Floor Management. Hannover: publish-Ing.

[19] Bataille, C., Åhman, M., Neuhoff, K., Nilsson, L.J., Fischedick, M., Lechtenböhmer, S., Solano-Rodriquez, B., Denis-Ryan, A., Stiebert, S., Waisman, H., Sartor, O., Rahbar, S., 2018. A review of technology and policy deep decarbonization pathway options for making energy-intensive industry production consistent with the Paris Agreement. Journal of Cleaner Production 187, 960–973.

[20] Bataille, C., Nilsson, L.J., Jotzo, F., 2021. Industry in a net-zero emissions world: New mitigation pathways, new supply chains, modelling needs and policy implications. Energy and Climate Change (2).

[21] Rissman, J., Bataille, C., Masanet, E., Aden, N., Morrow, W.R., Zhou, N., Elliott, N., Dell, R., Heeren, N., Huckestein, B., Cresko, J., Miller, S.A., Roy, J., Fennell, P., Cremmins, B., Koch Blank, T., Hone, D., Williams, E.D., La Rue Can, S. de, Sisson, B., Williams, M., Katzenberger, J., Burtraw, D., Sethi, G., Ping, H., Danielson, D., Lu, H., Lorber, T., Dinkel, J., Helseth, J., 2020. Technologies and policies to decarbonize global industry: Review and assessment of mitigation drivers through 2070. Applied Energy 266, 1–34.

[22] Wei, M., McMillan, C.A., La Rue Can, S. de, 2019. Electrification of Industry: Potential, Challenges and Outlook. Curr Sustainable Renewable Energy Rep 6 (4), 140–148.

[23] Lund, H., Werner, S., Wiltshire, R., Svendsen, S., Thorsen, J.E., Hvelplund, F., Mathiesen, B.V., 2014. 4th Generation District Heating (4GDH). Energy 68, 1–11.

[24] Fang, H., Xia, J., Jiang, Y., 2015. Key issues and solutions in a district heating system using low-grade industrial waste heat. Energy 86, 589–602.

[25] Knudsen, B.R., Rohde, D., Kauko, H., 2021. Thermal energy storage sizing for industrial waste-heat utilization in district heating: A model predictive control approach. Energy 234, 1–12.

[26] Konstantin, P., Konstantin, M., 2022. Praxisbuch der Fernwärme- und Fernkälteversorgung: Systeme, Netzaufbauvarianten, Kraft-Wärme-Kopplung, Kostenstrukturen und Preisbildung, 2. Auflage ed. Springer Vieweg, Berlin, Heidelberg.

[27] Kohne, T., Burkhardt, M., Theisinger, L., Weigold, M., 2021. Technical and digital twin concept of an industrial heat transfer station for low exergy waste heat. Procedia CIRP 104, 223–228.

[28] Nussbaumer, T., Thalmann, S., Jenni, A., Ködel, J., 2017. Planungshandbuch Fernwärme, Version 1.1 vom 21. September 2017 ed. EnergieSchweiz Bundesamt für Energie, Ittigen, Bern.

[29] Difs, K., Trygg, L., 2009. Pricing district heating by marginal cost. Energy Policy 37 (2), 606–616.

[30] Andiappan, V., 2017. State-Of-The-Art Review of Mathematical Optimisation Approaches for Synthesis of Energy Systems. Process Integr Optim Sustain 1 (3), 165–188.

[31] Di Somma, M., Yan, B., Bianco, N., Graditi, G., Luh, P.B., Mongibello, L., Naso, V., 2015. Operation optimization of a distributed energy system considering energy costs and exergy efficiency. Energy Conversion and Management 103, 739–751.

[32] Baumgärtner, N.J., 2020. Optimization of low-carbon energy systems from industrial to national scale. Dissertation. RWTH Aachen University, Aachen.

[33] Pintarič, Z.N., Kravanja, Z., 2015. The importance of proper economic criteria and process modeling for single- and multi-objective optimizations. Computers & Chemical Engineering 83, 35–47.

[34] Svetlova, E., van Elst, H., 2013. How is non-knowledge represented in economic theory?, in: Priddat. B., Kaballak, A. (Eds.), Ungewissheit als Herausforderung für die ökonomische Theorie: Nichtwissen, Ambivalenz und Entscheidung. Metropolis-Verlag, Marburg, pp. 41–72.

[35] Schwarz, H., 2019. Optimierung der Investitions- und Einsatzplanung dezentraler Energiesysteme unter Unsicherheit. Dissertation, Karlsruhe.

[36] Wald, A., 1945. Statistical Decision Functions Which Minimize the Maximum Risk. Annals of Mathematics (46), 265–280.

[37] Wirtz, M., Kivilip, L., Remmen, P., Müller, D., 2020. 5th Generation District Heating: A novel design approach based on mathematical optimization. Applied Energy 260, 1–20.

[38] Li, Y., Xia, J., Su, Y., Jiang, Y., 2018. Systematic optimization for the utilization of low-temperature industrial excess heat for district heating. Energy 144, 984–991.

[39] Zhang, L., Wang, Y., Feng, X., 2021. A Framework for Design and Operation Optimization for Utilizing Low-Grade Industrial Waste Heat in District Heating and Cooling. Energies (14), 2–21.

[40] Aydemir, A., 2018. Ermittlung von Energieeinsparpotenzialen durch überbetriebliche Wärmeintegration in Deutschland. Dissertation, Darmstadt.

[41] Fitó, J., Ramousse, J., Hodencq, S., Wurtz, F., 2020. Energy, exergy, economic and exergoeconomic (4E) multicriteria analysis of an industrial waste heat valorization system through district heating. Sustainable Energy Technologies and Assessments 42, 100894.

[42] Kurle, D., Schulze, C., Herrmann, C., Thiede, S., 2016. Unlocking Waste Heat Potentials in Manufacturing. 2212-8271 48, 289–294.

[43] Kohne, T., Theisinger, L., Scherff, J., Weigold, M., 2021. Data and optimization model of an industrial heat transfer station to increase energy flexibility. Energy Inform 4 (S3), 1–17.

[44] Posch, W., 2011. Ganzheitliches Energiemanagement für Industriebetriebe. Zugl.: Leoben, Montanuniv., Habil.-Schr., 2010, 1. Aufl. ed. Gabler, Wiesbaden.

[45] VDI Verein Deutscher Ingenieure e. V., 2011. Fabrikplanung: Planungsvorgehen. VDI-Verlag, Düsseldorf.

[46] Kurle, D., 2018. Integrated planning of heat flows in production systems. Springer International Publishing, Cham.

[47] Fazlollahi, S., Bungener, S., Mandel, P., Becker, G., Maréchal, F., 2014. Multi-objectives, multi-period optimization of district energy systems: I. Selection of typical operating periods. Computers & Chemical Engineering.

[48] Energiewirtschaftliches Institut an der Universität zu Köln (EWI), 2022. Szenarien für die Preisentwicklung von Energieträgern.

Biography

Thomas Kohne, M. Sc. M. Sc. (*1991) has been research associate and PhD student since 2018 and head of research group since 2021 at the Institute of Production Management, Technology and Machine Tools (PTW) at Technical University of Darmstadt. His personal research fields include waste heat integration and climate strategies of industrial companies.

Daniel Piendl, M. Sc. (*1997) has been student at the Technical University of Darmstadt since 2016. He has been student assistant at the PTW in the field of Energy Technologies and Applications in Production since 2018. His research fields include energy efficiency and industrial waste heat integration into district heating.

Prof. Dr.-Ing. Matthias Weigold (*1977) has been the head of the PTW at Technical University of Darmstadt since 2019. As director he is responsible for the research fields on Manufacturing Technology as well as Energy Technologies and Applications in Production. His personal research fields include digitization and climate neutrality in production.

4th Conference on Production Systems and Logistics

Literature Review of Process Models in Asset- and Maintenance-Management-Systems

Philipp T. Kraker[1]

[1]Chair of Economic- and Business Management/Montanuniversität Leoben, Leoben, Austria

Abstract

Due to the advancements in digitalization and increasing system complexities during the past decade, asset and maintenance management are becoming more important in companies. Especially in manufacturing companies, lean, effective and efficient production is necessary, which can only be achieved with optimal strategies for physical assets and excellent asset management, to master challenging market situations. System models are supporting management tools for the systematic development of asset and maintenance management in the company. One of the most common types of system models are process models, which are abstract representations of complex processes. They represent the chronological and factual sequence of functions, activities, essential subsystems, properties and interfaces. Numerous process models of maintenance and asset management have been published over the years, representing different objectives and aspects. This article provides a framework that clarifies the morphology of the models mentioned in literature. Finally, the similarities and differences regarding model application in practice and further research are discussed. Overall, the article intends to help researchers derive new, extended and optimized models for the domain.

Keywords

Asset Management; Maintenance Management; Process Models; Framework; Business Management;

1. Introduction

Increasing market dynamics, growing system complexity, shortened technology cycles, and rising competitive pressure are prevalent problems of manufacturing companies. These risks have a significantly strong impact on the physical assets of manufacturing companies, which are supposed to cover a high product portfolio, ensure a high degree of availability and produce high-quality products. To counter these sources of danger and risks in the best possible way and to be able to preserve the market position, dynamic further development across all areas of the company is essential. In this context, maintenance and, more comprehensive, asset management is becoming increasingly crucial as reliability requirements continue to rise. [1,2] The basis for efficient and effective maintenance and asset management is a model for the structure and description of the contents of a management system for the respective company. System models, which are essentially management tools that enable structured implementation, serve this purpose in particular, in this case, for asset and maintenance management. One of the most common types of system models are process models, which are abstract representations of the processes of complex structures. They represent the temporal and factual sequence of functions, activities, essential elements, properties and interfaces. [3,4] Over the past decades, various models have evolved, focusing on different aspects. These range from generic models to specially designed models for specific niche areas. Likewise, the various models differ significantly in the level of detail, which in turn influences the scope of the processes mapped.

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The main objective of this paper is to show the existing process models and their contents for the design and development of maintenance and asset management, with their differences, advantages, limitations and characteristics. For this purpose, a literature study was conducted, which screened known literature databases, university theses, and books in this field via internet searches.

2. Models in Asset- and Maintenance-Management-Systems

For further work, it is essential to understand which models were searched for and compared in the literature study. The aim was to specifically address process models that serve to introduce and build a structure in this domain, not to find philosophies or strategies in the field of asset management.

2.1 Process Models

The process model is the graphical, purpose-related and immaterial representation of a temporal and factual sequence of the function carried out on an object to ensure a better overview. [5,4] The goal is to represent complex processes simply and understandably to enhance understanding among the stakeholders as well as communication and to improve the company's success factors - such as cost, time, quality, flexibility, environment and safety. [6] The modelling of an enterprise process often turns out to be complex because the purpose of the process model can be lost sight of by unstructured proceedings. Process models are used in companies for a wide variety of purposes. Starting with the mapping and analysis of operational processes up to the use in projects for management system certifications. When creating these, it is essential to follow a structured procedure, such as the procedure from the project perspective, the procedure from the perspective of the process hierarchy, or the procedure from the perspective of the process dimensions.

2.2 Process Models in Asset- and Maintenance Management

In the domain of asset and maintenance management, process models can depict the holistic activities on the three different management levels.

The normative level deals with corporate policy, corporate goals, corporate constitution and corporate culture. To create benefits for the respective target groups define At this level, the principles, norms and rules for ensuring the company's viability and development. [7] The starting point is the corporate vision, which defines the corporate actions and forms the basis of the corporate policy and the corporate mission for the corporate development derived from it. It thereby creates legitimacy for the actions at the strategic level. [8,9]

Strategic management focuses on the creation, preservation and utilization of success potentials, for which resources must be used. [8] The main task of this level is the design of organizational structures and management systems, the design of relevant programs, as well as the problem-solving behaviour of the company's actors. The goal of strategic management is to influence the activities set and to perform actions in accordance with the defined policy, as well as to ensure the company's long-term future. [9,7]

The strategic management is implemented in the operational actions, which are focused on economic, performance, financial and information processes. Operational management aims to implement the targets defined at the strategic level and measures to achieve the corporate and asset management targets. [9]

A central role in a process model for asset and maintenance management is also given to the management functions with planning, control, information, organization and personnel management [10–12] this ensures a dynamic improvement and an orientation of the management system towards an efficient and effective management. [13] These management functions can also be used from the operational to the normative level.

Planning

The goal-oriented planning forms the main task of a manager and serves the systematic [14], prospective thinking through and definition of goals as well as measures and means for the goal reaching. [15] It also has the coordinating function of steering the corporate processes. [12] The issues that are examined in the course of planning are, on the one hand, the corporate goals (goal planning), the corporate structure (structure and provision planning) and, on the other hand, the planning of the process flows (process planning). All planning processes have in common that they are information processing operations or system design, serve to adapt to environmental changes, take place through a sequence of planning phases, and that planning itself must be planned and is an instrument of coordination which itself must be coordinated. [14]

Control

Control, the counterpart to planning, serves to reduce uncertainties in the planning process. These uncertainties range from checking assumptions and verifying the target effect of planned measures to monitoring the available resources and behaviour of those involved. [14] Thus, the main task consists of target-performance comparisons, evaluation of results, deviation analyses and, if necessary, adaptation of the planning and all other sub-management systems. [16]

Information

Planning and control require information supply. Thus, the goal of information is to provide management with results-oriented information with the necessary degree of accuracy and compression at the right place and at the right time. Important in information is the right balance between the content, the form of the statement and the information properties of the information. [14]

The main requirements for information supply from the point of view of planning and control are making planning problems visible, showing the information about the possibilities of action, and flexible adjustment to the changing environmental conditions. Furthermore, the information supply should be economical, user-adequate, and determined by a structured system with linear tasks. [16]

Organization

The goal-oriented control of operational activities is the primary goal of the organization. Thus, it is also one of the business management tools with the main task of coordination. These coordination activities can reach from the distribution of tasks over the organization of instruction and decision rights up to the organization of spatial-temporal relations of physical processes and information processes. Within the structure and operational organization, it covers this subrange of measures for coordinating tasks and the coordination between the management subsystems. [16]

Personnel management

Personnel management is understood to be that subsystem of management, which is directed at employee management. Thus, it includes the employees themselves, the managers controlling them, and all related instruments and processes. The central tasks of personnel management are recruitment, planning, administration, development, evaluation and controlling of personnel. [17] Since it takes place through social interactions, information plays a crucial role in this context. Planning, control, information and organization relates closely to personnel management, and the associated tasks only become effective through good personnel management. The difference between this and the other leadership subsystems is that personnel management is linked to the participation of the people concerned. The effectiveness of the other leadership subsystems only occurs when the respective output influences the behaviour of the employees, which in turn depends on personnel management. Since the measures of information, planning, control, and organization only become effective through personnel management, coordination among them is very important. [16]

Overall, the process model and its contents intend to support companies in designing and developing comprehensive asset and maintenance management in a structured manner.

3. Research Methodology and delimitations

Bibliographic searches were conducted in the following electronic databases:

- Scopus
- Web of Science

The search function was used to search the two electrical databases for the contents maintenance management, physical asset management, system models, process models, control loops and framework. The restriction also only includes titles from the year 1980 onwards. One thousand and two entries were found in total during the query. After excluding the following criteria, 14 articles remained:

- The article must represent a holistic maintenance management model and not be limited to a specific management area.
- The model presented in the article must be a process model.
- The model must not be a computer model or a computerized maintenance management system (CMMS).

For the papers, the title was screened at the beginning for a first elimination, then an abstract screening of the remaining contents was performed, so that further contents could be eliminated. A full text screening was performed for the remaining publications, finally the mentioned 14 contents remained. In addition to the 14 articles in the electronic databases, a literature search of books and university publications was conducted. In the case of the university publications, the focus was on the German and Austrian regions. Thereby further relevant contents for this literature study could be included. This way, 26 contributions were selected, representing the process models for asset and maintenance management. The further article will detail which levels and aspects of the management functions are included in the individual models.

4. Results of content analysis

Table 1. present the found 26 contributions. In the first step, the selected contributions were examined to determine which levels - normative, strategic and operational - are dealt with in the process model. A more detailed description of the individual levels can be found in Chapter 2 Process Models in Asset and Maintenance Management Systems. At the outset, it can be seen that the normative level is the least addressed in the literature and is rarely formulated. In the standards, the normative level is mentioned only very superficially [18–21], whereas in BIEDERMANN and FERNÁNDEZ, for example, this level is described in detail, since it has an influence on the overall design of the management system [22,23]. Most process models, almost all of them, focus on the strategic aspect and are mainly concerned with the choice of strategy. It is clear that the more recent contributions include predictive maintenance as a strategy choice, or that data analysis models are in use, reflecting the technological progress in maintenance. [24,25] Also the operational level is considered to a quite small extent; the level itself is cited in more than half of the contributions, but a more detailed elaboration of the operational activities rarely occurs.

Table 1: Process Models in Asset- and Maintenance Management

Nr. [Source]	Author	Title	Year	Normative Level	Strategic Level	Operational Level	Planning	Information	Organization	Control	Personnel Mgmt.
1 [26]	da Silva, R. F.; Souza, G.F.M. de	Modeling a maintenance management framework for asset management based on ISO 55000 series guidelines	2021		•	•	•			•	
2 [27]	Hassanain, M. A.; Froese, T. M.; Vanier, D. J.	Framework model for asset maintenance management	2003		•	•	•	•	•	•	
3 [25]	Linneusson, Gary; Ng, Amos H. C.; Aslam, Tehseen	A hybrid simulation-based optimization framework supporting strategic maintenance development to improve production performance	2020		•	•	•				
4 [28]	Marquez, A. C.; Gupta, J. N.D.	Contemporary maintenance management: process, framework and supporting pillars	2006		•	•	•	•	•		
5 [29]	Márquez, A. C.; León, P. M. de; Fernndez, J.F.G.	The maintenance management framework: A practical view to maintenance management	2009		•		•	•	•	•	
6 [30]	Biedermann H.	Organisation zur Realisierung der Instandhaltungsplanung.	1987	•	•	•	•		•		
7 [31]	Kinz A.	Ausgestaltung einer dynamische, lern- und wertschöpfungsorientierten Instandhaltung	2017	•	•	•	•	•	•	•	•
8 [22]	Biedermann H.; Kinz A.	Lean Smart Maintenance	2021	•	•	•	•	•	•	•	•
9 [18]	Austrian Standards Institute	Instandhaltungsprozess und verbundene Leistungskennzahlen - EN17007	2017	•	•	•	•	•	•	•	
10 [19–21]	International Organization for Standardization	Asset management - ISO 55000 Reihe	2014	•	•		•	•	•	•	
11 [32]	Campbell JD	Outsourcing in maintenance management: A valid alternative to selfprovision	1995		•	•	•		•		
12 [33]	Vanneste SG, Van Wassenhove LN	An integrated and structured approach to improve maintenance	1995			•	•			•	
13 [34]	Riis J, Luxhoj J, Thorsteinsson	A situational maintenance model	1997	•	•		•	•	•	•	

14 [35]	Wireman T	Developing performance indicators for managing maintenance	1998		•		•		•		
15 [36]	Duffuaa SO, Raouf A	Planning and control of maintenance systems	2015	•	•		•	•	•	•	•
16 [37]	Tsang A	Strategic dimensions of maintenance management	2002		•		•			•	•
17 [38]	Waeyenbergh G, Pintelon L	A framework for maintenance concept development	2002		•		•	•		•	
18 [39]	Murthy DNP, Atrens A, Eccleston JA	Strategic maintenance management	2002		•		•				
19 [40]	Abudayyeh O, Khan T, Yehia S, Randolph D	The design and implementation of a maintenance information model for rural municipalities	2005			•	•	•	•	•	
20 [41]	Pramod VR, Devadasan SR,	Integrating TPM and QFD for improving quality in maintenance engineering	2006		•		•		•	•	
21 [42]	Kelly A	Strategic maintenance planning	2007	•	•	•	•	•	•	•	
22 [43]	Söderholm P, Holmgren M,	A process view of maintenance and its stakeholders	2007	•	•	•	•	•	•	•	
23 [23]	Fernández, J.F.G.; Márquez, A. C.	Defining maintenance management framework	2012	•	•	•	•	•	•	•	•
24 [44]	Campos, M. A. López; Márquez, A. Crespo	Modelling a maintenance management framework based on PAS 55 standard	2011	•	•		•	•	•	•	•
25 [24]	Gallesi-Torres, A.; Velarde-Cabrera, A.	Maintenance Management Model under the TPM approach to Reduce Machine Breakdowns in Peruvian Giant Squid Processing SMEs	2020			•	•		•	•	
26 [45]	Palomino-Valles, A.; Tokumori-Wong, M.	TPM Maintenance Management Model Focused on Reliability that Enables the Increase of the Availability of Heavy Equipment in the Construction Sector	2020		•	•	•			•	
Sum				11	23	16	26	15	19	20	6

The five major management functions, planning, control, information, organization and personnel management, are addressed for further analysis of the various contributions. This involved examining which functions are covered in each model. The focus of the process models is on planning, which can be explained by the increased consideration of the strategic level. One of the main tasks of process models is to support planning tasks in order to ensure structured planning, which explains why the planning function is addressed in every process model listed. Especially the planning for the maintenance strategies to be used is presented in the papers. In addition, administrative planning activities are often identified in the process models as well.

The information function was observed in terms of the functions and activities between which the information structure is built and which information is to be communicated. About half of the contributions represent the information structure in the process model, or they show how the functions interact with each other and thus represent an information interface.

Some contributions deal with the organizational function in their description and illustration of the process models by showing the structure of the asset and maintenance organization. Based on the organizational structure's representation, the employees' functions are likewise mapped directly in the process model. This allows for a direct transition to personnel management, but only at a few contributions.

In the case of the control function, almost all contributions depict a controlling cycle. Either about PDCA or simple control loops to be able to control the management system. In terms of content, most process models describe the controlling function only marginally and hardly show a viable approach for implementation in companies. The detailed processes in the model themselves are hardly ever depicted in control cycles, or no control function is shown. This means that the quality aspect of the individual mapped processes is hardly present.

Despite the good representation of the organization and its functions, only a few contributions describe the direct influence of the co-workers on the management system. In some cases, human resources are described and perceived as necessary. Still, there is no focus on how to deal with employees or how personnel can be used to be able to cope with the diverse activities in a holistic asset and maintenance management.

5. Conclusion

In summary, it can be said that the existing process models in the area of asset and maintenance management primarily deal with strategic conditions, whereby the focus here is on the choice of strategy for the individual assets in the enterprise. Thus, the operational level and executive activities are included in most process models, but these activities are hardly ever dealt with or described in more detail. This follows from the fact that the activities of the operational employees in the different branches can be very heterogeneous. The normative level is barely considered in the previous process models, i.e. philosophies, missions or visions of the maintenance organization are rarely considered. Accordingly, the target system cannot be aligned with an adapted vision.

Most of the articles found, show that a maintenance management system is depicted as a process model since the four basic maintenance points are usually addressed. Especially the more current contributions describe an holistic asset management. A trend towards asset management is also visible in the process models. The expanded view of assets over the entire life cycle and more significant consideration of interdisciplinary topics are being examined in increasing detail and thus show the significant influence that asset management has on the entire company.

The focus on the management functions is clearly on planning, which is also described across all levels. The information and organization function influence themselves strongly since, by the illustration of the organization, the information structure can already be indicated. Mostly here, the paths and interfaces of the information are pointed out, and the contents are rarely dealt with. This is reflected in the control function again since a control loop for the improvement and illustration of key figures is given. However, hardly the more exact processes are dealt with, whereby direct controlling of the processes becomes difficult. As a result, the quality control of the actual execution of the processes is merely described on the surface, and companies see a need to catch up with a model that supports the quality of the maintenance activities and generally of the processes to be able to monitor and control them. Personnel management is also neglected in the process models; it is only presented as an important human resource, and the comprehensive functions of this topic are severely overlooked. This presentation of the process models is intended to support the user in finding the right model for his area, and also to show alternatives.

It is easy to see that the process models have evolved considerably over the years, especially in the concept of asset management, which makes the scope of consideration even more extensive. A need for research is seen in the area of the normative level, as well as in the function of personnel management and control. Particular attention should be paid to the quality control of the individual processes, making the processes more controllable and hence improving the efficiency of asset and maintenance management.

References

[1] acatech, 2015. Smart Maintenance für Smart Factories: Mit intelligenter Instandhaltung die Industrie 4.0 vorantreiben. utzverlag, München, 52 pp.

[2] Pawellek, G., 2013. Integrierte Instandhaltung und Ersatzteillogistik: Vorgehensweisen, Methoden, Tools. Springer, Berlin, Heidelberg, 328 pp.

[3] Bandow, G., Holzmüller, H.H. (Eds.), 2009. "Das ist gar kein Modell!": Unterschiedliche Modelle und Modellierungen in Betriebswirtschaftslehre und Ingenieurwissenschaften. Gabler, Wiesbaden.

[4] Rosemann, M., Schütte, R., 1999. Multiperspektivische Referenzmodellierung, in: Becker, J., Rosemann, M., Schütte, R. (Eds.), Referenzmodellierung. Physica-Verlag HD, Heidelberg, pp. 22–44.

[5] Rolland, C., Ufr, P.-s., 1994. Modeling the Requirements Engineering Process.

[6] Dombrowski, U., Horatzek, S., Bothe, T., 2002. Erfolgreiche Prozessmodellierung. Zeitschrift für wirtschaftlichen Fabrikbetrieb 97 (11), 584–587.

[7] Rüegg-Stürm, J., 2005. Das neue St. Galler Management-Modell: Grundkategorien einer integrierten Managementlehre ; der HSG-Ansatz, 8. Nachdr. d. 2. durchgesehenen u. korr. Aufl. ed. Haupt, Bern, 103 pp.

[8] Bleicher, K., 1995. Das Konzept integriertes Management, 3. Aufl. ed. Campus-Verl., Frankfurt/Main, 513 pp.

[9] Bleicher, K., 2011. Das Konzept Integriertes Management: Visionen - Missionen - Programme, 8., aktualis. u. erw. Aufl. ed. Campus-Verl., Frankfurt am Main, 723 pp.

[10] Biedermann, H., 2008. Anlagenmanagement: Managementinstrumente zur Wertsteigerung, 2., vollst. überarb. und aktualisierte Aufl. ed. TÜV Media, Köln, 167 pp.

[11] Biedermann H., 1992. Instandhaltungsmanagement, 2., völlig überarb. Aufl. ed. Verl. TÜV Rheinland, Köln, 797 pp.

[12] Koontz, H., Weihrich, H., 2015. Essentials of management: An international, innovation, and leadership perspective, Tenth edition ed. McGraw-Hill Education (India) Private Limited, New Delhi, 496 pp.

[13] Weber, J., 1994. Einführung in das Controlling, 5., durchges. und erw. Aufl. ed. Schäffer-Poeschel, Stuttgart, 423 pp.

[14] Horvath, P., 2012. Controlling, 12., vollständig überarbeitete Aufl. ed. Verlag Franz Vahlen, München, 832 pp.

[15] Wild, J., 1980. Grundlagen der Unternehmungsplanung, 4th ed. ed. VS Verlag fur Sozialwissenschaften GmbH, Wiesbaden, 217 pp.

[16] Küpper, H.-U., 2008. Controlling: Konzeption, Aufgaben, Instrumente, 5., überarb. Aufl. ed. Schäffer-Poeschel, Stuttgart, 634 pp.

[17] Gerlmaier, A., Gül, K., Hellert, U., Kämpf, T., Latniak, E. (Eds.), 2016. Praxishandbuch lebensphasenorientiertes Personalmanagement: Fachkräftepotenziale in technischen Entwicklungsbereichen erschließen und fördern, 1. Aufl. 2016 ed. Springer Gabler, Wiesbaden, 331 pp.

[18] Austrian Standards Institute, 2017. Instandhaltungsprozess und verbundene Leistungskennzahlen: Maintenance process associated indicators. Austrian Standards Institute/Österreichisches Normungsinstitut, Wien 03.080.10, 94 pp.

[19] International Organization for Standardization, 2014. Asset management - Management systems - Guidelines for the application of ISO 55001 03.100.01, 40 pp.

[20] International Organization for Standardization, 2014. Asset management - Management systems - Requirements 03.100.01, 24 pp.

[21] International Organization for Standardization, 2014. Asset management — Overview, principles and terminology 01.040.03; 03.100.01, 28 pp.

[22] Biedermann H., Kinz A., 2021. Lean Smart Maintenance: Agile, lern- und wertschöpfungs- orientierte Instandhaltung. Springer Gabler.

[23] Fernndez, J.F.G., Márquez, A.C., 2012. Defining maintenance management framework. Springer Series in Reliability Engineering 49, 127–147.

[24] Gallesi-Torres, A., Velarde-Cabrera, A., León-Chavarri, C., Raymundo-Ibañez, C., Dominguez, F., 2020. Maintenance Management Model under the TPM approach to Reduce Machine Breakdowns in Peruvian Giant Squid Processing SMEs. IOP Conf. Ser.: Mater. Sci. Eng. 796 (1), 12006.

[25] Linneusson, G., Ng, A.H.C., Aslam, T., 2020. A hybrid simulation-based optimization framework supporting strategic maintenance development to improve production performance. EUROPEAN JOURNAL OF OPERATIONAL RESEARCH 281 (2), 402–414.

[26] da Silva, R.F., Souza, G.F.M. de, 2021. Modeling a maintenance management framework for asset management based on ISO 55000 series guidelines. Journal of Quality in Maintenance Engineering.

[27] Hassanain, M.A., Froese, T.M., Vanier, D.J., 2003. Framework model for asset maintenance management. Journal of Performance of Constructed Facilities 17 (1), 51–64.

[28] Marquez, A.C., Gupta, J.N.D., 2006. Contemporary maintenance management: process, framework and supporting pillars. OMEGA-INTERNATIONAL JOURNAL OF MANAGEMENT SCIENCE 34 (3), 313–326.

[29] Márquez, A.C., León, P.M. de, Fernndez, J.F.G., Márquez, C.P., Campos, M.L., 2009. The maintenance management framework: A practical view to maintenance management. Journal of Quality in Maintenance Engineering 15 (2), 167–178.

[30] Biedermann, H., 1987. Planung in der Instandhaltung. Verlag TÜV Rheinland, Köln, 245 pp.

[31] Kinz, A., 2017. Ausgestaltung einer dynamische, lern- und wertschöpfungsorientierten Instandhaltung. Dissertation, Leoben, 228 pp.

[32] Campbell, J.D., 1995. Outsourcing in maintenance management. Journal of Quality in Maintenance Engineering 1 (3), 18–24.

[33] Vanneste, S.G., van Wassenhove, L.N., 1995. An integrated and structured approach to improve maintenance. EUROPEAN JOURNAL OF OPERATIONAL RESEARCH 82 (2), 241–257.

[34] Riis, J.O., Luxhøj, J.T., Thorsteinsson, U., 1997. A situational maintenance model. International Journal of Quality and Reliability Management 14 (4), 349–366.

[35] Wireman, T., 2005. Developing performance indicators for managing maintenance, 2nd ed. ed. Industrial Press, New York, 250 pp.

[36] Duffuaa, S.O., 2015. Planning and Control of Maintenance Systems: Modelling and Analysis, 2nd ed. 2015 ed. Springer, Cham, 348 pp.

[37] Tsang, A.H.C., 2002. Strategic dimensions of maintenance management. Journal of Quality in Maintenance Engineering 8 (1), 7–39.

[38] Waeyenbergh, G., Pintelon, L., 2002. A framework for maintenance concept development. International Journal of Production Economics 77 (3), 299–313.

[39] Murthy, D.N.P., Atrens, A., Eccleston, J.A., 2002. Strategic maintenance management. J of Qual in Maintenance Eng 8 (4), 287–305.

[40] Abudayyeh, O., Khan, T., Yehia, S., Randolph, D., 2005. The design and implementation of a maintenance information model for rural municipalities. Advances in Engineering Software 36 (8), 540–548.

[41] Pramod, V.R., Devadasan, S.R., Muthu, S., Jagathyraj, V.P., Dhakshina Moorthy, G., 2006. Integrating TPM and QFD for improving quality in maintenance engineering. Journal of Quality in Maintenance Engineering 12 (2), 150–171.

[42] Kelly, A., 2007. Strategic maintenance planning: An essential guide for managers and professionals in engineering and related fields, 1. ed., reprinted. ed. Elsevier Butterworth-Heinemann, Amsterdam, Heidelberg, 284 pp.

[43] Söderholm, P., Holmgren, M., Klefsjö, B., 2007. A process view of maintenance and its stakeholders. Journal of Quality in Maintenance Engineering 13 (1), 19–32.

[44] Campos, M.A.L., Márquez, A.C., 2011. Modelling a maintenance management framework based on PAS 55 standard. Qual. Reliab. Engng. Int. 27 (6), 805–820.

[45] Palomino-Valles, A., Tokumori-Wong, M., Castro-Rangel, P., Raymundo-Ibañez, C., Dominguez, F., 2020. TPM Maintenance Management Model Focused on Reliability that Enables the Increase of the Availability of Heavy Equipment in the Construction Sector. IOP Conf. Ser.: Mater. Sci. Eng. 796 (1), 12008.

Philipp T. Kraker (*1992) is a research assistant at the University of Leoben, at the Chair of Economics and Management Sciences, since he completed his master's degree in materials science. The focus of the research work is asset management and quality management, where experience is gained in research projects together with the industry.

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Method for Specifying Location Data Requirements for Intralogistics Applications

Jakob Schyga, Markus Knitt, Johannes Hinckeldeyn, Jochen Kreutzfeldt

Institute of Technical Logistics, Hamburg University of Technology, Hamburg Germany

Abstract

Various applications leverage location data to increase transparency, efficiency, and safety in intralogistics. There are several properties of location data, such as the data's degrees of freedom, system latency, update rate, or accuracy. To select a suitable indoor localization system, corresponding data requirements must be derived by analyzing the considered application. To date, the dependencies of the system performance and location data requirements have not been satisfactorily described in the literature. Thus, no method exists to adequately derive location data requirements. For intralogistics, such a method is of particular relevance due to the high-cost sensitivity and heterogeneity of partially safety-relevant indoor localization applications. To fill this gap, a method for selecting and quantifying location data requirements for the application in intralogistics is presented in this work, creating substantial added value for warehouse managers and system integrators. The method is based on a spatial model that is built on the premise that location data is used to determine the presence or absence of an entity in a multidimensional interest space. The usage of the method is demonstrated in an exemplary case study for the application of 'Automated Pallet Booking'.

Keywords

Indoor localization; Intralogistics; Data requirements; Spatial model; Method

1. Introduction

Industry 4.0, Smart Logistics, and Industrial Internet of Things are terms used to describe the ongoing shift in production and logistics driven by modern information and communication technologies. One of the key technologies in intralogistics is indoor localization [1]. Indoor Localization Systems (ILS) generate location data of entities, such as goods, assets, personnel, or vehicles that can be leveraged by a wide range of applications to increase efficiency, safety, transparency, and flexibility in intralogistics. The much-discussed Real-Time Locating Systems (RTLS) are a subcategory of ILS for real-time remote locating. 'Automated Pallet Booking' [2], 'Risk Assessment' [3], and 'Location-Dependent Order Allocation' [4] are just a few examples of the myriad applications of ILS presented in the literature.

For warehouse managers or system integrators to select a suitable ILS for an application, the requirements must be met by the system's performance. Mautz [5] lists the most important requirement parameters for ILS, such as accuracy, integrity, or market maturity. Measurable properties related to the location data itself are considered location data requirements, for which corresponding performance metrics can be determined by experimental evaluation. The results of such experiments are often published in benchmarking studies [6,7] and summarized in literature surveys [5,8]. But how are the data requirements for an application to be determined? As pointed out by Hohenstein and Günthner [9], data requirements depend on the specific implementation and environment of an application. Thus, providing universally applicable figures is not possible. Instead, methodical approaches can be applied to specify data requirements. High-level procedures

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for the determination of user requirements were proposed by Mautz [5] as well as Gladysz and Santarek [10]. However, when it comes to explicitly selecting and quantifying data requirements, they are not applicable.

In this work, a method is proposed to select and quantify data requirements for intralogistics applications. The remaining work is structured as follows. In Section 2 an overview of related work is presented to provide a basis for the method presented in Section 3. Subsequently, the usage of the method is demonstrated for the application of 'Automated Pallet Booking' in Section 4. Finally, the results are discussed and conclusions are made in Section 5.

2. Related work

This section provides an overview of the most relevant work regarding the specification of localization data requirements and concludes by pointing out the identified gaps. Individual indoor localization technologies are deliberately not presented, since data requirements must be considered independently of the functionality.

The most holistic examination of localization requirements is provided by Mautz [5], as part of an extensive literature survey on ILS. Mautz provides a list of 16 well-defined user requirement parameters, divided into the categories 'positioning', 'human-machine interface', 'security and privacy', and 'costs'. Requirement parameters of the 'positioning' category are 'accuracy', 'coverage', 'integrity', 'availability', 'continuity', 'update rate', 'system latency', and 'data output'. In addition, a generic procedure for capturing user requirements is provided. Finally, requirements for selected application domains are exemplarily derived, such as for 'Underground Construction' and 'Ambient Assisted Living'. However, the work lacks to provide information on how the data requirements are ultimately quantified.

Gladysz and Santarek [10] present a procedure for selecting suitable ILS for an application, whereby the initial step deals with the definition of requirements by describing the business case and determining the limits of acceptable requirement parameters. The authors list 'costs/benefits', 'accuracy', and 'reliability' as common requirements, but do not limit the possible parameters to be considered. In addition, a case study of a forklift truck control and diagnostic tool in a cold chain warehouse is presented. The minimum requirement for horizontal position accuracy is specified as 0.5m. Similar to the procedure provided by Mautz [5], the procedure presented by Gladysz and Santarek remains at a high level, without further explanation on how values are quantified.

Hohenstein and Günthner [9] present a survey to examine the suitability of 25 ILS for localizing forklift trucks. The considered evaluation criteria are 'localization accuracy', 'outdoor capability', 'flexibility', and 'scalability'. In addition, 'real-time capability' and 'integration effort' are mentioned as relevant parameters but were not further considered due to a lack of data availability. The localization accuracy is defined as the 95^{th} percentile of the horizontal position error. The authors identify the size of the object that must be (indirectly) localized as the relevant criterion to quantify the requirement for localization accuracy. For example, in the course of an automatic booking process, a pallet to be localized must be assigned to a storage location with a known position. The horizontal position accuracy requirement concerning the center of the pallet is accordingly determined by half the width of the storage location. For comparison, the authors give a rough range estimation for the required localization accuracy of five common areas/objects in intralogistics, such as 'storage area', 'storage aisle', and 'storage location'. A generalized method is not provided.

Although the performance requirements of ILS are discussed in several publications, depth is lacking when it comes to quantifying the data requirements. Dependencies of system performance and location data requirements are barely discussed. Hohenstein and Günthner [9] present an interesting approach to determine the requirements for the horizontal position error for the localization of forklift trucks in intralogistics based on the dimensions of the object or area of interest. To create significant added value for warehouse managers and system integrators, this approach must be generalized and further developed.

3. Method for deriving location data requirements

In this section, a method is presented for systematically deriving location data requirements. The method is based on the concept of localization functions and comprises the definition of data requirement parameters (Section 3.1), a generic model to describe the spatial dependencies of the data requirement parameters and localization functions (Section 3.2), and a procedure to support the systematical derivation of the defined parameters (Section 3.3).

3.1 Localization functions and data requirement parameters

Location data requirements are a subcategory of system requirements that deal with the properties of location data. Location data serve an application to enable localization functions that describe which entity (or entity class) is within (or outside of) a given multidimensional space. This space is considered ***Interest Space*** and the entity is considered ***Entity to be Localized***. If the *Interest Space* is entered or exited, an event is created and transmitted to an application. The application then processes the information to create value for the end-user. Figure 1 illustrates this process for an application with multiple localization functions, ILS, and *Entities to be Localized*.

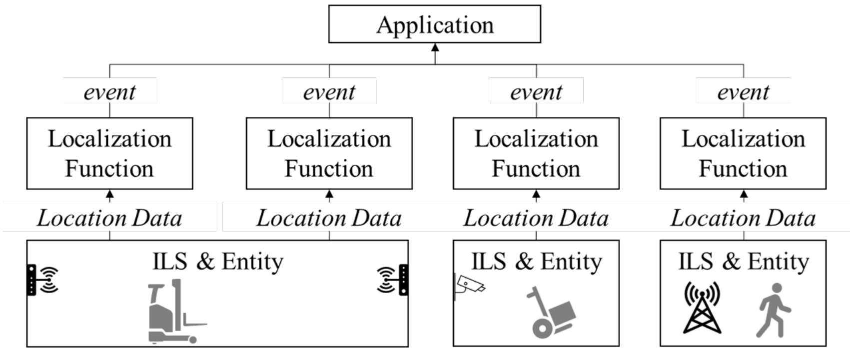

Figure 1: Different localization functions creating events for an application based on the location of different entities.

Location data ($\vec{L}$) are a set of discrete values that convey information about an entity's location over time. The term location ($\vec{L_t}$) denotes a position and orientation in space at a certain point in time. Considering a rigid body in three-dimensional space, $\vec{L_t}$ is given by $(x_t, y_t, z_t, \alpha_t, \beta_t, \gamma_t)$, with the position (x_t, y_t, z_t) and orientation $(\alpha_t, \beta_t, \gamma_t)$, whereby the z-axis is corresponding to the vertical direction. Hence, location data consist of up to six **Degrees of Freedom** (DoF). ILS often provide additional data, such as the velocity, acceleration, or the predicted position of an entity. This information can be crucial, for example, in controlling robots. If no additional data is provided, location data may be used for their calculation. When examining location data requirements for the computation of such data, different complex effects must be taken into account [11]. Therefore, the conclusions drawn in this work only apply to localization functions as explained above.

Location data can be differentiated according to the **Localization Type** into *absolute* and *relative localization* [5]. The term absolute localization refers to location estimation in a global frame of reference as defined by landmarks or anchor nodes. In contrast, relative locations are expressed in a local coordinate frame. Figure 2 shows the top view of a logistics scenario with a forklift truck ($O_{forklift}$) and a pallet (O_{pallet}) within an area of a warehouse (O_{area}). Here, absolute localization refers to the forklift's or the pallet's location in the global reference frame O_{area}. Relative localization refers to the forklift's location with respect to the pallet's location or vice versa.

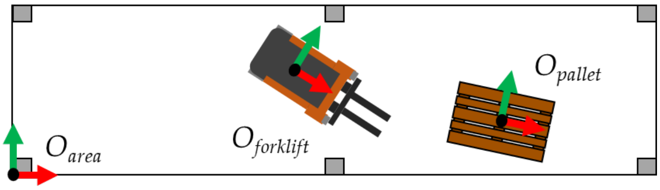

Figure 2: Absolute and relative localization

The location estimate is subject to various error components and thus differs from an entity's true location. The closeness of agreement between the location estimate and the true location is described by the term **Localization Accuracy** [12]. The associated absolute localization error vector is given as the elementwise distance between the location estimate and the true location. Localization errors can be expressed by each element or any combination, such as the horizontal position error.

A parameter closely related to localization accuracy is **Localization Repeatability**. Localization repeatability indicates the closeness of agreement between location estimates at the same true location [12]. Figure 3 visualizes the distinction between accuracy and repeatability. Repeatability can be high even when accuracy is low. In intralogistics applications, localization repeatability is relevant, if the *Interest Space* is specified with respect to location estimates from the same ILS. This is the case, for example, when a robot's navigation is based on a map recorded by the same system [13].

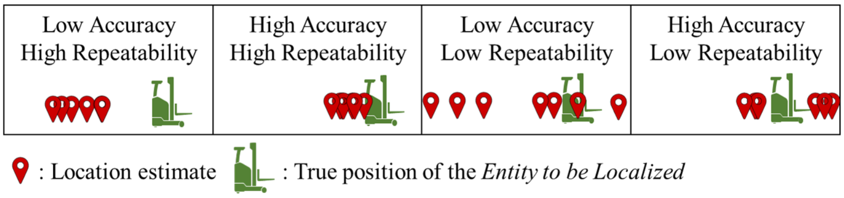

Figure 3: Difference between localization accuracy and repeatability

Relevant metrics for localization accuracy and repeatability are the percentiles of the localization error distribution, which indicate a value below which a certain percentage of location estimates fall. For example, for the horizontal position error, a 95th percentile of one meter indicates, that 95 % of location estimates from a set of location data map to a value below this number. Percentiles are essential from an end-user perspective as they indicate the **Confidence** with which a localization accuracy threshold will be met to reliably enable a localization function. The 95th percentile became established to define a comparable value for localization accuracy. However, depending on the required confidence of the location estimate, other percentiles can be considered.

Typically, ILS provide **Location Updates** periodically with a constant update rate (U). The time gap between two consecutive location measurements is then given by $t_g = 1/U$ (Figure 4). For moving entities, the update rate is relevant since the last location update could indicate the entity is within an *Interest Space* even though the space has already been exited, or vice versa. Besides periodic updates, location updates can be provided *upon request* by an outside trigger or *upon event* triggered by a sensor of the ILS [5].

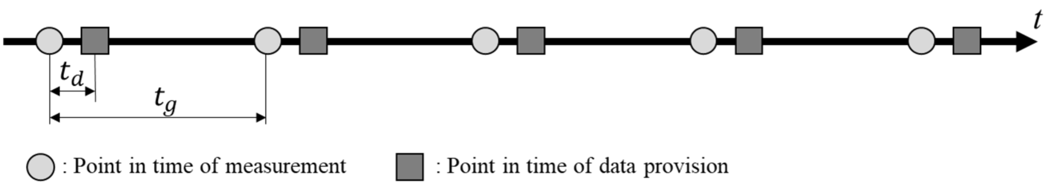

Figure 4: Time gap and system latency

Finally, the **System Latency** describes the time delay (t_d) from the actual measurement to the provision of the location data, whereby the timestamp associated with the location estimate is usually set to the measurement point in time. System latency is relevant when location data must be processed near real-time, which is often the case in safety-sensitive applications such as collision avoidance [5].

3.2 Spatial model of data requirements

The DoF, localization type, localization accuracy, localization repeatability, location update type, and system latency can be relevant data property parameters to determine the presence of an entity within an *Interest Space*. In this subsection, the dependencies of the data requirement parameters are described in a generic model under consideration of the spatial requirements of localization functions. Finally, the dependencies are expressed in a mathematical equation.

A location update provided by an ILS relates to a specific coordinate frame of the entity to be localized that is usually given by the location of a localization device. This is referred to as the ***Entity's Localization Frame*** (O_L). The coordinate frame that is to be determined as being within an *Interest Space* is referred to as the ***Entity's Interest Frame*** (O_I). Figure 5 illustrates the top view of an *Entity's Localization Frame* and the *Entity's Interest Frame* for a forklift truck. The location estimate of the ILS refers to the rear of the truck, whereby the center between the fork ends of the truck is the relevant location for the localization function. To compute the location of the *Entity's Interest Frame*, the coordinate transformation ($T_{L,I}$) must be applied to the location data provided by the ILS.

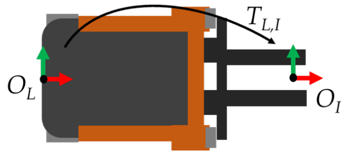

Figure 5: Top view of transformation between the *Entity's Localization Frame* and the *Entity's Interest Frame*

If the localization error at the *Entity's Interest Frame* is too high, the presence or absence of the entity within the *Interest Space* cannot be reliably determined. The closer the *Entity's Interest Frame* is to the boundary of the *Interest Space*, the smaller the localization error must be. The multidimensional space in which the *Entity's Interest Frame* is allowed to move without falsely triggering an event is referred to as ***Motion Space***. The closest distance for each of the considered DoF is referred to as ***Requirement Margin***. Optionally, a ***Safety Margin*** can be added. Figure 6 (left) illustrates these spaces for 2-DoF (x_t, y_t).

The *Requirement Margin* specifies the maximum localization error that a location estimate at the *Entity's Interest Frame* can have while ensuring the correct determination of presence inside or outside an *Interest Space*. The ***Uncertainty Space***, on the other hand, is introduced to describe the localization error at the *Entity's Interest Frame* as a consequence of the system's performance. It refers to the same dimension as the location estimate and comprises the three components shown in Figure 6 (right).

Depending on the relevant reference coordinates for the localization function, ***Static Uncertainty*** is either determined by the localization accuracy or by the localization repeatability of an ILS, transformed to the

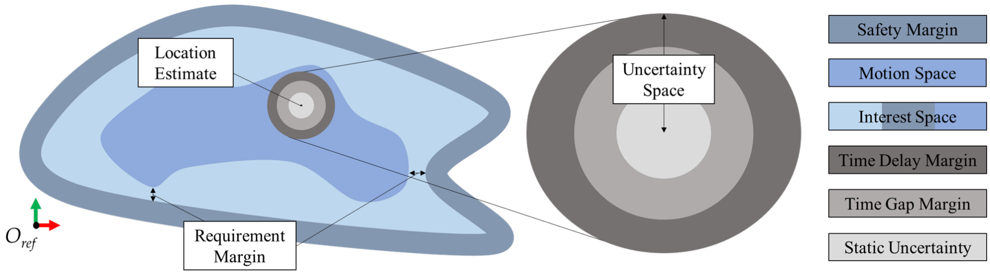

Figure 6: Planar view of spatial components for the *Requirement Margin* and the *Uncertainty Space*

Entity's Interest Frame. Rotational error components in the *Entity's Localization Frame* lead to additional translational error components for the location estimation in the *Entity's Interest Frame.* The *Static Uncertainty* ($\vec{P}_{C,Acc/Rep,I}$) at the *Entity's Interest Frame* is provided as the same percentile as the respective accuracy or repeatability of the ILS, which is chosen according to the required confidence level (C). This uncertainty component is referred to as static because it is considered to be independent of the entity's motion. This assumption applies to a good approximation at low velocities, depending on the applied localization technology. Time-related uncertainty components are additionally considered for dynamic scenarios. The ***Time Gap Margin*** refers to the uncertainty component that is resulting from the *Entity's Interest Frame* changing its location since the last location update (t_g). The *Time Gap Margin* is not relevant for location updates *upon request* or *upon event*, in which case the data is requested when required. Finally, the ***Time Delay Margin*** refers to the location uncertainty as a result of the system latency t_d. During this time delay, the entity's location changes according to its velocity components. Thus, the *Time Delay Margin* must be considered when the real-time location of the entity is relevant.

The dependencies of the presented model can be expressed in a mathematical equation. The *Requirement Margin* is denoted as a vector $\vec{R}$, with each element relating to a required DoF. The *Interest Space* is denoted as I, the *Motion Space* as M, and the *Safety Margin* as S. The *Uncertainty Space* $\vec{U}$ is a vector of the same dimension as $\vec{R}$ and is given as the sum of the *Static Uncertainty* $\overrightarrow{U_s}$, the *Time Gap Margin* $\overrightarrow{TG}$, and the *Time Delay Margin* $\overrightarrow{TD}$. From the condition that the data requirements must be met by the system performance, it follows

$$\vec{R}(I, M, S) \geq \overrightarrow{U_s} + \overrightarrow{TG} + \overrightarrow{TD}. \quad (1)$$

An upper bound for the time delay and the *Time Gap Margin* results from considering the maximum velocity ($\vec{v}_{max}$) of the *Entity's Interest Frame* multiplied by the maximum time gap or latency. With the accuracy or repeatability percentile for the chosen confidence, it follows

$$\vec{R}(I, M, S) \geq \vec{P}_{C,Acc/Rep,I} + \vec{v}_{max} * t_g + \vec{v}_{max} * t_d. \quad (2)$$

Equation 2 thus leads to a conservative estimate of the requirements. The left side of the equation can be estimated downward and the right side upward, so that the condition of a higher *Requirement Margin* than the *Uncertainty Space* remains satisfied. To quantify location data requirements, the components of this generic equation must be specified in terms of a particular localization function.

3.3 Procedure for deriving location data requirements

The presented spatial model and its associated equation form the basis for deriving location data requirements. In this subsection, a procedure with four main steps is presented that is used to specify the localization function (A), determine the *Requirement Margin* (B), estimate the *Uncertainty Space* (C), and finally calculate the data requirements (D). In the following, the steps are briefly explained in the context of intralogistics. The procedure is illustrated in (Figure 7).

Specify Localization Function (A): The basis for deriving data requirements is formed by specifying the localization function under consideration. For this purpose, it must be clarified which entity or entity class is to be localized (1) inside or outside which *Interest Space* (2). For example, should a person be localized in front of a shelf or a forklift in an aisle? The localization type (3) can already be deduced from the answer to the question of whether the relevant location data of the *Interest Space* should be specified with respect

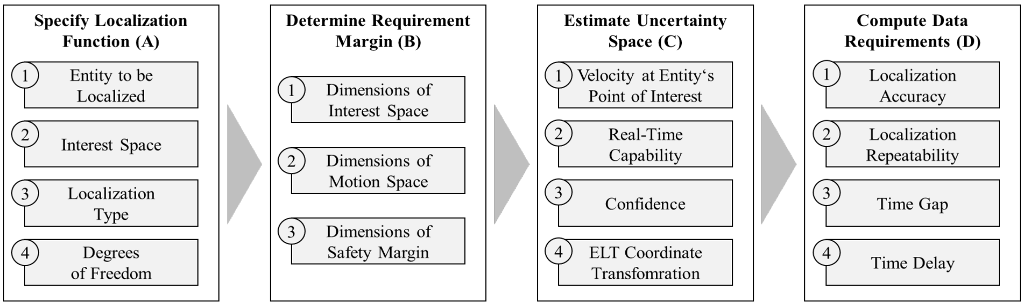

Figure 7: Procedure for deriving location data requirements

to the entity's location or a global reference frame. Furthermore, the relevant DoF of the *Interest Space* must be specified (4). Localization functions for intralogistics applications rarely require 6-DoF. Usually, roll and pitch can be neglected, resulting in location data with a maximum of 4-DoF (x, y, z, γ). Often, the number of DoF can be further reduced. For example, for ground-based vehicles, considering 3-DoF (x, y, γ) and for personnel, the position in the horizontal plane, i.e., the 2-DoF location (x, y), is usually sufficient.

Determine Requirements Margin (B): In the second step, the *Requirement Margin* is determined. This is done by considering the dimensions of the *Interest Space* (1), the *Motion Space* (2), and the *Safety Margin* (3) for the required DoF. The spatial structure of warehouses and production halls can be well described by rectangular areas or cuboid spaces. For example, an aisle or a storage area in a warehouse can be modeled by rectangles, while a typical storage compartment can be modeled by a cuboid. These abstractions and the resulting symmetries can prove useful in specifying the *Requirement Margin*. For example, if the presence of a forklift in a warehouse aisle is to be determined (localization function), the *Interest Space* is given by the boundaries to the adjacent aisles, including racks. However, the *Motion Space* is limited by the free aisle area and the forklift's dimensions. If the *Entity's Interest Frame* is in the center of the forklift, the boundary of the *Motion Space* is given by the free aisle area (without racks) minus half the width of the forklift.

Estimate Uncertainty Space (C): Next, the components of the *Uncertainty Space* are specified, i.e. the right-hand side of Equation 1. If the estimation of the time-related uncertainty components based on the maximum velocity is considered reasonable with respect to the given localization function, Equation 2 can be applied. (1) The maximum velocity ($\vec{\mathrm{v}}_{\mathrm{max}}$) at the *Entity's Interest Frame* can be estimated considering the application processes. (2) The *Time Delay Margin* ($\overrightarrow{\mathrm{TD}}$) must be considered, if the location data must be provided in near real-time. (3) The confidence level (C) can be chosen using standard percentiles or according to the *Six Sigma*-method, which has become an established quality management tool in the industry. (4) The coordinate transformation ($T_{L,I}$) between the *Entity's Localization Frame* and the *Entity's Interest Frame* can either be measured or estimated. If the transformation does not contain translational and rotational components, it does not influence the *Static Uncertainty* ($\overrightarrow{\mathrm{U_s}}$) and can therefore be neglected.

Compute Data Requirements (D): Finally, the data requirement parameters can be calculated. The *Uncertainty Space* can depend on multiple data requirement parameters, such as (1) localization accuracy, (2) localization repeatability, (2) time gap, and (3) time delay. If one uncertainty component is lower, another can be higher. There can be an infinite number of value combinations that satisfy the equation. The specified equation can therefore either be used to calculate different combinations of values or to prove the suitability of an ILS with given data requirement parameters.

4. Case study

The proposed method is applied to the exemplary application 'Automated Pallet Booking', which automatically reports the storage or retrieval of pallets in a storage compartment or area to the warehouse management system. This case study serves to demonstrate the feasibility and the usage of the method.

The case study focuses only on the localization function that associates a pallet to a storage compartment of a pallet rack. Thus, the *Entity to be Localized* is a pallet (A, 1) and the *Interest Space* is a storage compartment in a pallet rack (A, 2). Regarding the localization type (A, 3), the location of the storage compartment is known in a global coordinate system. Consequently, the absolute localization of the pallet is required. To determine which compartment a pallet is in, the horizontal and vertical positions are of relevance. Hence, 3-DoF (x, y, z) are considered (A, 4).

Next, the *Requirement Margin* must be determined. Figure 8 shows the front view of an exemplary pallet rack in which pallets are stored lengthwise. To ensure that a pallet can be assigned to the correct compartment, its presence must be distinguished from the adjacent storage compartment. The *Interest Space* is therefore given by a cuboid with the width, depth, and height of the storage compartment (B, 1). The *Motion Space* in x, relative to the center of the pallet, results from the space between two adjacent pallets (B, 2). Since the pallet is placed on the crossbar, the z-component of the *Motion Space* is zero. Therefore, in Figure 8, the *Motion Space* is visualized as a line in the xz-plane. The x and z-components of the *Requirement Margin* are marked as X_R and Z_R. Additionally, a *Safety Margin* is considered (B, 3). Analogous considerations can be applied to the y-component. The calculation of the individual values will not be discussed further, since the focus is on the method itself. For the following derivation of requirements parameters, a *Requirement Margin* of (0.3m, 0.5m, 0.15m) is assumed.

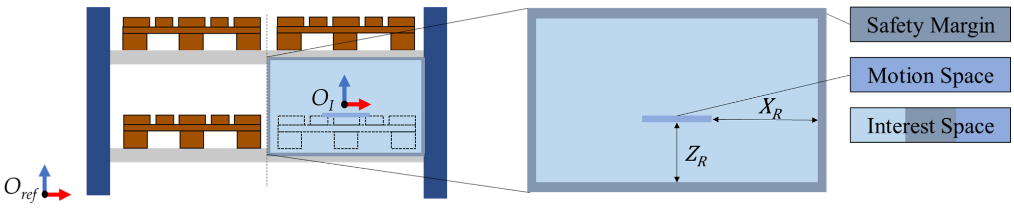

Figure 8: *Interest Space*, *Motion Space* and *Safety Margin* for the application 'automated pallet booking'

The vector for the maximum velocity is assumed to be (0.1 m/s, 0.7 m/s, 0.1 m/s), with substantially higher maximum velocity in the storage direction (C, 1). No real-time capability is required for the localization function (C, 2). Incorrect entries in the warehouse management system lead to various further mistakes and must be avoided. Therefore, a high confidence level (C, 3) of 4σ is exemplarily chosen, which refers to 0.62% false location estimates. The localization device is assumed to be attached at the center of the pallet, which is also the *Entity's Interest Frame*. Thus, the coordinate transformation from the *Entity's Localization Frame* into the *Interest Frame* can be neglected (C, 4). By inserting the values into Equation 2, it follows.

$$\begin{pmatrix} 0.3 \\ 0.5 \\ 0.15 \end{pmatrix} \geq \vec{P}_{4\sigma,Acc/Rep,I} + \begin{pmatrix} 0.1 \\ 0.7 \\ 0.1 \end{pmatrix} \frac{m}{s} * t_g. \tag{3}$$

Since the location of the *Interest Space* is provided in absolute coordinates, localization accuracy is the relevant criterion for the *Static Uncertainty* (D, 1). The localization repeatability can thus be neglected (D, 2). Table 1 shows the resulting 4σ-percentiles of the absolute accuracy for selected values of t_g (D, 3). For an ILS transmitting periodic location updates at an update rate of 2 Hz, corresponding to a time gap of 0.5s, the minimum localization accuracy would therefore be given by $\vec{P}_{4\sigma,Acc}$ equal to (0.25m, 0.15m, 0.12m). Based on these data requirements, an ILS suitable for the considered localization function can be selected.

Table 1: Location data requirements for different time gaps and 4σ-percentiles of the absolute accuracy components

t_g / [s]	0.1	0.2	0.3	0.4	0.5	0.6
$P_{4\sigma,Acc,x}$ / [m]	0.29	0.28	0.27	0.26	0.25	0.24
$P_{4\sigma,Acc,y}$ / [m]	0.43	0.36	0.29	0.22	0.15	0.08
$P_{4\sigma,Acc,z}$ / [m]	0.15	0.14	0.13	0.13	0.12	0.12

5. Discussion and conclusions

The potential of leveraging location data in warehouse and production environments is immense as a wide range of applications can be implemented or supported by location data. For warehouse and system integrators, selecting an appropriate ILS is key to implementing a reliable and cost-effective application. Although requirements for ILS have been studied in the literature, the dependencies between the data requirement parameters and spatial requirements have not been adequately described. Thus, a method for the systematic selection and quantification of data requirements does not yet exist. This work fills this research gap by providing a method for systematically deriving location data requirements for intralogistics applications. The method thus supplements the high-level methods for deriving user requirements for ILS as presented by Mautz [5] or Gladysz and Santarek [10]. The presented method comprises the following contributions. (1) Selection and definition of location data requirement parameters that are relevant in terms of the concept of localization functions, (2) a generic model describing the spatial dependencies of the application requirements and data requirement parameters, and (3) a procedure to support the systematic quantification of the data requirement parameters based on the presented model. To demonstrate the applicability of the presented method, a case study on the application of 'Automated Pallet Booking' was presented.

Some limitations of the proposed method remain. First, based on the generic equation of the spatial model (Equation 1), different abstractions were proposed to estimate the individual components. In practice, these should be treated with caution on a case-by-case basis. Often, the exact values are unknown and must be conservatively estimated. Second, the method is based on reliably determining the presence or absence of an entity in an *Interest Space*. This corresponds to a semantic discretization of location data. However, some applications require quasi-continuous location data, for example, to derive dynamic properties. Finally, the method focuses on the data requirement parameters relevant to localization functions. The selection of a system requires the consideration of many more requirements, such as 'size', 'integrity', or 'power supply'.

There are numerous benchmarking studies to evaluate the performance of ILS using various performance metrics. To be meaningful from the end user's perspective, the testing procedure and performance metrics should meet the application requirements. Currently, an application-driven framework is being developed that aims at the meaningful testing and evaluation of ILS [14]. Future work will integrate the discussed concepts and the presented method presented into a holistic approach for application-driven testing and evaluation of ILS.

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Federal Ministry of Education and Research

References

[1] Zoubek, M., Simon, M., 2021. A Framework for a Logistics 4.0 Maturity Model with a Specification for Internal Logistics. MMSJ 2021 (1), 4264–4274.

[2] Hohenstein, F.C., 2014. Systementwurf und Umsetzung einer funktionsintegrierenden Gabelstaplerlokalisierung für eine wandlungsfähige und effiziente Transportausführung. Dissertation. Lehrstuhl für Fördertechnik Materialfluss Logistik Technische Universität München, Garching b. München.

[3] Pradhan, N., Balasubramanian, P., Sawhney, R., Khan, M.H., 2020. Automated risk assessment for material movement in manufacturing. Gest. Prod. 27 (3).

[4] Hesslein, N., Wesselhöft, M., Hinckeldeyn, J., Kreutzfeldt, J., 2021. Industrial Indoor Localization: Improvement of Logistics Processes Using Location Based Services, in: Proceedings of the Advances in Automotive Production

Technology Theory and Application. Stuttgart Conference on Automotive Production (SCAP2020), Berlin, Heidelberg. Springer Berlin Heidelberg, pp. 460–467.

[5] Mautz, R., 2012. Indoor positioning technologies. Habilitation. ETH Zürich, Zürich, 129 pp.

[6] Abdulkadir Karaagac, Jetmir Haxhibeqiri, Matteo Ridolfi, Wout Joseph, Ingrid Moerman, Jeroen Hoebeke, Karaagac, A., Haxhibeqiri, J., Ridolfi, M., Joseph, W., Moerman, I., Hoebeke, J., 2017. Evaluation of accurate indoor localization systems in industrial environments, in: Proceedings of the 2017 22nd IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), Limassol, Cyprus. IEEE, pp. 1–8.

[7] Rehrl, K., Gröchenig, S., 2021. Evaluating Localization Accuracy of Automated Driving Systems. Sensors 21 (17).

[8] Zafari, F., Gkelias, A., Leung, K.K., 2019. A Survey of Indoor Localization Systems and Technologies. IEEE Commun. Surv. Tutorials 21 (3), 2568–2599.

[9] Hohenstein, F., Günther, W.A., 2013. Anforderungen und Fähigkeiten gegenwärtiger Stapler - Lokalisierung, 9. Hamburger Staplertagung.

[10] Gladysz, B., Santarek, K., 2017. An Approach to RTLS Selection, in: Proceedings of the 24th International Conference on Production Research (ICPR 2017). Posnan, Poland. DEStech Publications, Lancaster.

[11] Schyga, J., Rose, H., Hinckeldeyn, J., Kreutzfeldt, J., 2021. Analysis of the Operation of Industrial Trucks based on Position Data. Logistics Journal: Proceedings 2021.

[12] BIPM, IEC, IFCC, ILAC, IUPAC, IUPAP, ISO, OIML, 2012. The international vocabulary of metrology - Basic and general concepts and associated terms (VIM), 3 ed., JCGM 200:2012.

[13] Beinschob, P., Reinke, C., 2014. Advances in 3D data acquisition, mapping and localization in modern large-scale warehouses, in: Proceedings of the 2014 IEEE 10th International Conference on Intelligent Computer Communication and Processing (ICCP), Cluj Napoca, Romania. IEEE, pp. 265–271.

[14] Schyga, J., Hinckeldeyn, J., Kreutzfeldt, J., 2022. Meaningful Test and Evaluation of Indoor Localization Systems in Semi-Controlled Environments. Sensors 22 (7).

Biography

Jakob Schyga, M.Sc. (*1992) Research Associate at the Institute for Technical Logistics, Hamburg University of Technology. Jakob Schyga studied mechanical engineering and production at the Hamburg University of Technology from 2012 to 2018. Since 2019, Jakob Schyga has been working on the investigation and application of indoor localization systems in warehouses.

Markus Knitt, M.Sc. (*1992) Markus Knitt, M.Sc. (*1997) Research Associate at the Institute for Technical Logistics, Hamburg University of Technology. Markus Knitt studied mechatronics at the Hamburg University of Technology from 2016 to 2022.

Dr. Johannes Hinckeldeyn (*1979) Senior Engineer at the Institute for Technical Logistics, Hamburg University of Technology. After completing his doctorate in the UK, Johannes Hinckeldeyn worked as Chief Operating Officer for a manufacturer of laboratory technology for battery research. Johannes Hinckeldeyn studied industrial engineering, production technology, and management in Hamburg and Münster. Current research focuses on the optimization of logistics processes through digital technologies.

Prof. Dr.-Ing. Jochen Kreutzfeldt (*1959) Professor and Head of the Institute for Technical Logistics, Hamburg University of Technology. After studying mechanical engineering, Jochen Kreutzfeldt held various management positions at a company group specializing in automotive safety technology. Jochen Kreutzfeldt then took on a professorship for logistics at the Hamburg University of Applied Sciences and became head of the Institute for Product and Production Management. His current research focuses on warehouse and process optimization.

4th Conference on Production Systems and Logistics

Design Model For Traceability-Supported Assessment Of Product Carbon Footprint

Phillip Bausch [1], Astrid Weyand [1], Matthias Weigold [1], Joachim Metternich [1]

[1] *Technical University of Darmstadt, Institute for Production Management, Technology and Machine Tools, Darmstadt, Germany*

Abstract

The established approaches for calculating the Product Carbon Footprint (PCF) based on Life Cycle Assessment (LCA) only allow a cause-related determination of used resources to a limited extent. Even in situations where the direct measurement of resource consumption is recommended, PCF calculation is mainly carried out by means of allocation or estimations in industrial practice. In contrast, the use of traceability data offers promising opportunities for increasing the component specific transparency by linking continuously recorded resource flows and data available in software systems with time stamps and component/order IDs (traceability data). Based on the available component-specific database, companies can identify drivers and hotspots of carbon emissions for individual products and derive targeted measures to reduce these emissions.

This paper outlines a concept for a traceability-supported design model to determine the PCF based on the existing framework of LCA. Therefore, a literature review is conducted to identify and analyze existing concepts regarding the determination of PCF as well as requirements for a traceability-supported approach. By conducting an expert survey, these requirements derived from literature are evaluated and prioritized. Finally, the results are used to develop a design model for a traceability supported approach to determine the PCF and to indicate future research needs.

Keywords

Traceability Systems; Product Carbon Footprint; Resource Efficiency; Design Model; Process Transparency

1. Introduction

With a share of about 17% of the global CO_2-emissions, industrial production contributes significantly to the negative consequences of climate change [1]. Hence, targets for reducing these environmental impacts are increasingly being defined at the political level, especially in regard to the Paris Agreement [2]. The European Union, derives its Green Deal based on these objectives and aims to reduce greenhouse gas emissions by 55% until 2030 [3]. On a national level, the German Environment Agency aims to reduce emitted CO_2-equivalents in the industrial sector by approximately 35% in the period from 2021 to 2030 [4].

In order to identify hotspots and adequate measures for reducing the environmental impact in production processes, a transparent and detailed determination of caused CO_2-emissions is an essential prerequisite [5–8]. For this purpose, life cycle assessment (LCA) is a helpful and established method and provides a guideline at both company [9] and product [10] level. However, this approach still offers a variety of options to calculate the Product Carbon Footprint (PCF) and do not specify which option is the most suitable for a specific use case. Besides the actual measurement of resource consumption, allocation, estimation and the use of constant values from databases to assess CO_2-emissions are also possible [11]. As a result, certain

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limitations for the cause-related allocation of resource consumptions and CO_2-equivalents to a certain component or production order exist, making the results less meaningful and comparable.

Looking at different stakeholders, it is evident that there is an increasing need for a standardized and transparent approach. On the one hand, political initiatives oblige companies to transparently pass on PCF information to other companies and customers. These initiatives include the German Supply Chain Act and the development of the digital product passport of the European Union [12]. On the other hand, the demand from OEMs (e.g. in the automotive industry) [6] as well as from consumers [13] for transparent information on the environmental impact of products is steadily increasing.

The mentioned guidelines and approaches are primarily limited to building up transparency along the supply chain (cradle-to-grave), but do not provide precise guidance on data acquisition and PCF calculation within company boundaries (gate-to-gate). Scientific literature shows that certain use cases require the dynamic determination of a cause-related PCF. The following list gives an overview about relevant use cases:

- **Product planning and design:** By determining the PCF for each individual component, it is possible to analyze whether individual product design features or the use of certain manufacturing technologies increase the environmental impact during the manufacturing stage. This makes it possible to revise existing products or design new products target-orientated to minimize the environmental impact of production as early as the product planning stage. [14,15]
- **Live process monitoring and determination of key performance indicators (KPI):** A new level of transparency for process monitoring is created through continuous as well as order- or component-specific determination of resource KPI. Besides new analysis capabilities such as the trend analysis of environmental impacts on component level, the available data can now be used to raise employee awareness for saving resources on the shop floor. [16–19]
- **Identification of hotspots/measures on production level:** This new level of transparency can also be used to identify the main drivers of environmental impacts in the production process and to systematically prioritize improvement measures. Examples of such measures include adjustments of process parameters, efficient shutdown of production machines during non-productive times, or efficient startup/shutdown of specific machine aggregates. [19,20]
- **Production planning and control (PPC):** Using current and product- or order-related consumption data, resource efficiency and minimizing the PCF can be integrated as a new target variable in various PPC tasks such as lot size optimization or machine scheduling. [20–23]

In mass and large batch production, it is feasible to determine the PCF for these use cases by means of manual data acquisition, because of the manageable effort required to conduct specific measurements for a single or a small number of products. In make-to-order and small-batch production, however, it is not possible to determine the PCF with the appropriate granularity, correctness and currentness of data with reasonable effort. [24,25] The use of Industry 4.0 technologies, especially traceability technologies, provides great opportunities to solve these issues by automating data collection, connecting data to specific products and increase transparency of resource consumption along production chains and networks. [8,26].

This paper aims to assist in designing traceability systems for a cause-related determination of PCF and is structured as follows. Chapter 2 discusses the theoretical background to derive two research question. The methodological approach to address these research questions is presented in chapter 3. In Chapter 4, the findings of the literature review and the subsequent expert assessment are discussed in more detail. Based on these findings, a design model for the traceability-supported assessment of the PCF is developed in Chapter 5.

2. Theoretical background

2.1 Traceability Systems

According to Olsen and Borit, traceability is defined as „the ability to access any or all information relating to that which is under consideration, throughout its entire life cycle, by means of recorded identifications“ [27]. In the context of manufacturing, this refers to products, batches and production orders, as well as to operating resources and equipment [28]. AutoID technologies such as optical codes (e.g., Data Matrix Codes) or RFID and the assignment of unique IDs are used to make these objects identifiable [29]. Traceability data is usually differentiated into static and dynamic data [30]. By tracking objects at relevant process steps along a value stream, a traceability system generates dynamic data by combining object IDs, location data and timestamps. Based on this primary traceability data, the subsequent assignment of further dynamic data from other sources (secondary traceability data) is possible. [28] For example, resource consumption recorded with sensors can be assigned to an individual component [7]. In contrast, static data refers to order-related information such as bills of materials or product data, which does not change during the manufacturing process [30]. The main components of a traceability system are identification technologies, data acquisition, data linkage, and data communication with other information systems and stakeholders [31]. Data acquisition is usually characterized by continuous and automated data recording and includes the historization and linking of relevant data depending on the particular use case [32].

2.2 Product Carbon Footprint in manufacturing industries

Based on the International Standards on LCA [9,33] the requirements and guidelines to calculate the carbon footprint of products were published in 2018 [34]. The specified LCA procedure for PCF consists of the definition of the objective and the system boundaries, the life cycle inventory, the impact assessment and the evaluation of results [10]. However, uncertainties still occur regarding the needed data and whether as well as in which case assumptions or allocations are allowed. Further limitations regarding the use of the LCA in manufacturing are listed in Figure 1 and include the required human and financial resources, the static and non-recurring recording of primary data, and the missing integration into existing information systems on the shop floor level. [17] The comparative analysis of key features of traceability systems shows that they have significant potential to address these LCA limitations. In particular, the connection of different data sources offers the possibility of using real process data to determine the PCF. Moreover, continuous and automated data acquisition enables the development of a dynamic modeling approach of PCF (see Figure 1).

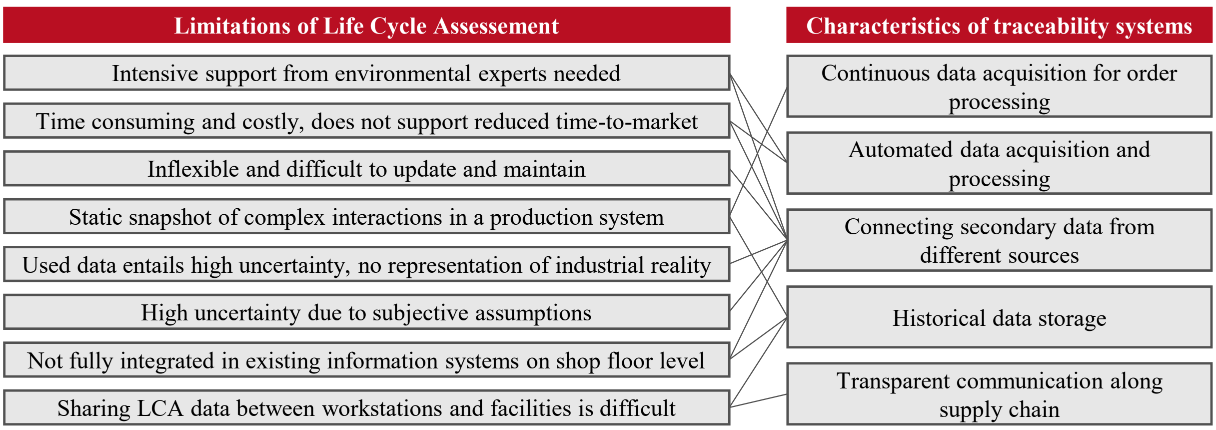

Figure 1: Limitations of LCA addressed by characteristics of traceability systems [17,32]

Traceability systems accordingly show huge potential to support the dynamic and cause-related determination of the PCF. As it is shown in the following chapter 4, existing concepts in the literature have so far been limited to pilot implementations and concept developments that focus on a specific use case. This paper aims to answer the following two research questions by analyzing these existing approaches:

1. Which design dimensions and methodological requirements must be considered to develop a traceability-based system to determine the PCF?
2. How can these design dimensions and requirements be integrated into a holistic design model?

The developed design model should support the technical implementation of such a system by outlining system elements and their connections that need to be configured as well as initialize the definition of further research needs.

3. Methodological approach

This paper follows a two-step methodology to answer the research questions. In the first step, a literature review following the procedure of Fink [35] is conducted to identify existing concepts for the use of traceability systems to determine the PCF. Seven relevant databases were identified and searched by combining pre-defined search terms of the topics PCF, traceability and manufacturing. The literature review was conducted in April 2022. With this approach, 761 papers were initially found. Using predefined inclusion and exclusion criteria, these results were gradually reduced to twelve remaining papers. Besides formal criteria such as language and accessibility, literature without specific references to gate-to-gate manufacturing processes or the use of traceability technologies were not considered. Through a subsequent forward/backward search, four more relevant papers were identified, resulting in 16 relevant and examined papers. The identified literature sources are either case studies, that describe exemplary implementations or concepts of related approaches. The approaches presented in the literature were examined for essential design elements as well as methodological requirements. To verify these results, an expert survey (n=33) was then conducted to evaluate the design dimensions and requirements by rating their importance on a five-point Likert-scale. Experts from the manufacturing sector, the ICT sector and scientists who have already gained experience with projects to determine the PCF for manufactured goods participated in the survey.

4. Identification of relevant design dimensions and requirements

The following section presents the design dimensions and requirements identified in the literature. According to Tao et al. [15], the relevant design dimensions are structured in the layers data acquisition, data processing and connection and application/services. These layers are chosen because they cover the entire process of data handling to implementation and ensure a holistic view on existing traceability-supported solutions. A total of 15 design dimensions can be derived. In addition, five requirements regarding the methodological approach are documented. For each identified design dimension and requirement, the expert assessment is evaluated using descriptive statistics. The rating for each item based on the five-point Likert-scale is interpreted as interval-scaled from 1 (not important) to 5 (very important), so that the results can be analyzed by using average (μ) and standard deviation (σ). The results of both literature review and expert assessment are presented in Table 1. The experts in general confirm the collected list of design elements that was based on literature, as most design elements are rated rather important ($\mu > 3.00$). Only the design dimension “real-time data acquisition” is rated less important. This ambiguous assessment seems plausible, as the real-time requirements strongly depend on the particular use case. Typical use cases such as the reporting of PCF information do not require real-time capability, whereas other use cases such as raising the awareness of employees on the shopfloor by means of KPIs require at least near-real-time data transmission.

Table 1: Design dimensions and requirements for the technical design model based on literature review

Data Acquisition	Description	Expert assessment
Integration of additional sensor technologies	Various sensors used for the continuous measurement of energy consumption (electrical energy, compressed air, etc.) and other resources [15,19–22,36–38],	$\mu = 4.69$ $\sigma = 0.82$

	in addition to sensors installed in production machines, retrofitting of additional sensors is also relevant [26,39] (in particular IoT sensors [16])	
Unique identification of component/batch/ production order	AutoID technologies used to identify and track process start and end of components, batches or production orders [15–22,26]; especially, RFID systems are proposed in literature [15–18,21] as well as information provided from MES and ERP systems [36,37]	$\mu = 4.34$ $\sigma = 0.94$
Standardized communication gateways	Use of standardized interfaces for the connection of machine data and sensors, most relevant standards mentioned by literature are OPC-UA and MQTT. [15,17–20,22,37–39]	$\mu = 4.25$ $\sigma = 0.76$
Automated data acquisition	Triggers for recording data are usually generated automatically (minimal process intervention by humans) [15–23,36–39]	$\mu = 4.53$ $\sigma = 0.72$
Continuous data acquisition	Regular and in-process measurement of data in contrast to recording data only once at a discrete point in time [15–20,22,23,26,36,37,39]	$\mu = 4.25$ $\sigma = 0.98$
Real time data acquisition	Not only continuous but also real-time data acquisition and provisioning [15–19,22,23,37,39]	$\mu = 2.88$ $\sigma = 0.93$

Data Connection and Processing	**Description**	**Expert assessment**
Connection to different data sources	Connection to higher-level information systems (e.g. MES, ERP or energy management systems), used to access static data (e.g. product/order information, energy mix) [15,22,40] and dynamic data (e.g. energy flow data [17,39] and material flow/scheduling [22,36,37,39])	$\mu = 4.09$ $\sigma = 0.86$
Central data model	Mathematical relationships to calculate PCF, connecting all relevant data points needed for PCF calculation [15,17,18,22,36–38]	$\mu = 3.77$ $\sigma = 0.94$
Specific sub-models for each process step	Different material and resource flows with unique characteristics for different manufacturing technologies or each process step [16,21–23,26,36,37]	$\mu = 3.34$ $\sigma = 1.11$
Storage of historical data	Time-related analyses is enabled by storage of raw data as well es resulting PCF data [16,18–23,26,36–38]	$\mu = 4.00$ $\sigma = 0.88$
Validity, authenticity and accuracy of data	Importance of the quality of recorded data in the sense of validity, authenticity and accuracy of data [16,17,21,37,39]	$\mu = 4.63$ $\sigma = 0.55$
Connection to LCI database	Provision of values for aggregation of resource consumption along the life cycle (if not known) [17,22,39,40]	$\mu = 3.68$ $\sigma = 0.89$

Application/ Services	**Description**	**Expert assessment**
Ability to perform simulations	PCF used as input data for simulation models to support decision making scenarios [16,38], for example in production planning and control [17,21,36]	$\mu = 3.41$ $\sigma = 1.01$
Visualization	Environmental effects displayed as KPI or graphical representations depending on relevant stakeholders [15,18,19], for example PCF per process [17] or cumulative resource consumptions or consumption profiles [37]	$\mu = 4.25$ $\sigma = 0.76$
Decision Support	Detailed PCF database supports decision making [16,18,20,22], like adaptation of product portfolio [40], prioritizing saving potentials [37], lot-size optimization [36] and machine allocation [20,23]	$\mu = 4.13$ $\sigma = 1.01$

Methodological Requirements	**Description**	**Expert assessment**
Conformity with existing PCF standards	Concepts analyzed [14–20,26,37,39,40] are mostly based on widely used standards of LCA [9] and PCF [10]	$\mu = 4.30$ $\sigma = 0.78$
Clustering of product families	Clustering product families can reduce effort for products with similar design features and process configurations [40]	$\mu = 3.63$ $\sigma = 0.85$

Flexibility regarding changing process or product	In make-to-order and small batch production variable process sequences and product characteristics (e.g., material) occur, approach to determine PCF needs to be flexible regarding adding, removing, and modifying process and product configurations [14]	$\mu = 4.35$ $\sigma = 0.61$
Support of alternative calculation approaches	Flexibility in DIN ISO 14067 (e.g., regarding defining system boundaries or deciding between, direct measurement, allocation, or estimation of resource consumptions) has to be considered for a traceability-based approach as well [16,19,22]	$\mu = 3.70$ $\sigma = 0.79$
Value-added/non-value-added resource consumptions	Resource consumptions captured not only during manufacturing of a product, also non-value-added consumptions (e.g. during waiting and setup times) is assigned to a product or batch, can be influenced by the variation of batch sizes [19,21,36,37]	$\mu = 3.71$ $\sigma = 0.86$

5. Development of the design model

Each design dimension rated as important by experts is used is considered for the developed technical design model. The design model is structured in the same layers as the literature review: data acquisition, data processing and connection as well as application/services (see Figure 2).

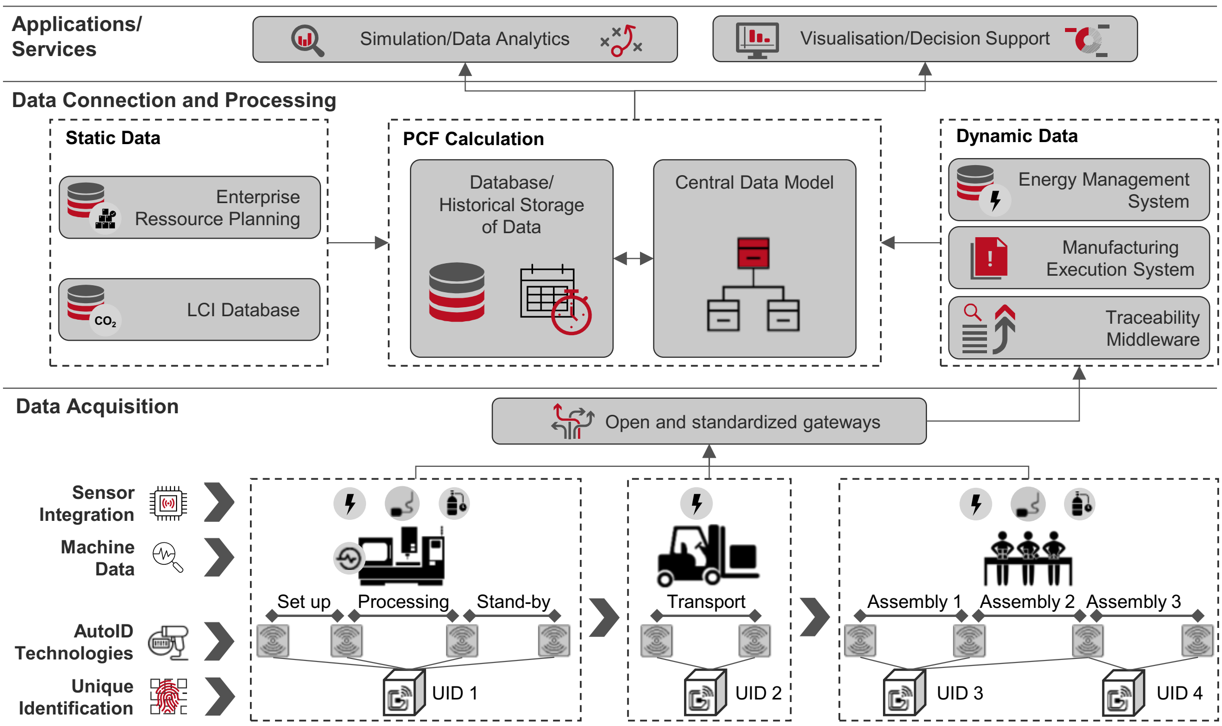

Figure 2: Design model for the traceability-supported assessment of PCF

5.1 Data acquisition

The data acquisition layer consists of two main system elements: The traceability system and the monitoring of resource consumption via sensors and/or machine data. The basic functionalities of a conventional traceability system remain unchanged. Alongside the assignment of unique IDs via AutoID technologies to the respective traceability object (product, batch, production order), readers are used to track these objects along the process chain [41]. However, the exact definition of these acquisition points requires a use case specific allocation along the process chain depending on various factors:

- Definition of system boundaries (PCF): Depending on the chosen system boundaries certain process steps (the ones with supposably highest impact) of the production process (for example consisting of processing, transport and assembly) must be captured by the traceability system, others can be left aside.

- Differentiation of value-added and non-value-added resource consumptions: If this differentiation is necessary for an intended use case, additional scan processes per traceability object might be considered to track and subsequently reduce set up or stand-by related resource consumptions.
- Different approaches to calculate PCF: Depending on the chosen approach for a certain process step (primary data, allocation, estimation), different configurations of scan points are suitable.

Integration of sensors is needed to enable a continuous and automated monitoring of resource consumptions. The implementation strategy must be formulated according to the examined manufacturing technology and must consider characteristics of the consumption profile of every resource. The sensor-based resource monitoring should be used primarily for resources that have a supposably significant impact on the overall PCF and for those resources for which a variation in consumption depending on the examined product is expected. [23,36,37] If a detailed analysis of a certain machine tool is intended, status data of single machine aggregates can be used to monitor their specific resource consumption [42]. For the connection of these sensor and machine data as well as the traceability system to higher level information systems, open and standardized gateways such as OPC-UA and MQTT should be used (see Chapter 4).

5.2 Data connection and processing

The data connection and processing layer is structured according to the distinction of static and dynamic data in conventional traceability-systems. On the one hand, dynamic data contains the in-line acquired traceability data, commonly pre-processed in specific software solutions (middleware). The resource-related data from sensors or machines, including energy consumption for technical building services, is typically collected in energy management systems (EMS). Additional dynamic data like the production orders or process progress is usually processed in manufacturing execution systems (MES). Depending on the individual infrastructure of a company, different systems such as IoT platform solutions or process control systems have to be considered to gather this dynamic data. On the other hand, static data from different sources such as ERP needs to be taken into account for PCF determination. Meta data for the current energy mix to estimate carbon emissions of the electrical energy used (usually static, in specific use cases possible to be implemented as dynamic data) or supplier data for raw material information is usually provided in ERP systems. Furthermore, meta data for product families can be accessed as well in ERP systems to identify products with similar characteristics. To limit the effort required to determine the PCF, these products can be evaluated in the same manner. To access carbon emissions of certain resources, that cannot be measured or estimated by a company itself (e.g., raw material or operating resources), respective values can be accessed in LCI databases. Prospectively, these values could be included in ERP systems for the list of parts.

The connection of the above-mentioned dynamic and static data points takes place in the central data model. This model must include all mathematical relations for calculating carbon emissions and be able to map those to individual products. It consists of separate sub-models for different process steps to model process-specific characteristics and to allow flexibility regarding the process chain configuration. [16,21,23,36,43] By historizing PCF data in a central database, long-term analyses for different use cases are possible in addition to the live monitoring of PCF. The implementation of this data model can be done using IoT platforms that enable data connection from various sources via standardized interfaces and can map the data processing rules defined in the data model. When connecting these data points, measures must be considered to ensure the distinct identification of data and data sources and requirements concerning correctness and accuracy are fulfilled.

5.3 Applications/Services

To implement the use cases presented in chapter 1, appropriate applications and services can be implemented, either integrated into existing information systems such as MES or developed as customized software solutions. An essential element of these solutions is the implementation of use case-dependent human machine interfaces (HMI) that provide information and visualization for the respective stakeholder, for example the worker on the shop floor. If necessary for decision support services, historized data can be processed in simulation models or other algorithms to enable specific use cases analyses.

6. Conclusion and Outlook

Based on a literature review, existing concepts for traceability-based assessment of PCF in gate-to-gate manufacturing processes were analyzed and examined for relevant design dimensions and methodological requirements. After evaluating the results through an expert survey, they were used to develop a design model for traceability-based determination of PCF. The developed design model serves as a framework for the implementation of a traceability-supported systems.

Still, the resulting framework indicates further research needs. Methodological approaches should be developed that enable the target orientated configuration of each design dimension depending on the intended use case and individual requirements. In particular, the following research needs can be derived based on the identified design dimensions:

- Integration of additional sensors: A methodology is needed that indicates, which resources should be monitored continuously based on the intended use case and the characteristics of resource consumption profiles such as intensity and variation.
- Configuration of traceability systems: Depending on the intended use case and the chosen approach to conduct the assessment of PCF, a different configuration of the traceability system concerning the amount, allocation and granularity along the process chain is needed. The development of appropriate design guidelines can support companies in designing tailored solutions.
- Data modeling: Transferable and generic data model structures and elements should be developed that can be adapted according to specific requirements as well as product and process configurations.

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References

[1] Oliver J., Peters, J., 2020. Trends in global CO2 and total greenhouse gas emissions: 2020 Report. PBL Netherlands Environmental Assessment Agency, Den Haag, 85 pp.

[2] Bundesministerium für Umwelt, Naturschutz, nukleare Sicherheit und Verbraucherschutz (BMUV), 2021. Die Klimakonferenz in Paris. Bundesministerium für Umwelt, Naturschutz, nukleare Sicherheit und Verbraucherschutz (BMUV). https://www.bmuv.de/WS202. Accessed 3 October 2022.

[3] European Parliament, 2022. EU responses to climate change. European Parliament. https://www.europarl.europa.eu/news/en/headlines/society/20180703STO07129/eu-responses-to-climate-change. Accessed 10 September 2022.

[4] Umweltbundesamt, 2022. Berechnung der Treibhausgasemissionsdaten für das Jahr 2021 gemäß Bundesklimaschutzgesetz: Begleitender Bericht, Dessau-Roßlau, 40 pp.

[5] Topic, M., Biedermann, H. Increasing Resource Efficiency Through Digitalization, in: Zoran Anisic, Bojan Lalic, Danijela Gracanin, J. Paulo Davim (Eds.), Proceedings on 25th International Joint Conference on Industrial Engineering and Operations Management – IJCIEOM, pp. 1–11.

[6] Jaeger, F.A., Saling, P., Otte, N., Steidle, R., Bollen, J., Golembiewski, B., Dencic, I., Letinois, U., Rehl, T., Wunderlich, J., 2022. Challenges and requirements of exchanging Product Carbon Footprint information in the supply chain. E3S Web Conf. 349, 7005.

[7] Urnauer, C., Schreiber, M., Bausch, P., Metternich, J., 2021. Anwendungen aktiver Traceability-Systeme. Zeitschrift für wirtschaftlichen Fabrikbetrieb 116 (3), 166–170.

[8] 2017. Ressourceneffizienz durch Industrie 4.0 - Potenziale für KMU des verarbeitenden Gewerbes, Berlin, 274 pp.

[9] DIN Deutsches Institut für Normung e. V., 2021. Umweltmanagement – Ökobilanz – Grundsätze und Rahmenbedingungen. Beuth Verlag, Berlin 13.020.10; 13.020.60, 36 pp.

[10] DIN Deutsches Institut für Normung e. V., 2019. Treibhausgase – Carbon Footprint von Produkten – Anforderungen an und Leitlinien für Quantifizierung. Beuth Verlag, Berlin 13.020.40, 98 pp.

[11] Guinée, J.B., Heijungs, R., Huppes, G., Zamagni, A., Masoni, P., Buonamici, R., Ekvall, T., Rydberg, T., 2011. Life cycle assessment: past, present, and future. Environmental science & technology 45 (1), 90–96.

[12] Adisorn, T., Tholen, L., Götz, T., 2021. Towards a Digital Product Passport Fit for Contributing to a Circular Economy. Energies 14 (8), 2289.

[13] Shekarian, E., Marandi, A., Majava, J., 2021. Dual-channel remanufacturing closed-loop supply chains under carbon footprint and collection competition. Sustainable Production and Consumption 28 (3), 1050–1075.

[14] Merschak, S., Hehenberger, P., Bachler, J., Kogler, A., 2020. Data Relevance and Sources for Carbon Footprint Calculation in Powertrain Production, in: Nyffenegger, F. (Ed.), Product Lifecycle Management Enabling Smart X. Springer International Publishing AG, Cham, pp. 203–214.

[15] Tao, F., Zuo, Y., Xu, L.D., Lv, L., Zhang, L., 2014. Internet of Things and BOM-Based Life Cycle Assessment of Energy-Saving and Emission-Reduction of Products. IEEE Trans. Ind. Inf. 10 (2), 1252–1261.

[16] Tu, M., Chung, W.-H., Chiu, C.-K., Chung, W., Tzeng, Y., 2017. A novel IoT-based dynamic carbon footprint approach to reducing uncertainties in carbon footprint assessment of a solar PV supply chain. 4th International Conference on Industrial Engineering and Applications (ICIEA), 249–254.

[17] Cerdas, F., Thiede, S., Juraschek, M., Turetskyy, A., Herrmann, C., 2017. Shop-floor Life Cycle Assessment. Procedia CIRP 61 (2), 393–398.

[18] Hagen, J., Büth, L., Haupt, J., Cerdas, F., Herrmann, C., 2020. Live LCA in learning factories: real time assessment of product life cycles environmental impacts. Procedia Manufacturing 45 (1), 128–133.

[19] Weyand, A., Schmitt, S., Petruschke, L., Elserafi, G., Weigold, M., 2021. Approach for Implementing New Topics in Learning Factories – Application of Product-specific Carbon Footprint Analysis. SSRN Journal.

[20] Metternich, J., Schebek, L., Andel, R., 2021. Fit für die Zukunft - Ressourceneffizienz in Produktionsprozessen. Hessen Trade & Invest GmbH, Wiesbaden, 72 pp.

[21] Xiong, W., Huang, H., Li, L., Gan, L., Zhu, L., Gao, M., Liu, Z., 2022. Embodied energy of parts in sheet metal forming: modeling and application for energy saving in the workshop. Int J Adv Manuf Technol 118 (11-12), 3933–3948.

[22] Zampou, E., Plitsos, S., Karagiannaki, A., Mourtos, I., 2014. Towards a framework for energy-aware information systems in manufacturing. Computers in Industry 65 (3), 419–433.

[23] Wang, E.-J., Lin, C.-Y., Su, T.-S., 2016. Electricity monitoring system with fuzzy multi-objective linear programming integrated in carbon footprint labeling system for manufacturing decision making. Journal of Cleaner Production 112 (3), 3935–3951.

[24] Melin, H.E., 2019. Analysis of the climate impact of lithium-ion batteries and how to measure it. Circular Energy Storage, 17 pp.

[25] Olatunji, O.O., Akinlabi, S.A., Ayo, O.O., Madushele, N., Adedeji, P.A., Fatoba, S.O., 2019. Drivers and barriers to competitive carbon footprint reduction in manufacturing supply chain: a brief review. Procedia Manufacturing 35 (6), 992–1000.

[26] Sossenheimer, J., Weyand, A., Schreiber, M., Hartmann, L., Fischer, J., Schebek, L., Metternich, J., Abele, E., 2019. Data Acquisition System in Value Streams for Resource Consumption Monitoring and Workpiece

Traceability, in: Wulfsberg, J.P., Hintze, W., Behrens, B.-A. (Eds.), Production at the leading edge of technology. Springer, Berlin, Heidelberg, pp. 593–602.

[27] Olsen, P., Borit, M., 2013. How to define traceability. Trends in Food Science & Technology 29 (2), 142–150.

[28] Schreiber, M., Metternich, J., 2022. Data Value Chains in Manufacturing: Data-based Process Transparency through Traceability and Process Mining. Procedia CIRP 107 (11), 629–634.

[29] Schuitemaker, R., Xu, X., 2020. Product traceability in manufacturing: A technical review. Procedia CIRP 93, 700–705.

[30] Schreiber, M., Bausch, P., Windecker, M., Metternich, J., 2021. Traceability-Systeme als Enabler für Process Mining. Zeitschrift für wirtschaftlichen Fabrikbetrieb 116 (10), 722–727.

[31] GS1 Germany GmbH, 2012. Von Tracking & Tracing profitieren: Strategien und Umsetzungshilfen für effiziente Rückverfolgbarkeit, Köln, 130 pp.

[32] Schuh, G., Anderl, R., Dumitrescu, R., Krüger, A., Hompel, M. ten, 2020. Der Industrie 4.0 Maturity Index in der betrieblichen Anwendung: Aktuelle Herausforderungen, Fallbeispiele und Entwicklungstrends (acatech KOOPERATION). acatech, München, 44 pp.

[33] DIN Deutsches Institut für Normung e. V., 2021. Umweltmanagement – Ökobilanz – Anforderungen und Anleitungen. Beuth Verlag, Berlin 13.020.10; 13.020.60, 70 pp.

[34] ISO, 2022. Greenhouse gases - Carbon footprint of products - Requirements and guidelines for quantification. https://www.iso.org/standard/71206.html. Accessed 3 October 2022.

[35] Fink, A., 2010. Conducting research literature reviews: From the Internet to paper, 3rd ed. ed. Sage, Thousand Oaks, Calif., 253 pp.

[36] Li, W., Alvandi, S., Kara, S., Thiede, S., Herrmann, C., 2016. Sustainability Cockpit: An integrated tool for continuous assessment and improvement of sustainability in manufacturing. CIRP Annals 65 (1), 5–8.

[37] Vikhorev, K., Greenough, R., Brown, N., 2013. An advanced energy management framework to promote energy awareness. Journal of Cleaner Production 43 (3–4), 103–112.

[38] Vogt, A., Müller, R.K., Kampa, T., Stark, R., Großmann, D., 2021. Concept and Architecture for Information Exchange between Digital Twins of the Product (CPS) and the Production System (CPPS). Procedia CIRP 104, 1292–1297.

[39] Chit, T.W., Ning, L., Paliath, N.A., Long, Y.M., Akhtar, H., Shanshan, Y., 2021. IIoT-enabled and Data-driven Sustainability Evaluation Framework for Textile Supply Chain. 16th Conference on Industrial Electronics and Applications (ICIEA), 297–304.

[40] Grenz, J., Cerdas, F., Herrmann, C., 2022. LCA based analysis of product portfolios - towards decarbonization. Procedia CIRP 105 (5), 519–524.

[41] Ustundag, A., Cevikcan, E., 2018. Industry 4.0: Managing The Digital Transformation. Springer, Cham, 286 pp.

[42] Sossenheimer, J., Vetter, O., Abele, E., Weigold, M., 2020. Hybrid virtual energy metering points – a low-cost energy monitoring approach for production systems based on offline trained prediction models. Procedia CIRP 93 (6-7), 1269–1274.

[43] Sarikaya, E., Weyand, A., Dück, D., Weigold, M., 2022. Model-based method for low-effort part-specific CO2-accounting during the production on machine tools using PLC data. 18th Global Conference on Sustainable Manufacturing (GCSM), Berlin.

Biography

Phillip Bausch, M. Sc. has been a researcher and PhD student at the Institute of Production Management, Technology and Machine Tools (PTW) at the Darmstadt University of Technology since 2019. His research interests include the traceability of components and equipment, as well as the optimization of production processes.

Astrid Weyand, M. Sc. has been a researcher and PhD student since 2019 and head of research group since mid-2021 at the PTW at Technical University of Darmstadt. Her research focus is on the field of methods to improve resource efficiency in industry, including the carbon footprint calculation.

Prof. Dr.-Ing. Matthias Weigold has been the head of the PTW at Technical University of Darmstadt since 2019. As director he is responsible for the research fields on Manufacturing Technology as well as Energy Technologies and Applications in Production. His personal research fields include digitization and climate neutrality in production.

Prof. Dr.-Ing. Joachim Metternich has been the head of the Institute for Production Management, Technology and Machine Tools (PTW) at the Darmstadt University of Technology since 2012. In addition, Prof. Metternich is the spokesman for the Center of Excellence for Medium-Sized Businesses in Darmstadt and president of the International Association of Learning Factories.

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Evaluating The Ecological Sustainability Of Production Networks – A Databased Approach

Günther Schuh[1], Seth Schmitz[1], Tino X. Schlosser[1], Martin Welsing[1]
[1]*Laboratory for Machine Tools and Production Engineering (WZL) of RWTH Aachen University, 52074 Aachen, Germany*

Abstract

The design of global production networks influences the ecological sustainability of manufacturing operations, since it determines the environment with which a production process interacts. Historically sustainability has not been a primary goal for the design of production networks and its evaluation remains a challenge. The multiple goals of sustainability and complex structures of production networks constitute to a high modelling effort that can only be managed with databased solutions. To further decrease the modelling expenditures, the data used in such a solution should be already available or easy to obtain. This paper presents a methodology and data framework to evaluate various ecological sustainability goals, which are impacted by the design of global production networks. The approach is validated with a supplier for household appliance manufacturers.

Keywords

Ecological Sustainability; Global Production Networks; Data Framework; Modelling

1. Introduction

Global production networks (GPNs) are in a perfect storm at the start of the new decade [1]. In addition to the effects of digitalization and increasingly protectionist policies, the imperative of sustainability represents a new challenge for global manufacturing companies. GPNs are directly affected by the demands for greater sustainability, as the production network configuration of a GPN influences the ecological sustainability of value chains [2]. Nowadays, industrial value creation largely takes place in GPNs [3]. Therefore, the design of these networks influences what resources are used for production activities worldwide. Location-dependent factors that influence the environmental impact of a factory include national electricity mixes, regional water shortages, municipal recycling rates and local biodiversity. Further the manufacturing industry and associated transportation account for three-quarters of the global energy consumption [4]. Allocating manufacturing activities to green energy sites will mitigate the environmental impact of this energy consumption.

In the past established methods for designing GPNs merely considered criteria related to economic competitive advantages such as costs, flexibility, delivery capability and quality [5]. Therefore the associated evaluation models only included the system elements of GPN, but not their sustainability-relevant attributes. However most elements in a GPN have quantifiable properties that have a direct influence on sustainability targets, such as energy, water and material consumption or the generation of waste and emissions. For the evaluation of the ecological sustainability, information about these properties is absolutely necessary. In particular, the complexity of GPN, which include both a local product and process view as well as a global location view on different environmental conditions, poses a challenge. Therefore, there is a need for a methodology to assess the ecological sustainability of GPN [6]. Due to the size and complexity of such

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networks and the multidimensionality of ecological sustainability, the associated models must be data-based and scalable [7].

The added value of information gained through more detailed modelling should always be in proportion to the associated, increasing effort [8]. A driver of effort is that much of the required sustainability-related information is currently not collected in companies and must be gathered at a corresponding cost [9]. The background to this is that little use is made of the possibilities of digital data processing. Instead, data is transferred using Excel and similar manual interfaces, especially if the data requirements of the new model are not clearly defined and documented [10]. Production networks contain a large number of system elements, which cannot be completely taken into account for the modelling. The appropriate level of abstraction depends strongly on the respective task and the system under investigation, so that no uniform definition is possible [11]. Approaches that have a high level of aggregation cannot represent the exact mechanisms in the network [12]. On the other hand, approaches with a high level of detail have such a large information need that they are also not operational [13]. This creates the challenge that there is no uniform abstraction level for the scope of observation therefore it leads to the need to develop a data model that enables a flexible aggregation thanks to suitable syntax and semantics.

2. State of the art

In this context, research approaches regarding the ecological sustainability evaluation of production network design should be considered. The most current and relevant approaches are presented in the following.

The software tool "*OptiWo*" represents the core of the solution approach for data-based production network evaluation developed by SCHUH ET AL. [14]. The tool offers the possibility to model a production network according to a data model. The required data can be entered by the users and derived from the operational IT systems [15]. Required data sets for network modeling include location, machinery, process chain and transportation data [16]. The IT-based solution offers a clear data modeling and key figure calculation, which is partly combined with optimization approaches. However, due to the focus on cost calculation, the approach does not offer the possibility to map impact relationships in the context of ecological sustainability. The influencing factors and elements involved are partially modeled, but without attributes about the required information for the calculation of sustainability parameters. The work of MOURTZIS ET AL. includes a software solution consisting of various tools with the aim of determining the optimal design of product networks capable of manufacturing individual products according to customer requirements. The criteria taken into account are production and transport costs, lead time, quality, reliability, dynamic complexity, and the ecological indicators CO2 emissions and energy consumption [17]. Even though sustainability-related goals were considered, the aspects of water use, materials, waste and biodiversity are missing from the work.

The information model developed by CABRAL aims to measure the agility, resilience and environmental characteristics of a supply chain. The required key figures were developed on the basis of a literature research and validated by a Delphi survey of experts from science and industry [18]. However, the focus is more on supply chain management, i.e. operational control, and not on the long-term and strategic design of a production network. The approach of HELMIG serves to evaluate the use of sustainable logistics concepts in corporate networks. For this purpose, a system of key figures, a mapping of network elements and a structuring of logistics concepts were developed as descriptive elements. The sustainability-related indicators considered include energy consumption, packaging quantities, recycling rates, and noise. There is no consideration of a broader understanding of sustainability and a complete production network configuration [19].

The use of data from the operative supply chain control for the realization of life cycle assessments (LCA) represents the core idea of the work of PAPETTI ET AL. For the implementation of the method, a web tool was developed, which is used according to the developed procedure. Especially for the challenges of databases and structures as well as the derivation of quantities for the LCA, a detailed solution is described. Allocation decisions, on the other hand, are ignored and a reference is made to the standardized procedure of the LCA for the indicator calculation [20]. In the study by BORONOOS ET AL. a multi-objective mixed integer programming problem for the design of a closed-loop green supply chain network was developed. The proposed model aims at minimizing total costs, total CO2 emissions and robustness costs in forward and reverse direction of the material flow simultaneously. By integrating various political regulatory mechanisms, the approach offers a degree of novelty. At the same time, this led to the case that no further sustainability targets were integrated in addition to the quantity of emissions [21].

In summary, approaches to evaluate the sustainability of production operations and supply chains can be found in the literature. However, a detailed focus on the ecological sustainability of GPNs and their impact due to allocation decisions is lacking.

3. Conception of the approach

The approach should enable the evaluation of the ecological properties of a production network with as minimal effort as possible. For this purpose, the approach is divided into three parts: the data model, the information identification and the calculation of the evaluation results. The considered ecological sustainability aspects of this evaluation are based on the relevance analysis of SCHUH ET AL. [22]. The same applies to the data model, which is based on preliminary work by the same authors, due to its established benefits regarding operational performance [15]. The connection of the information needs of the data model with potential sources is derived out of a literature research on the different types of sources. The final calculation of evaluation parameters adapts the balancing idea in accounting. Since not all formulas can be presented in the scope of this publication, only an exemplary explanation takes place, which is extended in the application in section 4.

3.1 Data model for production network evaluation

The UML modelling standard is used to represent and document the structure of the data model. From this standard, the class diagram method is used to represent the objects and properties of a network as corresponding classes and attributes. The presented data model is based on the framework presented by SCHUH ET AL. and was extended to fit the data needs of a sustainability evaluation [14].

For a better overview and modular use, the model is divided into four levels. The four levels are the network, location, system and process levels. These levels are based on the established structural levels of a production network [23]. To ensure that the model functions properly and makes sense, the data structure and the accounting formulas were reviewed in semi-structured interviews and workshops with experts from industrial companies and adjusted as necessary. Figure 1 shows the complete data model with all classes and their associations. It can be seen that the individual levels and modules have internal relationships and defined interfaces to the outside. At the network level, the focus is particularly on the connections between the network nodes, i.e. the locations or production sites. Since only the configuration and not the coordination of the network is modelled, mainly transports and the associated objects are represented. An elementary class is therefore the transport route, which defines the logistical connection between two locations.

In the location layer, the nodes of the network, i.e. the different locations, are modelled. The sustainability properties of a production site are modelled both with the class attributes and via an assignment to profiles. Profiles are used to summarize the sustainability attributes of a particular category. In addition, multiple sites in close proximity can have the same profile, reducing modelling efforts. The energy profile indicates which energy types and emission factors are available to the site for the purchase of electricity, heat, cooling and steam. The circularity profile refers to the site-specific options for reusing materials in the sense of a circular economy.

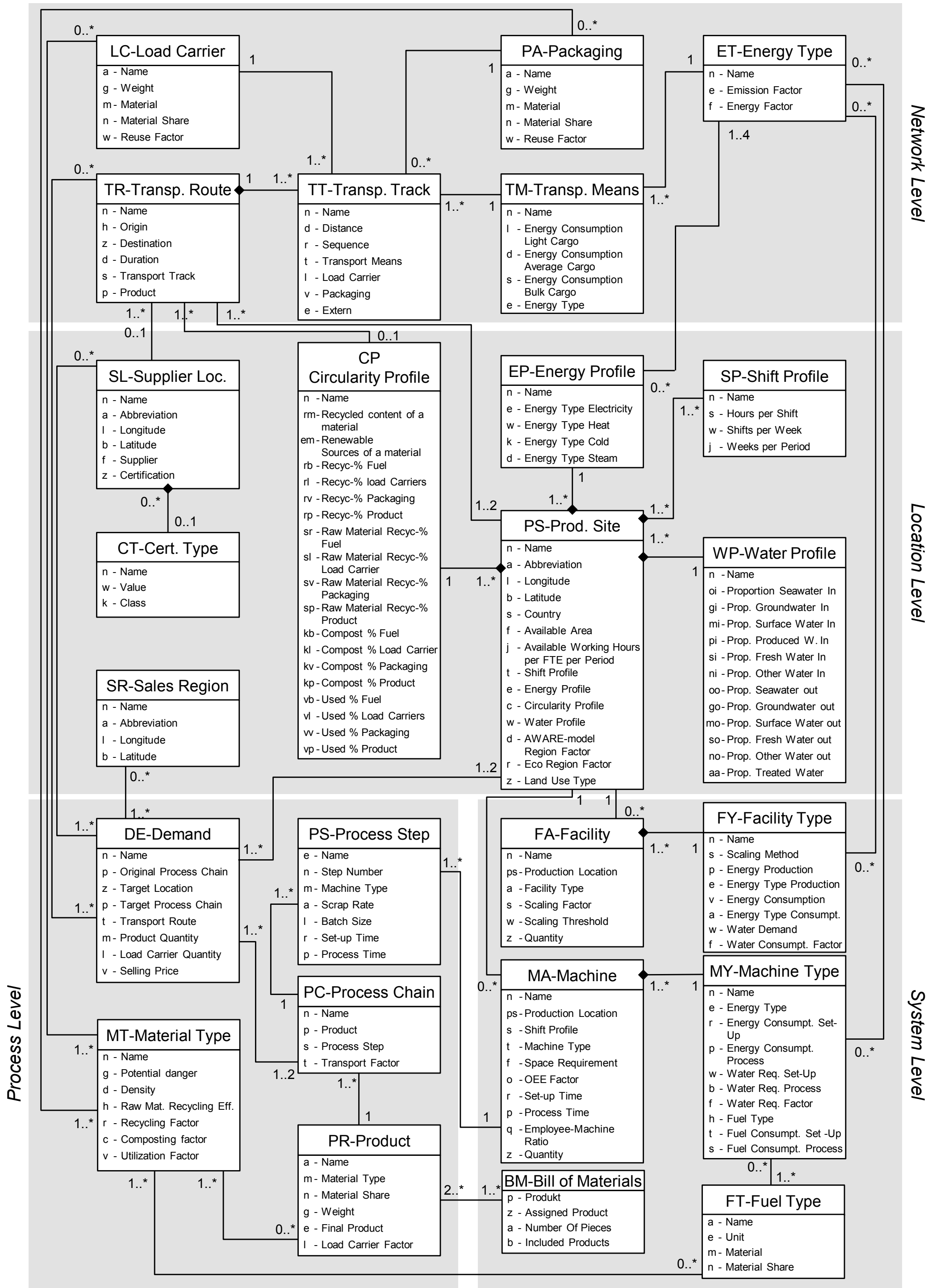

Figure 1: Data model for the ecological evaluation of production network configuration

The system level summarizes the production segments, systems and technologies allocated to a site. To keep the model manageable and at low-effort, only machines and facilities are explicitly named. Both are implemented in a scalable detail. For example, a machine can describe a single workstation or a complete production line. The difference between machines and facilities in this model lies in the proximity to the manufacturing process, which is also clear with the association assignment.

The process level maps which production processes take place in the network so that intermediate or end products are created. In addition to the closely linked products and production processes, the demand for these and the quantities per process are also an important component of this level. For a functioning model, it is necessary that the respective products and their production processes at one or more locations are allocated to the machines available there. For each of these allocations, the number of units of the products to be manufactured must also be defined. All this information is managed in the demand class. The attributes of these classes define which quantities flow from one process chain to the next and at which location both process chains are located. If these locations are different, a transport route must also be specified.

3.2 Identification of data sources for the data model

Structuring the information in a data model is merely the basis for modelling the ecological sustainability of production network configurations. In operational use, the procurement of the necessary data in particular is crucial for the success of a sustainability evaluation. As shown in Table 1, potential sources of information are differentiated both by their type and by their availability. On the one hand, information is either knowledge or data based, i.e. it is either stored on data carriers in the form of databases or systems or is available as knowledge in a person's memory. Second, a source is either internal or external to the company. Internal sources are exclusively accessible to the company because they are owned by the company or work for the company as employees. External sources are public and thus accessible to a wide audience despite possible restrictions.

Table 1: Possible data sources for the different objects of the data model

Source Type	Data Source	Network Level	Location Level	System Level	Process Level
Internal Data Carrier-based Information Sources	PLM	LC, PA			MT, PR, BM
	ERP	TR, TT, LC	SR, SL, PL, SP	MA, FA, FT	DE, MT, PC, PS, PR, BM
	MES			MA, MY	PS, PR
	CRM	PA	SR		DE, PR
	WMS	LC, PA, TM	SP	FA, FY	DE
	BIM	ET	PL, EP, WP, CP	MA, FA, FY	
	SCM	TR, TT, TM, ET	SL, SR, CT		DE
Internal Knowledge Carrier-Based Information Sources	F&E				PS, PR, MT, BM
	Controlling	TR	SR, SL, PS, EP, WP, CP	FA, FY	DE, MT, BM, PC, PS
	Production	LC , PA	PS, SP	MA, MY, FA, FY, FT	DE, PC, PS, PR, BM
	Sales	PA	SR		DE
	Logistics	LC, TT, PA, TM, ET	SR, SL, PS	FA, FY	DE, PC
	Facility Mgmt.	ET	PS, CP, EP, WP	MA, MY, FA, FY	
	Procurement	TM, LC, PA	SL, CT		
External Data Carrier-based Information Sources	LCA Databases	TR, TM, ET, LC, PA	PL, CT, WP, CP	FT, FY, MT	MT
	Official Statistics	TR	EP, WP, SP, CP		DE
	NGO/IGO Databases		EP, WP, CP		MT
	Standards	ET			MT
	Other Publications	TT, TM	PS, EP, WP, CP	FY, TM, MA	PC
External Knowledge Carrier-based Information Sources	Science	ET, LC, PA, TM	PL, CT, EP	FY, MY, FT	MT
	NGOs/IGOs	ET, TR	CT, CP, EP, WP		DE, MT
	Consultant	TM, ET	CT, SL, CP, EP, WP	MA, MY, FY	PC
	Associations	TR, TT, TM, ET	CT		
	Bench-marking	LC, PA, TR, TT	PL, BM	MY, FY	
	Stakeholders		CT, SL, CP, EP,WP		

Optimally, the attributes of all classes are filled for each level. Table 1 shows how the attributes can potentially be obtained from the different data sources. The attributes are marked in abbreviated form. The upper case letters correspond to the abbreviation for the class name. The meaning can be taken from the respective UML diagram in Figure 1. It should be noted that the assignment is structured generically and follows the established logic of the respective data sources. If the knowledge or data carriers are known in detail, further sources of information must be consulted and the assignments extended or adapted accordingly.

3.3 Calculation of evaluation parameters based on the data model

To calculate the evaluation parameters of the ecological sustainability of the production network the balancing idea is central, since every material does enter and leave the different boarders of the investigated system at some point. The balancing of the presented data model follows the logic shown in Figure 2. The overall balance of the production network consists of several sub-balances for the individual elements at and between the production sites. These elements correspond to the objects of the data model presented in part 3.1. For each sub-balance, both the input and the output with which the respective object interacts with the local environment must be considered. Depending on the location, the sustainability properties of the input and output vary, which also changes the sustainability indicators of the network. All balance sheet performance indicators are calculated on the basis of the objects and attributes of the data model. The variables in the formulas correspond to the attributes of the data model and adopt the notational logic already presented.

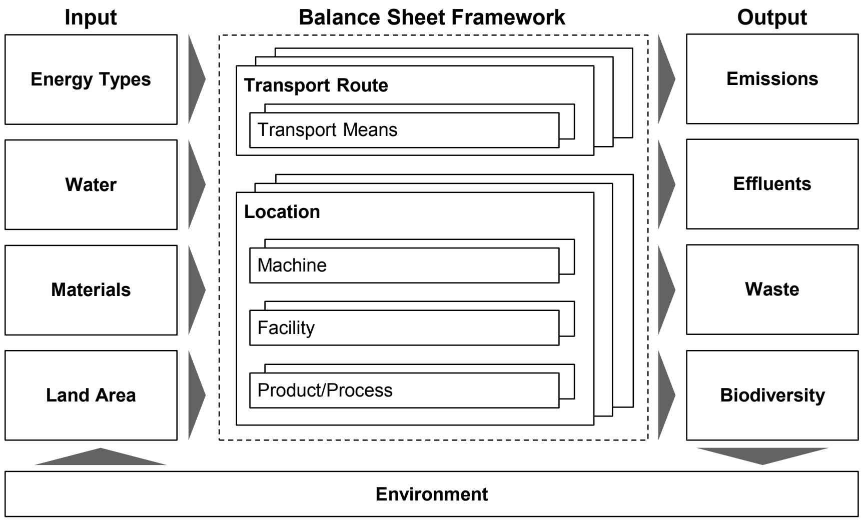

Figure 2: Balance sheet framework based on the data model for ecological sustainability evaluation

As an example the calculation of energy and emission related evaluations is presented. The calculation of the other evaluation parameters can be derived following the same logic. However, due to the limits of this publication not all formulas are published. The calculations of sustainability indicators for energy and emissions are closely linked, since greenhouse gases are generated during the conversion of primary energies to secondary energies, depending on the energy source. Figure 3 illustrates this relationship of input and output variables as well as the elements of the production network model involved.

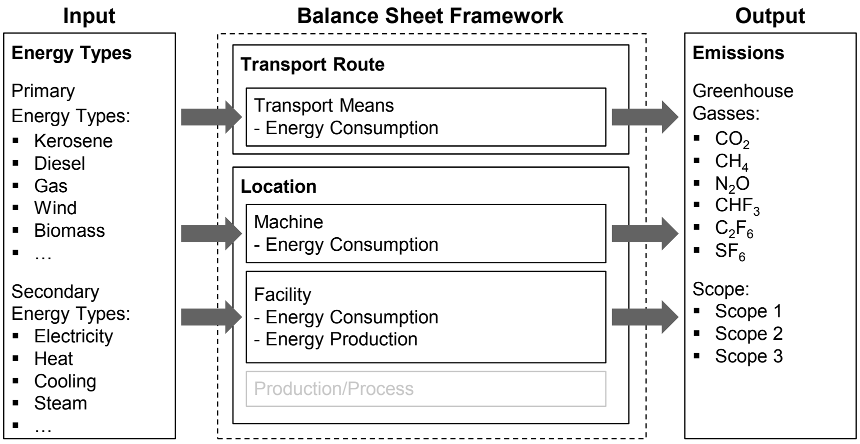

Figure 3: Balance sheet framework for the evaluation of energy and emissions

An essential key figure for the sustainability accounting of a production network is the total energy required. This is calculated using the equation in formula 1. The formula shows that, according to the model logic, there are three main types of energy consumers in the network. These are transports, machinery and facilities. The demand for transports is directly influenced by the network configuration. The demand for machines and facilities is only slightly influenced in terms of cooling and heating capacity per location. However, the type of energy sources available per site varies greatly, as shown above.

$$E_{total.} = E_{transports} + E_{machinery} + E_{facilities} \tag{1}$$

Formula 2 shows how the total energy required for transports is calculated using the data model. All variables are taken from the data model in Figure 1. According to Association of German Freight Forwarders and Logistics Operators (DSLV), the most important factors for the energy consumption of a means of transport are its capacity utilization, load type, driving style, route and traffic as well as the mass of the freight and the distance covered [24]. In practice, part of the transports are carried out by service providers, which is why real consumption values, capacity utilization as well as driving mode and traffic are unknown. Therefore, for the present model, these aspects are ignored and the density of freight is simplified to three types of cargo.

$$E_{transports} = \sum_{TR} \sum_{TT} \sum_{PR} \sum_{TM} \sum_{ET} \begin{matrix} G_{TR,TT,PR} * TTd_{TR,TS} * Tb_{TR,TT,PR,TM} * \\ (TMl_{TM} \vee TMd_{TM} \vee TMs_{TM}) * ETf_{TM,ET} \end{matrix} \tag{2}$$

Thus, in formula 2, the total energy demand is calculated by summing up the energy demand per transport route TR, track TT, product PR and the means of transport TM used as their energy types ET. Essential for this is the total weight of the transport units per product $G_{TR,TT,PR}$, which is also called the shipment weight and consists of the product and the packaging weight. This is multiplied with the distance of each track $TTd_{TR,TS}$, the binary decision variable if the track is $Tb_{TR,TT,PR,TM}$ utilized, the load specific energy consumption of the vehicle $(TMl_{TM} \vee TMd_{TM} \vee TMs_{TM})$ and the associated energy factor of the fuel $ETf_{TM,ET}$. Detailed information of each variable in the formula can be obtained from the class diagram defined in Figure 1. Some of these variables are dependent on further calculations. E.g. the shipment weight is the sum of the product weight, packaging weight and load carrier weight for each transportation unit. The packaging is used for every product unit, while the load carrier can carry as many products as defined by the transportation factor.

The presented data model in section 3.1 allows the calculation of further evaluation parameters, with limited effort regarding data procurement and implementation. The following application of the framework with a real company gives further examples on what parameters can be derived.

4. Application

The company considered for the validation is a supplier for household appliance manufacturers. Critical key figures were changed within the scope of publication for reasons of confidentiality. This has no effect on the results. The company employs over 5,000 people worldwide and generates sales of over 500 million euros. For historical reasons, the company has its roots and headquarters in Germany, but produces for its customers worldwide. The company produces at six locations: Germany, China, Austria, Turkey, Croatia and USA. In Croatia, no final products are manufactured, only components. The production network is generally based on a local-for-local configuration, although there are exceptions. For reasons of technology protection, a chemical compound is only mixed at the German site, which is a lead factory. Some stabilization rings are manufactured exclusively in Austria. Except for Germany, the temperature limiter is assembled at all sites. Germany sources this from Croatia.

Various internal and external sources were used to gather information. For example, experts from the Supply Chain department were asked about the availability of ports, rail routes and airports. The transport quantities were taken from the ERP system. The corresponding distances were determined using Google Maps and a sea distance calculator. Information on packaging and load carriers was taken from the PLM system and validated by an on-site investigation at the German locations. Information about the product and its physical properties were taken from the parts lists of the ERP system and measurements performed.

The identified key performance parameters calculated with the data model were used to identify possible courses of action. The most promising options were generated and evaluated as scenarios using a software demonstrator, which included the data model and calculation logic. The first simulated improvement action was to relocate production for the North America market from Turkey to the USA. In addition, approximately 300 tons of chemical compounds would have to be transported from Germany to the USA. The site in Turkey would take on half a million products from China as a compensation. This relocation was promising, as the environmental impact at the Chinese site is worse than in Turkey. Another improvement was offered by eliminating air freight. This reduces both greenhouse gas emissions and transportation costs. The third measure considered was the establishment of a holding plate production and stamping machine in Turkey.

The improvements that can be achieved with the three options for action presented are shown in Table 2. The results show that adapting the network improves the eco-efficiency of the energy demand by 27.8%. Even more successful is the improvement of the eco-efficiency of greenhouse gas emissions from 9,003 to 16,129 Euro revenue per emitted ton of CO_2e. No improvement was achieved in water use, waste and land use. Since only one product was considered and no sites were downsized or upsized, the demand of the plants could not be changed. In addition, recycling was possible at each site, so no improvements could be achieved through product relocation.

Table 2: Evaluation and improvement of the ecological production network performance

Key Performance Indicator	Unit	Value Before Improvement	Value After Improvement	%
Eco-efficiency of Energy Demand	EUR/MWh	6,949.87	8,883.90	27.8
Eco-efficiency of Greenhouse Gas Emissions	EUR/tCO2e	9,003.31	15,961.73	77.2
Intensity of Transport	kgCO2e/tkm	0.0741	0.0174	-76.4
Eco-efficiency of Water Demand	EUR/m³	0.102	0.102	0.0
Eco-efficiency of Water Consumption	EUR/m³	-	-	-
Eco-efficiency of The Amount Of Waste For Disposal	EUR/(kg+l)	1,071.89	1,049.03	-2.1
Eco-efficiency of Hazardous Waste	EUR/(kg+l)	-	-	-
Eco-efficiency of Land Use	EUR/m2	2,120.28	2,120.28	0.0
Eco-efficiency of Potentially Species Lost	EUR/PDF	2.29E+18	2.29E+18	0.0

5. Conclusion

Global production networks are an essential component of the globalized society of the 21st century. At the same time, global production networks are also emblematic of the exponential growth of humanity over the past centuries and the resulting negative consequences for other forms of life on the planet. For this reason, the production networks of the future must not be planned and evaluated according to the premises of the past. Rather, sustainability-oriented criteria must be considered alongside competition-oriented criteria.

The present work offers an approach for this. The developed evaluation method differentiates the ecological sustainability of the input and output of production networks according to the site-specific characteristics. In this way, network planning can take into account that local limits are not exceeded and resources are only used where nature or man can provide them sustainably to a sufficient degree. The costs of transporting resources in the network are also taken into account and weighed against the advantages of local sustainability. The major influence of global production networks on sustainability is transformed from a weakness to a strength with the developed methodology. By moving production activities to an environment that can provide and process the required inputs and outputs in a sustainable manner, the ecological sustainability of products and processes will be improved without having to adapt the technology.

The developed methodology is a promising approach for assessing the ecological sustainability of production network configuration. At the same time, the methodology offers possibilities for extensions and future research activities, which could not be mapped within the scope of the present work. The isolated consideration of ecological sustainability allows a more detailed assessment, but at the same time contradicts the principle of the holistic nature of sustainability. For a complete evaluation of the sustainability of a production network, it is therefore necessary to integrate the economic and social aspects. A detailing of the data model is also conceivable, provided that the resulting effort is accepted.

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References

[1] UNCTAD, 2020. World Investment Report: International Production Beyond the pandemic. United Nations Publications, New York.
[2] Sihag, N., Leiden, A., Bhakar, V., Thiede, S., Sangwan, K.S., Herrmann, C., 2019. The Influence of Manufacturing Plant Site Selection on Environmental Impact of Machining Processes. Procedia CIRP 80, 186–191.
[3] Lanza, G., Ferdows, K., Kara, S., Mourtzis, D., Schuh, G., Váncza, J., Wang, L., Wiendahl, H.-P., 2019. Global production networks: Design and operation. CIRP Annals 68 (2), 823–841.
[4] EIA, 2020. International Energy Outlook: Delivered energy consumption by end-use sector and fuel. U.S. Energy Information Administration. https://www.eia.gov/outlooks/aeo/data/browser/#/?id=15-IEO2019&region=4-0&cases=Reference&start=2010&end=2020&f=A&linechart=Reference-d080819.2-15-IEO2019.4-0&map=&sourcekey=0. Accessed 1 October 2021.
[5] Friedli, T., Lanza, G., Remling, D. (Eds.), 2021. Global Manufacturing Management. Springer International Publishing, Cham.
[6] Eslami, Y., Lezoche, M., Panetto, H., Dassisti, M., 2020. On analysing sustainability assessment in manufacturing organisations: a survey. International Journal of Production Research 4 (1), 1–32.
[7] Saxena, P., Stavropoulos, P., Kechagias, J., Salonitis, K., 2020. Sustainability Assessment for Manufacturing Operations.
[8] Reuter, C., Prote, J.P., Stöwer, M., 2015. Aggregation of Production Data for the Strategic Planning of Global Production Networks. AMM 794, 461–469.
[9] Bicalho, T., Sauer, I., Rambaud, A., Altukhova, Y., 2017. LCA data quality: A management science perspective. Journal of Cleaner Production 156, 888–898.

[10]Benfer, M., Peukert, S., Lanza, G., 2021. A Framework for Digital Twins for Production Network Management. Procedia CIRP 104, 1269–1274.
[11]Benfer, M., Ziegler, M., Gützlaff, A., Fränken, B., Cremer, S., Prote, J.-P., Schuh, G., 2019. Determination of the abstraction level in production network models. Procedia CIRP 81, 198–203.
[12]Ferdows, K., 2018. Keeping up with growing complexity of managing global operations. Int Jrnl of Op & Prod Mnagemnt 38 (2), 390–402.
[13]Gützlaff, A., 2022. Entscheidungsprozess zur kontinuierlichen Gestaltung von Produktionsnetzwerken. Dissertation, Aachen.
[14]Schuh, G., Potente, T., Kupke, D., Varandani, R., Hausberg, C., 2012. An Evolutionary Approach for Global Production Network Optimisation. Procedia CIRP 3, 382–387.
[15]Schuh, G., Potente, T., Kupke, D., Varandani, R., 2013. Innovative Approaches for Global Production Networks, in: Windt, K. (Ed.), Robust Manufacturing Control. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 385–397.
[16]Varandani, R.M., 2014. Managementkomplexität als Gestaltungsgröße kostenoptimierter globaler Produktionsnetzwerke. Zugl.: Aachen, Techn. Hochsch., Diss., 2014, 1. Aufl. ed. Apprimus Verlag, Aachen, 217 pp.
[17]Mourtzis, D., Doukas, M., Psarommatis, F., 2015. A toolbox for the design, planning and operation of manufacturing networks in a mass customisation environment. Journal of Manufacturing Systems 36, 274–286.
[18]Cabral, I.F., 2011. An information model for lean, agile, resilient and green supply chain management. Dissertation.
[19]Helmig, J., 2012. Bewertung des Einsatzes von nachhaltigen Logistikkonzepten in Unternehmensnetzwerken. Zugl.: Aachen, Techn. Hochsch., Diss., 2012, 1. Aufl. ed. Apprimus Verlag, Aachen, 85 pp.
[20]Papetti, A., Marconi, M., Rossi, M., Germani, M., 2019. Web-based platform for eco-sustainable supply chain management. Sustainable Production and Consumption 17, 215–228.
[21]Boronoos, M., Mousazadeh, M., Torabi, S.A., 2021. A robust mixed flexible-possibilistic programming approach for multi-objective closed-loop green supply chain network design. Environment, Development and Sustainability 23 (3), 3368–3395.
[22]Schuh, G., Gützlaff, A., Schlosser, T., Welsing, M., Balgar, L., 2022. How to measure ecological sustainability in manufacturing?: A literature review of indicator frequency and relevance. 6th World P&OM Conference Special Issue 12 (1), 1–17.
[23]Prote, J.-P., 2017. Verursachungsgerechte Bewertung von Standortalternativen in Produktionsnetzwerken. Dissertation, 1. Auflage ed.
[24]DSLV, 2013. Berechnung von Treibhausgasemissionen in Spedition und Logistik gemäß DIN EN 16258: Begriffe, Methoden, Beispiele. Deutscher Speditions- und Logistikverband e.V. (DSLV), Bonn.

Biography

Günther Schuh (*1958) holds the Chair of Production Systems at the Laboratory for Machine Tools and Production Engineering WZL at RWTH Aachen University, is a member of the board of directors of the Fraunhofer Institute for Production Technology IPT and director of the Research Institute for Rationalization (FIR) at the RWTH Aachen.

Seth Schmitz (*1991) studied Business Administration and Engineering specializing in Mechanical Engineering at the RWTH Aachen University and Tsinghua University. He is Head of the Production Management Department at the Laboratory for Machine Tools and Production Engineering WZL at RWTH Aachen University.

Tino X. Schlosser (*1989) studied Business Administration and Engineering specializing in Mechanical Engineering at the RWTH Aachen and Tsinghua University. He is Team Lead Global Production in the Production Management department at the Laboratory for Machine Tools and Production Engineering WZL at RWTH Aachen University.

Martin Welsing (*1992) studied Business Administration and Engineering specializing in Mechanical Engineering at the RWTH Aachen, University of Arizona and Tsinghua University. He is a researcher in the Production Management department at the Laboratory for Machine Tools and Production Engineering WZL at RWTH Aachen University.

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Evaluating Ecological Sustainability For The Planning and Operations Of Storage Technologies

Philipp Braun[1], Hendrik Rose[1], Niklas Hesslein[1], Harsha Vadapalli[1], Johannes Hinckeldeyn[1], Jochen Kreutzfeldt[1]

[1]*Institute of Technical Logistics, Hamburg University of Technology, Germany*

Abstract

With an expected future increase of costs for carbon emissions the logistics industry is targeting to design sustainable warehouses to reduce their carbon footprints. To do so, it is required that every aspect of a warehouse from its general design to the transport processes and technologies must be assessed in terms of its carbon footprint. In this article the carbon footprint, which can be traced back to the storage technology employed within a storage area is analysed. The approach includes surface, material, and technology-related data to calculate the carbon footprint of a logistics concept. Firstly, different dimensions of storage technology carbon footprints are identified. A comprehensive model is provided to calculate the carbon footprint of alternative storage technologies in a warehouse. The model is applied in a case study with actual data from a warehouse planning project in the German production industry comparing three alternative storage technologies for a small part storage solution. The author's find highest carbon footprint in the application of an autonomous guided vehicle shelving system compared to automatic storage and retrieval system and manual storage solution using Kanban racks.

Keywords

Warehouse planning; Ecological sustainability; Storage technologies; Carbon emissions

1. Introduction

Warehouses are substantial parts of global supply networks, as they build the main interface between an organization's supply, its production, and its interface to the customer. Global uncertainties in supply chains, however, have led organizations in production and e-commerce to increase their stocks preventing future supply bottlenecks resulting in the need of more storage areas. In Germany, the warehouse capacities have increased by 19 % within one year [1]. The recent rising demand of storage surface enhances the need of new and larger logistics hubs and the efficient use of the existing logistics technologies. Planning and designing these new warehouses, the major targets are the implementation of efficient material flows and storage concepts to achieve the highest decrease in storage and transport costs.

Besides the strive for economic efficiency, the contribution of logistics to greenhouse gas emissions has gained attention [2]. According to Doherty & Hoyle [3] a substantial amount of 11% of the total greenhouse gas emissions from logistics can be traced back to warehousing and its operational activities. As costs for greenhouse gas emissions raise [4], designing and building ecologically sustainable warehouses will become a competitive factor throughout economy. Therefore, the assessment of ecological sustainability of a warehouse building as well as its processes and storage technologies is to be integrated into the planning of new warehouses.

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Assessing the sustainability of buildings has been subject to many investigations recently [5,6]. However, the sustainability analysis of storage technologies within warehouses is limited. Hence, the objective of this research is to develop a model to assess the ecological sustainability of different storage technology scenarios for newly designed warehouses. Two research questions are explored to satisfy this objective:

- RQ1: Which dimensions are to be considered to assess the carbon footprint of storage technologies?
- RQ2: How can the carbon footprint of different storage technologies be calculated to compare different alternatives in terms of their ecological sustainability?

For the assessment of the above research questions the analysis concept and model are applied on data of a practical warehouse planning project, comparing three different storage technology concepts in terms of their carbon footprints for the chosen storage technology in a case study.

First, an overview of the existing literature about the sustainability assessment of storage technologies and warehouses is given. The article continuous with the introduction of a concept for an model to analyse the respective carbon footprint for a given storage technology. The developed and implemented model is then applied to three planning scenarios of a warehouse planning project to compare the carbon footprint for each storage technology. The article closes with a conclusion, its limitations, and an outlook for further research in the field of warehouse sustainability assessment.

2. Related literature

Traditional logistics and material flow planning methods with a focus on warehouse planning projects follow strict planning stages [7]. Within these stages, warehouse concepts will be developed by defining the project scope, conducting data analysis, developing a planning baseline (processes, system boundaries and dimensioning of storage technologies), elaborate a detailed logistics concept and a final realization of the project [8]. These warehouse concepts often consist of invest and operational budgets, material flow definitions, surfaces, and layouts as well as the integration of qualitative criteria by benefit value analyses [9]. More recent planning approaches also focus on the integration of stakeholders and managing uncertainties within the planning [10]. None of these approaches explicitly include parameters to evaluate the sustainability of alternative planning scenarios.

Existing evaluation frameworks for calculating the carbon footprint resulting from storage technologies in warehouses focus on evaluation criteria and emissions resulting from the warehouse operations. In a study conducted by Torabizadeh et al. [11] evaluation criteria are collected from existing literature and weighted for a utilization in sustainability assessments. The weighting of criteria was done by expert interviews and questionnaires. In this study criteria from all sustainability fields (ecologic, social, and economic) are included. Another study proposes an evaluation approach with a focus on the carbon emissions resulting from the warehouse operations [12]. It includes lighting as well as heating, cooling, and ventilation (HVAC). The operative emissions are further investigated in terms of energy consumed by transport technologies to maintain warehouse operations in the storage technologies. The work of Lewczuk et al. [13] proposes another calculation method to estimate the energy consumption resulting from the warehouse operations in different storage technologies. Here, the dimensions HVAC, lighting, IT systems and operations are considered. Indices, which indicate the share of automated storage technologies and the share of energy from photovoltaic systems, are included. Further studies investigate the energy consumption of different warehouse equipment in existing warehouses and integrates the costs of carbon emissions [14,6,15]. The detailed view on the energy consumption of transport technologies is also investigated in the literature. Energy consumption estimations were performed for operations with forklift trucks [16,17] and transports performed by mini load cranes in automatic storage and retrieval systems (ASRS) [18–20]. Other specific investigations were performed on the heating and temperature distribution in high warehouse buildings [21–23]. The reviewed studies show evaluation frameworks for operative energy consumptions and carbon footprints of warehouses as well as analyses of historic energy consumption in existing warehouses.

General literature reviews on sustainable warehousing regard trends and future research demands in the field of sustainability assessments. The study of Bartolini et al. [2] states that carbon emission taxes will influence warehouse operations in the coming years. Further, they define research demands for measures of warehouse sustainability to highlight optimization potentials, conducting case studies based on empirical data, evaluation models for carbon emissions and smart lighting systems. The investigations of Udara Willhelm Abeydeera et al. [24] support these demands by the need for tracking and predicting carbon emissions as well as identifying optimization and mitigation potentials. According to Bank & Murphy [25] research on metrics, standards and guidelines for sustainable warehousing is demanded. Further research on sustainability in logistics is performed in the areas of building and transport emissions. In the field of transport emissions analytical models and simulations studies are available [26,27]. The field of building emission research is conducted to estimate carbon emissions resulting from the construction activities of warehouse buildings [5]. From the literature, a clear demand for new and revised models for estimating the sustainability of future warehouses in early stages of planning projects can be extracted.

The existing literature presents a variety of approaches for estimating the carbon emissions or energy consumption in warehouse planning projects. The dimensions of these approaches cover the major operative emissions by considering transports, HVAC, and lighting. To the best knowledge of the authors, none of these approaches includes the emissions resulting from the installation of storage technologies in warehouses. Further, existing approaches are quite extensive and not always applicable in warehouse planning projects due to data availability and project timelines.

3. Concept of a model for determining carbon emissions resulting from storage technologies

To address the gaps in the existing literature, this section proposes a new concept and an analytical model to assess the ecological sustainability of alternative storage technologies within warehouse planning projects (Figure 1). In contrast to existing literature, the ecological sustainability of different planning scenarios is assessed by determining the carbon footprint in the construction and operation of storage technologies. The model is designed as an analytical model to estimate future carbon footprints of warehouses in early planning phases with limited data input. The model requires a fixed set of input parameters, which provides a baseline for subsequent evaluation steps. The evaluation of alternative storage technologies is performed under consideration of the dimensions heating, lighting, additional building construction, operational and storage technology production emissions. The output values can be converted to total carbon emissions for construction and operations using carbon equivalents for the different energy sources consumed.

The model input is separated in three categories. (1) Building-related information form the first category. Here, surface and heating demand in the different storage areas are required. (2) SKU (stock keeping unit)-related information are parameters determining the storage conditions required by the materials and parts to be stored. This category contains the storage technologies, locations required and lighting demands. (3) Dynamic data are required for determining the in- and outbound movements to be performed within the storage areas using respective transport technologies like forklift trucks or ASRS shuttles. Storage technology-related information includes the raw materials to produce the structural components of the racking and control technologies. Further, the steps within the production process need to be available as well as transports efforts performed within the production process.

The first dimension of evaluation is the calculation of heating emissions. Here, the heating energy per storage area is determined. Second, the determination of the lighting energy emissions is included by calculating the number of required headlights. As some technologies require additional surfaces, the category additional building construction emissions identifies these construction emissions. The major operational emissions result from the movements of goods. Using dynamic data, the energy consumption per movement of applied transport technologies (e.g., ASRS, conveyer, or forklift trucks) is analysed. For storage technology emissions the evaluation includes carbon emissions of the raw materials (e.g., steel), the different production processes. Further, transport efforts and packing materials for production and transhipment are utilized.

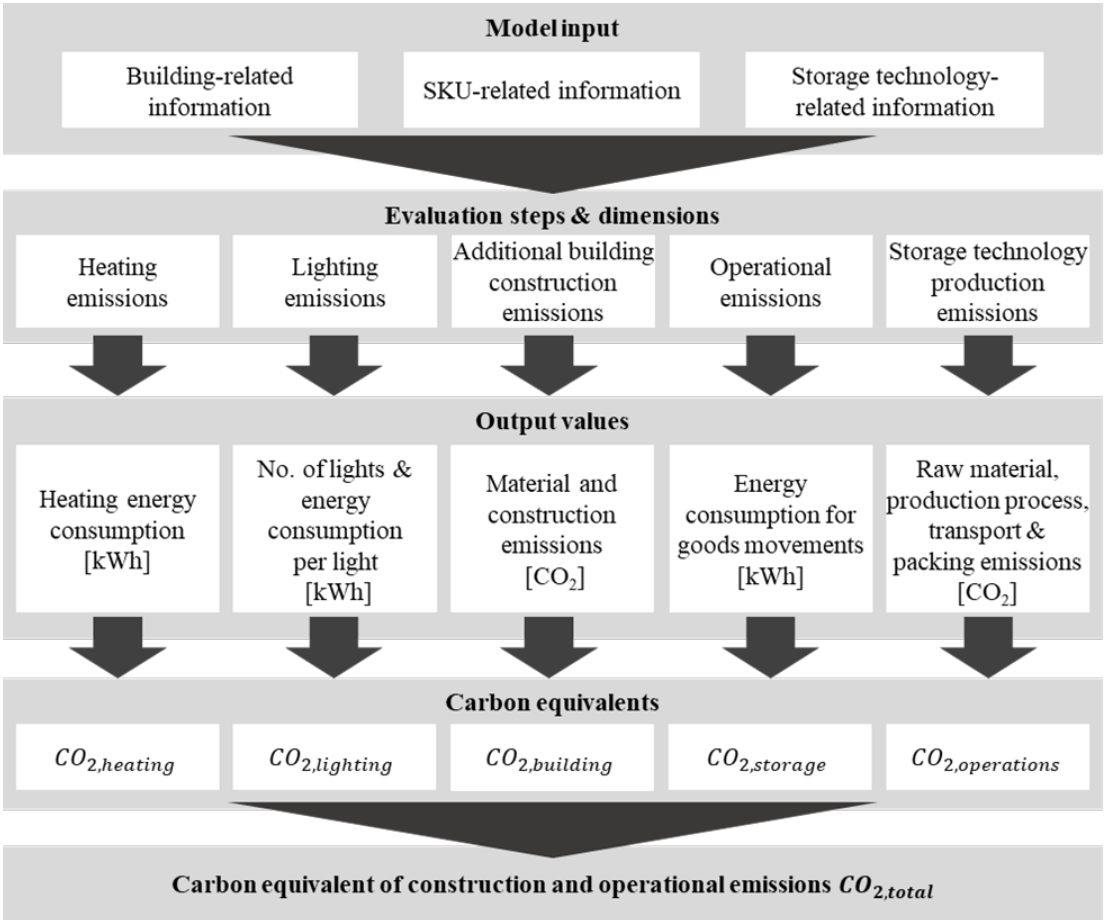

Figure 1: Concept of the calculation model from carbon emissions resulting from storage technologies.

Finally, the model attributes all individual dimensions to a single measure

$$CO_{2,total} = CO_{2,heating} + CO_{2,lighting} + CO_{2,building} + CO_{2,storage} + CO_{2,operations} \qquad (1)$$

in the form of carbon emissions. If the single dimensions cannot directly provide a carbon emission value, equivalents will be applied to convert energy consumptions to carbon emissions [28]. In this manner, the model can provide a single and central value which allows users to compare the carbon emissions of different planning scenarios and determine the influences of the different technologies and dimensions within the model. Further, all values are based on actual energy and emission data.

In the remaining part of this section, the calculation steps to evaluate the emissions in the five dimensions are described. The **heating emissions** are mainly based on the calculation of the heating load to maintain a given temperature. The calculation results in the energy consumed to maintain the temperature and can be converted to an equivalent value of the corresponding carbon emissions. This calculation requires an input of the geometric dimensions of the warehouse and the storage height, which is to be heated. Further, energy consumption is highly depended on the heating system installed in the warehouse and the regional environmental conditions of the warehouse location. Operational data is utilized to integrate the operational hours and working days of logistics operations in the warehouse. The heating load

$$E_{heating} = E_{sqm} * A_{surface} * t_{operations} \quad (2)$$

calculates the heating energy for the utilized surface in kilowatt hours per year. This calculation was adapted and simplified from Lewczuk et al. [13]. E_{sqm} represents the energy to maintain the given temperature at one square meter (sqm) in the warehouse at a given storage height. $A_{surface}$ is the surface of the warehouse to be heated. The operational hours per year are given by $t_{operations}$. The calculation of the carbon footprint

$$CO_{2,heating} = CO_{2,heating,kWh} * E_{heating} \quad (3)$$

is performed by using a carbon equivalent value $CO_{2,heating,kWh}$ per kWh in the given country.

The calculation of **lighting emissions** is performed by considering the lumens required per surface area. Thereby, the total amount of lights required can be calculated and traced back to the consumed electric energy. The calculation of required electric energy for lighting

$$E_{lighting} = \sum_{i=1}^{n} \frac{A_i * l_i}{l_{light}} * E_{light} * t_{operations} \quad (4)$$

starts with the calculation of the of required lights per storage area. A_i defines the surface of a given storage area i, l_i integrates the required lumens per sqm within the storage area and l_{light} is the number of lumens delivered by a single light. Including the electric energy per light E_{light} and the operational hours $t_{operations}$ the electric energy for lighting in all storage areas n is calculated. Using the carbon equivalent for electric energy the total carbon emitted by lighting $CO_{2,lighting}$ is determined.

The calculation of **additional building construction emissions** is realized by accounting the emissions for the raw material and the construction by carbon equivalent values. The calculation of raw material emissions

$$CO_{2,building} = \sum_{j=1}^{m} \sum_{k=1}^{o} CO_{2,material,j,k} * V_{i,k} \quad (5)$$

integrates all storage areas which require specific building facilities m and all materials o utilized within the construction process. The carbon equivalent value $CO_{2,material,j,k}$ represents the carbon emissions of one volume unit of a specific material utilized in the construction. $V_{i,k}$ is the volume of the specific material used in the building process.

The calculation of **emissions resulting from the storage technology installations** itself are determined by the emissions of included raw materials, production processes of the storage technologies, transports and used packing materials (Figure 2).

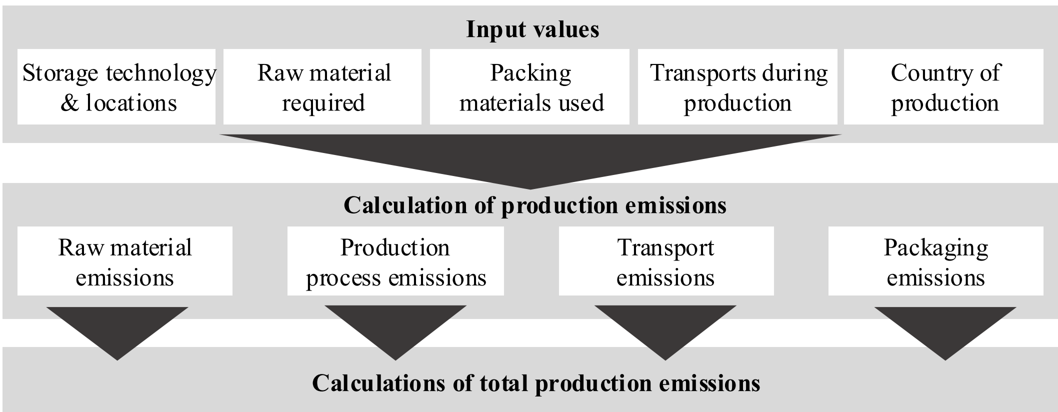

Figure 2: Calculation process for determining the production emissions

The emissions from raw materials for all storage technologies m and all applied materials o is determined by material quantity per unit of a given storage technology.

$$CO_{2,materials} = \sum_{j=1}^{m} \sum_{k=1}^{o} Q_{material,j,k} * CO_{2,material,j,k} * Units_m \quad (6)$$

The carbon equivalent $CO_{2,material,j,k}$ specifies the carbon emissions per ton of the respective material quantity $Q_{material,j,k}$. These values are multiplied with the number of units of a storage technology required in a planning scenario. The production emissions

$$CO_{2,production} = \sum_{j=1}^{m} \sum_{k=1}^{o} Q_{material,j,k} * CO_{2,production,j,k} * Units_m \quad (7)$$

are calculated in accordance with the calculation of emissions from raw materials (6) except the carbon equivalent value $CO_{2,production,j,k}$ for a specific production process required in the manufacturing of a storage technology. The transport emissions

$$CO_{2,transport} = \sum_{j=1}^{m} d_j * CO_{2,km} \quad (8)$$

for all storage technologies m is determined by the traveled distances d_j and a carbon equivalent value $CO_{2,km}$ of the acquired transport mode. The emissions from packing material for all storage technologies m and all applied packing materials o

$$CO_{2,packing} = \sum_{j=1}^{m} \sum_{k=1}^{o} Q_{packing,j,k} * CO_{2,packing,j,k} \quad (9)$$

are determined by the quantity of all utilized packing materials $Q_{packing,j,k}$ and their respective carbon equivalent value $CO_{2,packing,j,k}$.The total carbon emissions resulting the utilized storage technologies are given by the sum of all sub calculations.

$$CO_{2,storage} = CO_{2,materials} + CO_{2,production} + CO_{2,transport} + CO_{2,packing} \quad (10)$$

The **operational emissions** are highly dependent on the applied storage technology, distances to be travelled in a warehouse for the picking and replenishment process as well as dynamic data regarding the in- and outbound. The storage technologies define the transport technologies utilized within the picking and replenishment process. Here, the emissions vary from manual transports, which do not directly lead to carbon emissions as no energy is consumed to perform the processes, to fully automated storage technologies. ASRS' perform all transports by picking robots and conveyor systems with significant consumptions of electric energy. The dynamic data of the in- and outbounds defines the quantity of transports to be performed within the storage technologies. As the calculation of the operational emissions $CO_{2,operations}$ is highly dependent on the storage technologies, this work cannot provide a generic approach to determine the carbon emissions of transport technologies. Therefore, the calculation of operations emissions must be specified within in planning projects according to the storage technologies to be designed.

The total carbon footprint $CO_{2,total}$ is calculated by the sum of all sub steps within the model. Thereby, this work proposes an approach which enables logistics planners to estimate future carbon footprints resulting from storage technologies in warehouse planning projects. The model concept comprises emissions determined by the construction of the storage technologies as well as emissions of the operations of the future warehouse for a certain period of investigation.

4. Case study – Comparison of small part solutions from a practical warehouse planning project

This section aims to describe the relationships between the chosen dimensions of the proposed model and the overall carbon footprint of small part storage technologies in a future warehouse on the basis of the research procedures for explanatory case studies [29]. The case was selected based on an anonymous dataset resulting from a practical planning project of a warehouse to secure the supply of a production site. Therefore, a storage inventory analysis and acquisition of dynamic data regarding the goods movements in the warehouse was performed. This forms the baseline for the calculation of future storage locations and surface demands.

Three scenarios of a small part storage solution including an ASRS, a fully manual Kanban rack area and an autonomous guided vehicles (AGV) shelving system are compared. The ASRS scenario can be integrated in a one storied warehouse. The remaining scenarios required a second floor due to higher surface requirements and low utilization of the available height. Table 1 presents the basic planning parameters of the project. The model considers the required surface calculated from storage capacity requirements, building surfaces, which is required to construct the system, transport technologies to maintain operations, the major production steps to process the raw materials and the amount of raw steel needed to produce the racks.

Table 1: Parameters of the planning scenarios

Scenario	Surface [sqm]	Add. building surface [sqm]	Transport technology	Energy consumption [kWh]	Production processes	Raw material volume [t]
ASRS	350	0	Mini load	1.78	Hot rolling, coating	52.5
AGV-shelving	1400	1150	AGVs	3.2	Hot rolling, coating	26.5
Kanban racks	1400	1150	Manual	0	Hot rolling, coating	32.6

For all planning scenarios, general input parameters serve as underlaying conditions. In the future warehouse a heat pump heating system is applied to maintain a temperature of 20°C up to a height of 4.8 m. This leads to an electricity consumption of 80.72 kWh per year and sqm [13]. The carbon equivalent values were taken from available data on the energy share in Germany [28]. The amount of required light intensity is assumed at 300 lumens per sqm. The operational hours were assumed as 4,200 h per year. To calculate operational emission dynamic data from the current warehouse was analyzed. On average, the system is required to fulfill 700 storage movements per day.

The results of the model (Figure 3) show the carbon emissions of the planning scenarios for the construction emissions (production and additional building emissions) and recurring emissions within 10 years (heating, lighting, and operational emissions). With a total of 525 tons of CO_2 the ASRS system shows the lowest carbon footprint compared to a manual Kanban rack zone (780 tons of CO_2) and the AGV-shelving (860 tons of CO_2). Amongst all scenarios, significant differences are indicated for the production emissions and for the heating emissions. With the highest amount of raw material to be processed, the ASRS indicated the highest carbon footprint in production (steel bar construction). As the ASRS solution can be integrated into a one story building no additional building surface required.

The scenario AGV-based shelving system leads to the highest overall emissions as a large-scale area is to be heated and the amount of raw material required for production. Across all scenarios the production, additional building (concrete) and heating emissions are the major contributors to the overall emissions. It can be obtained that on the one hand automation leads to higher emissions in the production of the storage technologies. On the other hand, the long-term emission savings for heating can be expected with lower surface demands. These investigations can be used when it comes to the mitigation of fixed emissions from the construction of storage technologies and the amount of electric energy required from renewable energies to maintain low emissions in operations. The implementation of highly densified storage systems is expected to decrease the overall carbon footprint of a warehouse can therefore enhance the ecological sustainability. This work is based on a practical and ongoing planning project. For this reason, a validation by actual emission measurements is a task for future research activities.

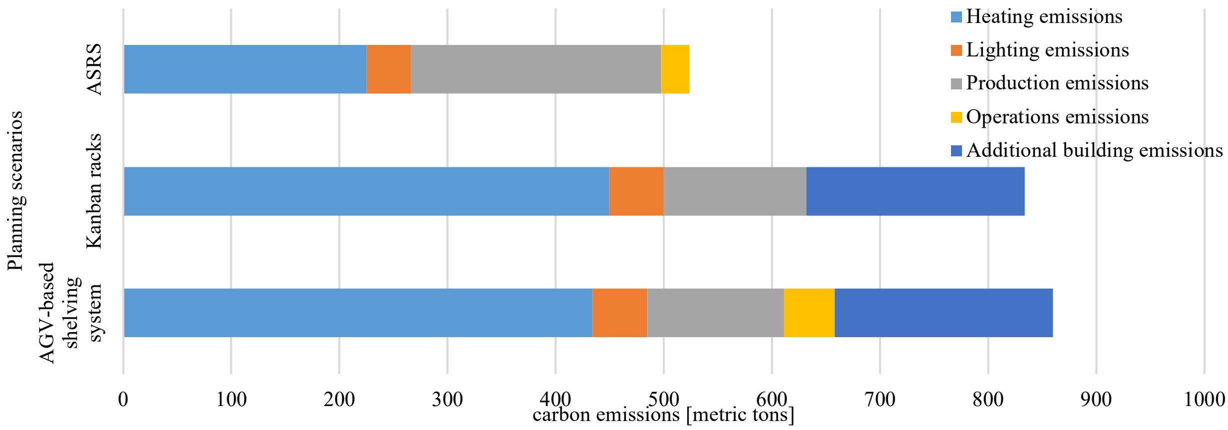

Figure 3: Carbon emissions calculated over a period of 10 years

5. Conclusion and outlook

The proposed model is a data-based method to be applied in the early planning phase of a logistics concept to estimate future carbon emissions. The model provides an approach to assess the carbon footprint of alternative storage technologies in warehouse planning projects. According to RQ1, the approach combines the dimensions heating, lighting, additional building, operational and production emission in a comprehensive calculation method. These dimensions cover the emissions resulting from the construction and production of storage technologies as well as emissions of the warehouse operations. Within the dimensions, the model allows the comparison of alternative storage technologies by determining the energy consumptions and applying carbon equivalent values in a structured approach (RQ2). The combined emissions calculated for each storage technology indicate the overall carbon footprint per planning scenario. To carry out this evaluation building-related, SKU-related and storage technology-related inputs are needed.

The model was applied on a dataset resulting from a practical warehouse planning project to compare competing storage technologies for small parts in standard boxes. The results show a lowest carbon footprint for an ASRS solution and a highest footprint for an AGV-based shelving system. The major reasons were the low heating emissions in the ASRS scenario due to smallest building surface required by the utilization of the full storage height, the additional building surface required for AGV-based shelving system and Kanban racks. From these investigations, it can be noted that automated solutions with high surface densification can result in a lower overall carbon footprint. With rising costs for carbon emissions, the lower carbon footprint systems like ASRS might have an impact on investment decisions in the planning phase of warehouses.

For practical applications, this work offers a manageable and structured approach for accounting carbon footprints to alternative storage technologies. It can serve as a decisions support when it comes to the selection of a preferred planning scenario. The model opens the possibility to explore optimization potentials for operational emissions (lighting, heating, and operational transport emissions). Mitigation potentials (e.g., renewable energy sources) can be illustrated for emissions for additional building and production as these cannot be directly influenced.

However, the model is limited as sustainable logistics warehouse includes further aspects e.g., energy sources and waste management. Further, the market of storage technology for a specific type of SKU is very diverse with a manifold of different suppliers, providing different production and distribution methods. Due to very specific building electronics and machinery components like AGVs and conveying machines, a method of their dedicated carbon footprint cannot be delivered by this approach. To further validate the assumptions and calculations determined in this article, the sample size of case studies should be extended and more storage technologies for big and palatized parts must be included.

Future research activities will focus on applying the approach in further warehouse planning projects and thereby increase the sample size of available use cases. The model will be extended in terms of the production emissions to include further materials and processes especially for electronic components in storage technologies. It is planned to improve the validity of the model by simulation studies.

References

[1] Scheunemann, H., 2022. Logistics and Industrial Market Overview Germany: Demand significantly increased compared to the previous year. Jones Lang LaSalle. https://www.jll.de/en/trends-and-insights/research/logistics-and-Industrial-market-overview. Accessed 30 October 2022.

[2] Bartolini, M., Bottani, E., Grosse, E.H., 2019. Green warehousing: Systematic literature review and bibliometric analysis. Journal of Cleaner Production 226 (21), 242–258.

[3] Doherty, S., Hoyle, S., 2009. Supply Chain Decarbonization: The role of logistics and transport in reducing supply chain carbon emissions. Worlds Economic Forum, Geneva. https://www3.weforum.org/docs/WEF_LT_SupplyChainDecarbonization_Report_2009.pdf. Accessed 30 October 2022.

[4] Bundesregierung Deutschland, 2020. Incentives for fewer CO2 - carbon dioxide emissions: CO2 - carbon dioxide has its price. Bundesregierung Deutschland. https://www.bundesregierung.de/breg-en/issues/climate-action/fewer-co2-emissions-1797122. Accessed 1 November 2022.

[5] Cook, P., Sproul, A., 2011. Towards low-energy retail warehouse building. Architectural Science Review 54 (3), 206–214.

[6] Rai, D., Sodagar, B., Fieldson, R., Hu, X., 2011. Assessment of CO2 emissions reduction in a distribution warehouse. Energy 36 (4), 2271–2277.

[7] VDI 5200, 2011. Factory planning. Verein Deutscher Ingenieure.

[8] Hompel, M. ten, Schmidt, T., Nagel, L. (Eds.), 2007. Materialflusssysteme: Förder- und Lagertechnik, 3rd ed. Springer-Verlag Berlin Heidelberg, Berlin, Heidelberg.

[9] Martin, H., 2016. Transport- und Lagerlogistik: Systematik, Planung, Einsatz und Wirtschaftlichkeit, 10th ed. Springer Vieweg, Wiesbaden.

[10] Kreutzfeldt, J., Braun, P., Schyga, J., Hilbrich, S., Hinckeldeyn, J., 2019. Planning of large-scale logistics sites, in: Proceedings for 23. International Conference on Material Handling, Constructions and Logistics, pp. 1–10.

[11] Torabizadeh, M., Yusof, N.M., Ma'aram, A., Shaharoun, A.M., 2020. Identifying sustainable warehouse management system indicators and proposing new weighting method. Journal of Cleaner Production 248 (7), 119–130.

[12] Freis, J., Vohlidka, P., Günthner, W., 2016. Low-Carbon Warehousing: Examining Impacts of Building and Intra-Logistics Design Options on Energy Demand and the CO2 Emissions of Logistics Centers. Sustainability 8 (5), 448–484.

[13] Lewczuk, K., Kłodawski, M., Gepner, P., 2021. Energy Consumption in a Distributional Warehouse: A Practical Case Study for Different Warehouse Technologies. Energies 14 (9), 2709–2734.

[14] Elhedhli, S., Merrick, R., 2012. Green supply chain network design to reduce carbon emissions. Transportation Research Part D: Transport and Environment 17 (5), 370–379.

[15] Zajac, P., Kwasniowski, S., 2017. Zero energy buildings in the logistics warehouse systems, in: Proceedings of International Conference on Advances in Energy Systems and Environmental Engineering, pp. 1–8.

[16] Boenzi, F., Digiesi, S., Facchini, F., Mossa, G., Mummolo, G., 2016. Greening Activities in Warehouses: A Model for Identifying Sustainable Strategies in Material Handling, in: Proceedings of the 26th International DAAAM Symposium 2016, pp. 980–988.

[17] Carli, R., Digiesi, S., Dotoli, M., Facchini, F., 2020. A Control Strategy for Smart Energy Charging of Warehouse Material Handling Equipment. Procedia Manufacturing 42 (1), 503–510.

[18] Eder, M., Kartnig, G., 2018. Calculation method to determine the throughput and the energy consumption of S/R shuttle systems. FME Transaction 46 (3), 424–428.

[19] Lerher, T., Edl, M., Rosi, B., 2014. Energy efficiency model for the mini-load automated storage and retrieval systems. The International Journal of Advanced Manufacturing Technology 70 (1-4), 97–115.

[20] Rücker, A., Rief, J., Fottner, J., 2020. An investigation of mean energy demand, performance and reference cycles for stacker cranes. FME Transactions 48 (2), 307–312.

[21] Besler, M., Cepiński, W., Kęskiewicz, P., Skrzycki, M., 2019. Analysis of annual energy consumption by a warehouse building, in: Proceedings of the International Conference on Advances in Energy Systems and Environmental Engineering, pp. 1–8.

[22] Porras-Amores, C., Mazarrón, F., Cañas, I., 2014. Study of the Vertical Distribution of Air Temperature in Warehouses. Energies 7 (3), 1193–1206.

[23] Wang, L.L., Li, W., 2017. A study of thermal destratification for large warehouse energy savings. Energy and Buildings 153 (20), 126–135.

[24] Udara Willhelm Abeydeera, L.H., Wadu Mesthrige, J., Samarasinghalage, T.I., 2019. Global Research on Carbon Emissions: A Scientometric Review. Sustainability 11 (14), 3972–3997.

[25] Bank, R., Murphy, R., 2013. Warehousing Sustainability Standards Development, in: Prabhu, V., Taisch, M., Kiritsis, D. (Eds.), Advances in Production Management Systems. Sustainable Production and Service Supply Chains, vol. 414. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 294–301.

[26] Ambroziak, T., Jachimowski, R., Pyza, D., Szczepański, E., 2014. Analysis of the traffic stream distribution in terms of identification of areas with the highest exhaust pollution. Archives of Transport 32 (4), 7–16.

[27] Jacyna, M., Wasiak, M., Kłodawski, M., Lewczuk, K., 2014. Simulation model of transport system of Poland as a tool for developing sustainable transport. Archives of Transport 31 (3), 23–35.

[28] Ember Climate, 2022. Germany. Ember Climate. https://ember-climate.org/countries-and-regions/countries/germany/. Accessed 30 October 2022.

[29] Ridder-Hans, G., 2020. Case Study Research: Approaches, Methods, Contribution to Theory, 2nd ed. Rainer Hampp Verlag, Augsburg, München, 234 pp.

Biography

Philipp Braun, M. Sc. (*1992) is a research associate at the Institute of Technical Logistics at Hamburg University of Technology. Philipp Braun completed his studies in industrial engineering with a focus on information technologies and logistics at Hamburg University of Technology in 2020.

Hendrik Rose, M. Sc. (*1994) is a research associate at the Institute of Technical Logistics at Hamburg University of Technology. Hendrik Rose completed his studies in industrial engineering with a focus on general engineering science and logistics at Hamburg University of Technology in 2020.

Niklas Hesslein, M. Sc. (*1995) is a research associate at the Institute of Technical Logistics at Hamburg University of Technology. Niklas Hesslein completed his studies in industrial engineering with a focus on logistics at Hamburg University of Technology in 2019.

Harsha Vadapalli, B. Sc. (*1998) is a student assistant at the Institute of Technical Logistics at Hamburg University of Technology. Harsha Vadapalli studies Mechanical engineering and management since 2019.

Johannes Hinckeldeyn, Dr. (*1979) is Chief Engineer at the Institute of Technical Logistics at Hamburg University of Technology followed his PhD in the UK, Johannes Hinckeldeyn served as Chief Operating Officer for a manufacturer of measurement and laboratory technology for battery research. Johannes Hinckeldeyn studied business engineering, production engineering and management in Hamburg and Münster.

Jochen Kreutzfeldt, Prof. Dr.-Ing. (*1959) is Professor and Head of the Institute for Technical Logistics at Hamburg University of Technology. After studying mechanical engineering with a focus on production engineering, Jochen Kreutzfeldt held various executive positions within a company specializing in automotive safety technology. Subsequently, Jochen Kreutzfeldt took over a professorship for logistics at the Hamburg University of Applied Sciences as head of the Institute for Product and Production Management.

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Digital Twin in the Battery Production Context for the Realization of Industry 4.0 Applications

Robert Ludwigs[1], Jessica Schmied[1], Henning Clever[1], Heiner Heimes[1], Achim Kampker[1]
[1]*Chair of Production Engineering of E-Mobility Components (PEM) of RWTH Aachen, Aachen, Germany*

Abstract

Due to the worsening climate change drastic changes in the transportation sector are necessary. Crucial factors for sustainable energy supply are reliable and economical energy storage systems. Associated with that is the development of giga factories with a capacity of up to 1000 GWh in 2030 in Europe (currently 25 GWh) for the production of battery cells especially for the automotive sector, which is one of the largest emitters of greenhouse gases in Europe. In addition to the required investments, high scrap rates due to unknown interdependencies within the process chain represent a central challenge within battery cell production. Another key challenge in series production is the product tracking along the value chain, which consists of continuous, batch and discrete processes. Because of its complexity the battery cell production industry is predestined for Industry 4.0 applications in order to meet the current challenges and to make battery cell production more efficient and sustainable. Digital twins and the use of AI algorithms enable the identification of previously unknown cause-effect relationships and thus a product improvement and increased efficiency. In this paper, the digital twin of a battery cell production will be developed. For this purpose, general requirements for the field of battery cell production are first determined and relevant parameters from the literature as well as from a production pilot line are defined. Based on the requirements and the selected parameters a corresponding structure for the digital twin in battery cell production is built and explained in this contribution. This provides the basis for measures to optimize production, such as predictive quality.

Keywords

Battery Cell Production; Industry 4.0; Digital Twin; Production Efficiency; Electromobility

1. Introduction

This paper presents a possible concept for the realization of a digital twin in the context of battery production. The focus lies on the digital twin of the battery cell and its components. Scrap rates in battery cell production are significantly higher than in other highly automated industries [1,2]. A major cause of this is a lack of understanding of interactions between process and product quality. A tool for the investigation and analysis of such interactions is the digital twin. The information model developed in this paper is intended to serve as the basis for the software implementation of a standardized digital battery cell twin. Among other things, this will enable standardized access to cell data and reduce the effort required to analyze large volumes of cell data. One challenge in the development of a digital cell twin arises from the fact that both the properties of the cell and the requirements for the digital twin change over the life cycle of the battery cell. As a result, the digital twin may differ in its characteristics compared to the real object and depending on the use case. In some cases, a real (interim) object can also be represented by several digital twins. In the context of product development, a battery cell twin is used to predict the subsequent cell parameters [3]. In the operation

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of a battery system of an electric vehicle, a battery cell twin can be used to predict the remaining lifetime based on current cell data or the twin can be used to control an optimal operation of the cell [4].

2. State-of-the-Art

2.1 Digital Twins in the Production Context

In the course of the digital transformation towards Industry 4.0, the digital twin is one of the frequently used terms in research and industry. However, there is no uniform technical understanding in the specialist community. It is apparent that there is no standardized digital twin and that its concrete form depends on the "positioning in the lifecycle, the use cases and business models" [5]. However, experts agree that, according to the original definition by GRIEVES, it is a virtual image of the reality [6]. The digital twin serves as a digital model for the abstract description of a class of physical units (e.g. product, machine, etc.) and its informations as well as the simulation for the prediction and optimization of the behavior of the performance characteristics [5]. A key requirement for digital twins, included in most definitions, is the ability to run scenarios and try out alternatives. These are often basic simulation models - in the case of production systems - event-based discrete flow simulation models [7].

Only in recent years the term simulation has gained acceptance in the production environment [8], whereas prior to 2017 it did not necessarily mean simulation, but rather the digital capture of all associated data [9]. This newer definition is adopted in the context of this paper. The digital twin is not to be confused with the digital shadow, which is referred to in other sources as a system for pure data acquisition without control by a simulation[10]. In the context of this paper, the digital shadow is not considered further.

2.2 LIB Manufacturing

The production of battery cells can be divided into the three steps of electrode manufacturing, cell assembly and cell finishing [11,12]. Figure 1 shows the different process steps and equipment for the production of lithium-ion cells in pouch format based on the pilot line of the eLab at RWTH Aachen University. The electrode manufacturing consists of a dry and a wet mixing process, in which the slurry for anode and cathode is produced. The slurry is coated onto current conductor foils (copper for anode, aluminum for cathode) and then convection or laser dried before entering the calendering process [13,14]. During the cell assembly, the electrodes are conveyed to the mechanical stamping line where they are cut into individual electrode sheets. The sheets are stacked (Z-folded) and contacted by ultrasonic welding. The cell stack is then placed in a thermoformed pouch foil and filled with electrolyte under vacuum and subsequently sealed. In the last phase, the cells proceed through the formation and aging step in a climate-controlled chamber, where they undergo the initial electrical loading and unloading, as well as quality testing over several days [15].

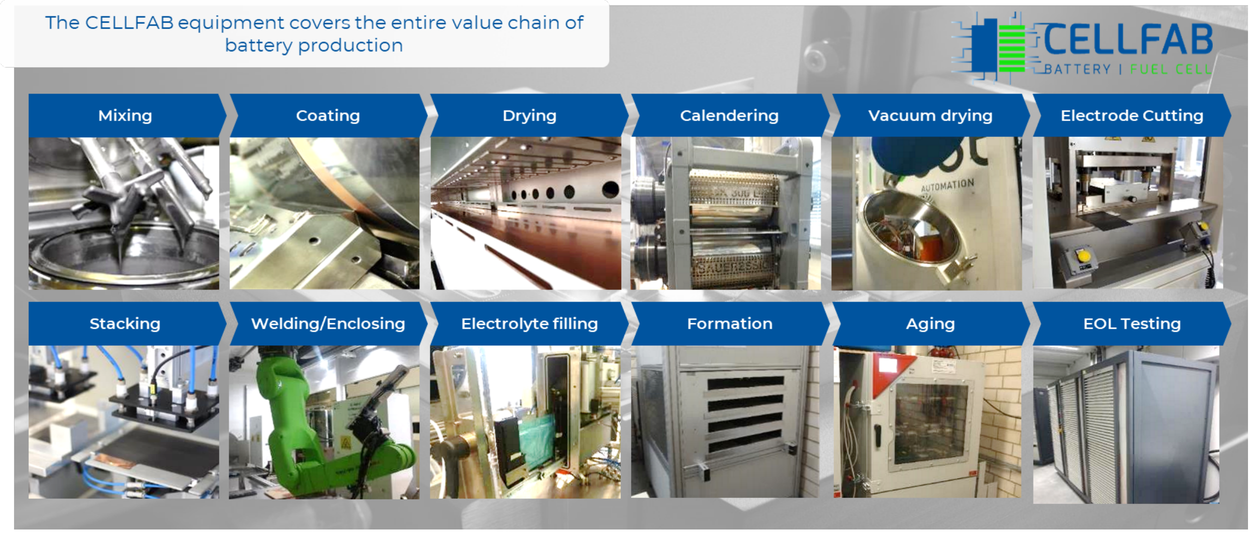

Figure 1: Process steps in battery cell production at the eLab of RWTH Aachen University

2.3 Digital Twins in LIB Manufacturing

In the field of battery production, there are currently only a few concepts concerning the digital twin, which will be analyzed in this section. KIES ET AL. identified, tracked and modeled 118 Parameters in the electrode production [16]. Example parameters are particle size, weight of the electrodes at the end of the production line and input materials. The aim of collecting these parameters is to create a traceability system which allows the production owner the best possible overview for each cell which results in a more realistic reflection of the battery systems' performance [17,18]. ROHKOHL ET AL. used the principle of a digital twin in the anode mixing [19]. They implemented a Gaussian Model which fitted to the actual dosage rates to their expected values during operation. After training and fitting the gaussian model to the actual dosage rate distribution the AI could approximate the expected distribution for a specific process parameter set. This leads to an increase in the mixing process stability. With the tool "Roboguide" from RobotStudio it is possible to create a digital twin of a cell stacking robot. Running a simulation of the digital twin of the process allows detecting collisions between robots and other objects, simulate the payload capacity of the robot and evaluate and optimize time taken for a sequence of movements in the cell stacking process [20]. AYERBE ET AL. review modelling approaches and analyze how they can be combined with data acquisition instruments and communications protocols in order to present a framework for building a digital twin. However, many challenges, including the setting of standards regarding models and data reporting remain unsolved [21]. Big players recognize the potential of the digital twin as well. Northvolt and Siemens reached a cooperation agreement to build an intelligent battery manufacturing plant and apply digital Twin to set up a product life management system based on closed-loop manufacturing [22]. Overall, the literature research revealed a missing product focus along the whole production chain. Furthermore, the predictive quality aspect of the cell within the digital twin is missing in the literature. What stands out in the research is a missing standard for the digital twin in the battery production. None of the sources established or used a standard in their works. This paper addresses this specific research deficit and presents a possible approach.

3. Information Model for a Digital Cell twin

The complexity of a digital battery cell twin differs greatly depending on what is to be achieved with the help of the twin. For example, a digitized BoM (Bill of Materials) that is updated automatically can already be defined as a part of the digital twin [23]. A digital BOM offers companies a simplified management of products and operations. Specific requirements are placed on a twin in the production context, which are explained below. In the first subchapter, the general structure of the digital twin and its information model is presented in detail. Subsequently, the general twin is subdivided into sub-twins based on the production requirements. This is required considering the intermediate products and corresponding quality. Finally, the connection between the digital battery cell twin and the plant twin is displayed.

There are already some publications dealing with the digital twin in battery cell production, such as KORNAS ET AL., TURETSKYY ET AL., AYERBE ET AL. and SCHNELL ET AL. [21,24–26]. In contrast to the first two papers, the present paper shows a structuring of data which takes place following a real object. For this purpose, sub-twins are introduced. On the one hand, this structured collection facilitates the interpretation of the data by humans. On the other hand, the standards simplify the feeding of data from production as well as the access to this data for analysis purposes. AYERBE ET AL. present a very comprehensive framework in which especially the modeling as well as the communication between plant and product are in the foreground. However, a concrete information model for the digital product twin is missing. In contrast to SCHNELL ET AL., a stronger structuring of the data takes place in the digital twin. In general, the present information model also integrates geometric and material data into the twin, which are partially insufficiently considered in other twins. These enables a better comparability of the production data from different production sites.

3.1 Structure of the Digital Twin

A digital twin is supposed to monitor the real object throughout its entire life cycle, from the sourcing of raw materials to development and recycling (Figure 2).

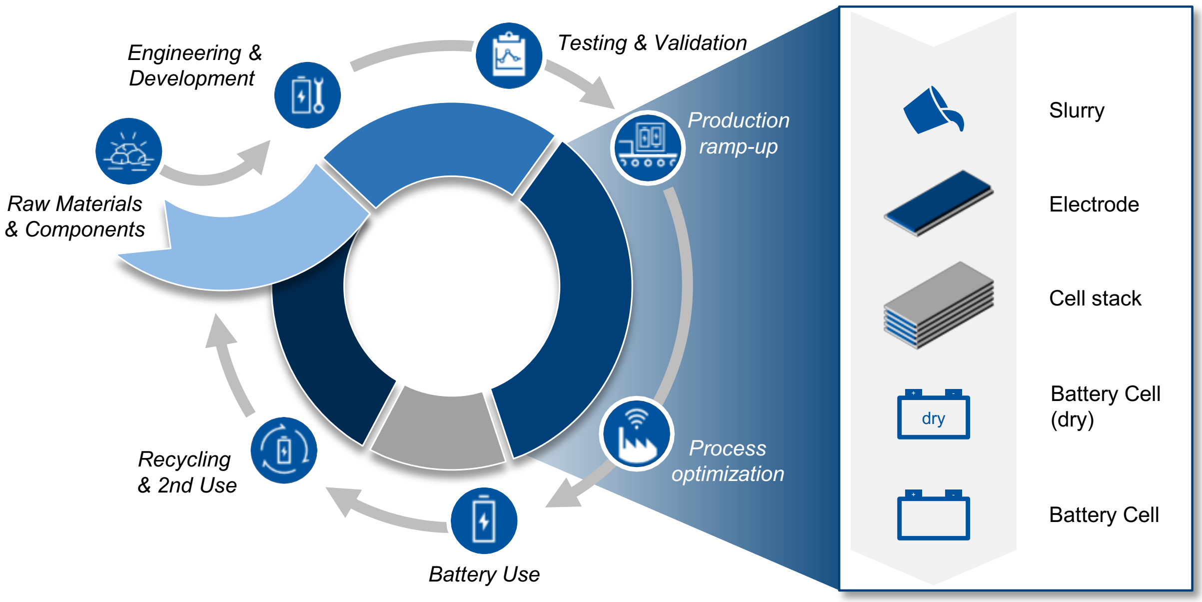

Figure 2: Battery Life cycle (left) and sub-twins during the production process (right)

The focus of this work is on the application of digital twins in the production context. The underlying use case is predictive quality. Predictive quality is a method that allows the prediction of the final product quality based on current information taken from the production process. For example, the quality of battery electrodes can be predicted already in the mixing process step, where the slurry is mixed [3]. Predictive quality allows errors to be detected at an early stage and reduction of defects as well as rework [27]. For battery production, this means that quality characteristics of the finished battery cell should already be determined and influenced in upstream production steps based on intermediate products. Predictive quality is of major relevance to battery cell production because rework is not possible in the production process. This is due to the many coating, wetting, cutting and joining manufacturing processes, which cannot be corrected in practice. Digital twins are particularly suitable for the implementation of predictive quality use cases. The basis of such a digital twin is a comprehensive and standardized data-based description of the real object [28]. In order to realize such a data-based description, an information model must first be created, which defines the structure for storing all relevant product data [29]. An example for the structure of an information model for a battery cell is shown in Figure 3.

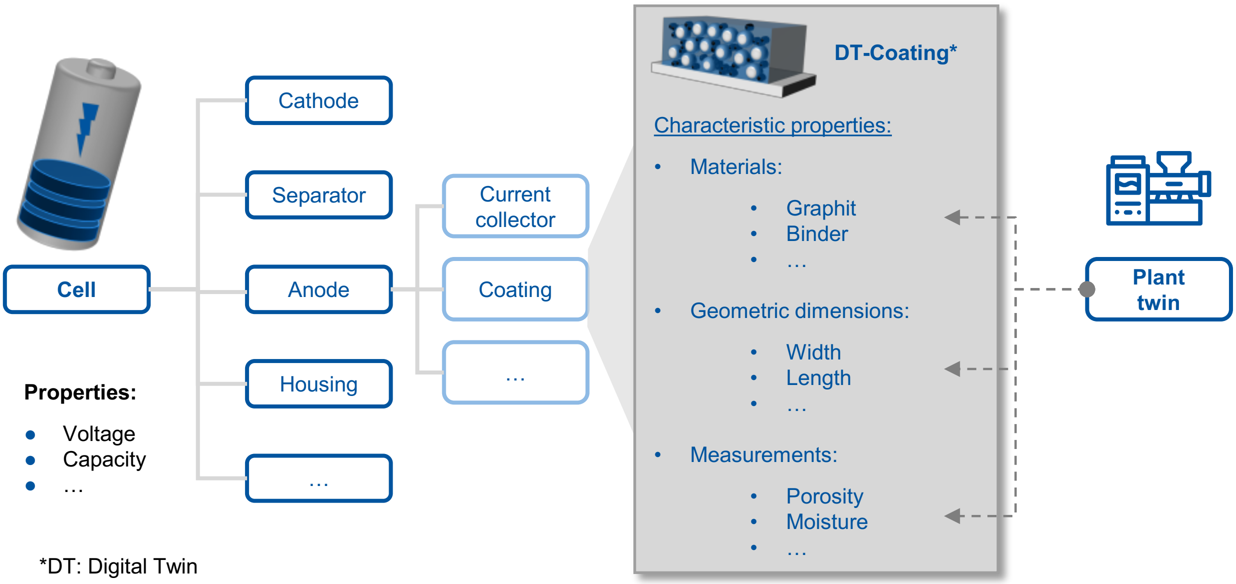

Figure 3: Information model for a lithium-ion battery cell and interface to plant twin

The data structure corresponds to the physical structure of the real object. In a first step, the battery cell object is divided into its central components. These include, for example, the two electrodes (cathode and anode), the separator and the housing. In a second stage, the components of the cell are further subdivided. For example, the anode consists of an anode collector and a coating. Specific product properties are assigned to the subcomponents at this level in a second structuring step. In this process, all characteristic features necessary for a complete description of the object are to be recorded. These characteristics can be divided into material properties, geometric characteristics, and measured values. Geometric features are defined as all features that characterize the dimensions and shape of the product. Material properties include all properties that describe the material, such as material type and proportions. The last category, measured values, includes all characterizing data of the physical object, which are measured during the process or are given based on data sheets. In particular, the category measured values was chosen for this information model with the background that the cell twin was developed for production. For this purpose, the twin is to be fed by data from production, which are measured inline or offline. The structure shown in Figure 3 represents a kind of container, which is successively filled with data during the production process. The system can be compared to that used in object-oriented programming. The battery cell represents a class. In this class, the cell characteristics are defined by attributes or instance variables, as in programming [30]. For each new produced cell now, an object of the class battery cell is created, which has the same attributes as the other objects of the class battery cell. The goal of this structuring is on the one hand to reduce the complexity of a cell-associated database, on the other hand, to realize a logical division of the data. The standardized storage of the data enables the implementation of APIs with the help of which simulation programs and AI-based analyses can be automated. In addition, the standardization enables automated allocation and retrieval of data. The modularity of the structure also allows the model to be extended if new parameters are added or removed. This may be the case, for example, with new technologies such as solid-state batteries. Another advantage of the information model is the ability to filter the stored data by specific components. For example, electrodes of several battery cells can be compared with little effort. A fixed structure also allows the definition of interfaces to other twins, such as those of intermediate products or the production infrastructure.

3.2 Subdivision into Sub-Twins for the Requirements in Production

For the digital twin of battery cells in the production context, a subdivision of the cell twin into so-called sub-twins is reasonable. This is done on the background that the semi-finished products such as slurry or electrode stacks change fundamentally in cell production until the end of cell finalization and thus the data-based description also undergoes fundamental changes. For example, the data-based description of slurry, which is at the beginning of the process, is not possible with an information model for a coated electrode or even finished battery cell. However, the sub-twins are not to be considered in isolation but serve as suppliers of data for the final cell twin and are thus part of it in the overall context.

Thus 5 sub-twins in the course of production can be defined as shown in Figure 2: Slurry, electrode coil, cell stack, cell (dry) and battery cell. A new information model is necessary in each case when the object properties change fundamentally, for example through the addition of a new component. In the step from the electrode coil to the cell stack, for instance, the separator is added. This structuring is important because data is transferred, added, or dropped from one sub- twin to the next until the final battery cell twin is created. For further instance, the particle size distribution of the twin slurry is transferred to the twin electrode, but the characteristic slurry viscosity does not longer exist in the case of the (dried) electrode. The stacking accuracy is an example of a characteristic that is added in the stacking process step and did not exist previously. To explain it again in the image of object-oriented programming, the individual sub-twins represent different classes, which are characterized by different attributes. Beyond that a subdivision is important, to be able to establish connections between different characteristics. For example, the coating no longer has a (relevant) viscosity, but conclusions can be drawn from the quality of the coating to the viscosity. This requires linking the data set with simulations.

3.3 Connection Cell Twin Plant Twin

The basis of a digital twin is the data set available for it. To create this, the database of the twin must be filled with corresponding data according to the structure of the information model from Chapter 3.1 and 3.2. Sources used as input can be data sheets, CAD models, measurement results (offline and online) or process parameters. In order to be able to transfer the data to the twin, corresponding interfaces must be defined for the twin of the battery cell or its intermediate products.

For the exchange of data with the production infrastructure, a standardized structured database and corresponding interfaces must also be available on the production side. A corresponding information model could have the structure shown in Figure 4. This can also be the basis for a digital plant or process twin.

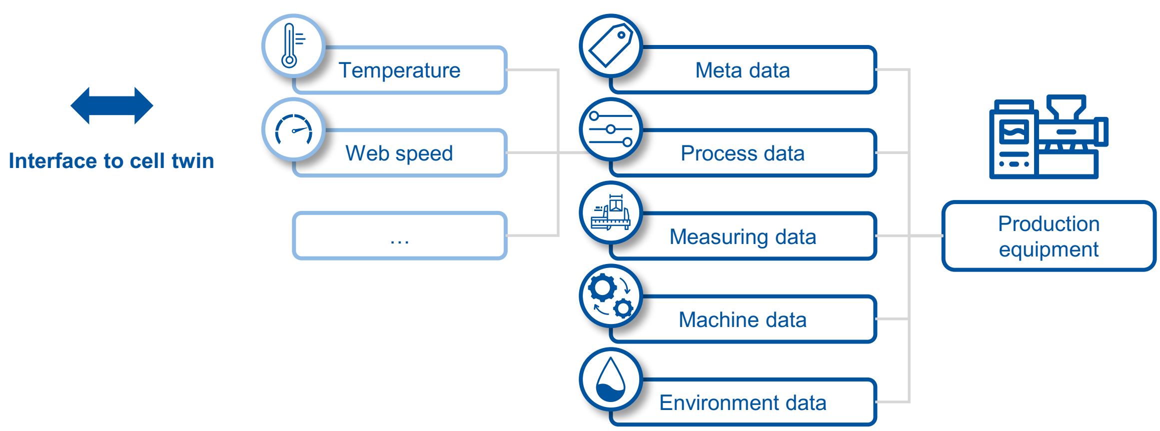

Figure 4: Potential Data model for production equipment (plant twin) and interface to battery cell twin

The two categories of process and measurement data are particularly relevant as an input for the product twin since these data have a direct influence on the product or characterize it. Process data is defined as data that can be set on the machine and characterize the process, such as temperature, web speed or mixing time.

Measured data are features that serve to characterize the processed product, such as coating thickness or viscosity. Data of other categories play a subordinate role for the predictive quality application, which is why they will not be discussed further here.

4. Using the Twin in Battery Cell Production

The information model can be converted into a defined data structure using the Asset Administration Shell (AAS). This is intended to become the standard for the implementation of digital twins within the framework of Industry 4.0 [31]. It provides the possibility to describe an object digitally. In addition, the AAS has interfaces so that instances can be mapped to OPC UA or MQTT. The AAS Explorer is available for free on GitHub.

One potential use case for the digital cell twin in association with predictive quality, which has been established prototypically in a battery production line at the RWTH Aachen University, is the prediction of coating thickness in electrode production (Figure 5). To meet the requirements of the development departure that defines certain cell specifications and to be able to guarantee a certain quality, the thickness of the coating must be homogeneous and within fixed tolerance limits. The homogeneity and thickness of the coating depends to a large extent on the quality of the used slurries as well as the coating equipment. In order to reduce rejects at an early stage, the quality of the produced electrode is to be predicted with the aid of simulations. The simulation is based on the data of the slurry twin as well as the plant twin. As plant twin in this context is meant a digital twin of the production equipment. If necessary, adjustments were made to the slurry (e.g., recipe) and the system settings (e.g., mixing speed) based on the simulation results. Integration of such a simulation on an edge device connected to the PLC could enable a closed loop process optimization. As a result, electrode quality is to be increased and scrap reduced at an early stage.

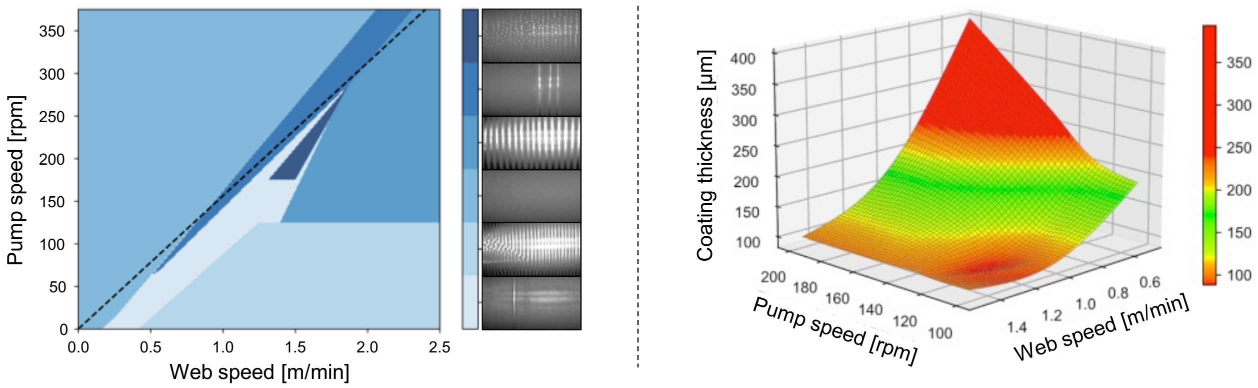

Figure 5: Machine learning based prediction of coating patterns (left) and coating thickness (right)

5. Conclusion and Outlook

This study has shown how production oriented digital twin approaches can be used to implement predictive quality battery cell production. The presented paper defines individual (sub)cell-twins that represent different intermediate products in production. These specific attributes of the sub-twin are assigned to in a structured way. However, in order to have a complete digital battery cell twin, an interface to the plant twin is necessary. With this information, the processed product can be fully characterized and provides the basis for prediction of product quality in subsequent process steps is possible. The use of digital twin models enables the determination of effects of individual parameters on cell quality and the corresponding product characteristics. With the help of this approach, an adaptive production control can be implemented in a use-case. In addition, the simulation of cell quality during production serves as a decision-making basis for the introduction of changes in production. As a next step of research, the approach should be implemented and tested in further battery production situations on a pilot scale. If the results from the pilot manufacturing runs are reproducible in industrial production environments, the approach would help to improve the product quality and decrease the scrap rate. For the implementation of the predictive quality use case, the information model presented here must be adapted depending on the production equipment and the existing database. One challenge is the accuracy of the simulations. These must be able to predict real processes with high accuracy. Otherwise, the adjustments to the production parameters will not lead to quality improvements. A closed loop control of the machines based on simulation results also requires direct and automated access to the machine control system, which represents a challenge from a safety perspective.

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References

[1] Duffner, F., Mauler, L., Wentker, M., Leker, J., Winter, M., 2021. Large-scale automotive battery cell manufacturing: Analyzing strategic and operational effects on manufacturing costs.

[2] Kehrer, M., Locke, M., Offermanns, C., Heimes, H., Kampker, A., 2021. Analysis of Possible Reductions of Rejects in Battery Cell Production during Switch-On and Operating Processes. Energy Technol. 9 (7), 2001113.

[3] Robert Schmitt, Reiner Kurzhals, Max Ellerich, Guido Nilgen, Norberg Miller, 2020. Predictive Quality - Data Analytics in produzierenden Unternehmen, in: , Internet of Production - Turning Data into Value, pp. 226–253.

[4] Singh, S., Weeber, M., Birke, K.P., 2021. Implementation of Battery Digital Twin: Approach, Functionalities and Benefits. Batteries 7 (4), 1–21.

[5] Eigner, M., 2020. Digitaler Zwilling – Stand der Technik. Zeitschrift für wirtschaftlichen Fabrikbetrieb 115 (s1), 3–6.

[6] Grieves, M., Vickers, J., 2017. Digital twin: Mitigating Unpredictable Undesirable Emergent Behavior in Complex Systems, in: , Transdisciplinary Perspectives on Complex Systems: New Findings and Approaches. Springer International Publishing, pp. 85–113.

[7] Overbeck, L., Rose, A., May, M., Lanza, G., 2022. Nutzungskonzept für Digitale Zwillinge von Produktionssystemen. Zeitschrift für wirtschaftlichen Fabrikbetrieb 117 (4), 244–248.

[8] Cimino, C., Negri, E., Fumagalli, L., 2019. Review of digital twin applications in manufacturing. Computers in Industry 113, 103–130.

[9] Negri, E., Fumagalli, L., Macchi, M., 2017. A Review of the Roles of Digital Twin in CPS-based Production Systems. Procedia Manufacturing 11, 939–948.

[10] Stark, R., Kind, S., Neumeyer, S., 2017. Innovations in digital modelling for next generation manufacturing system design. CIRP Annals 66 (1), 169–172.

[11] Duffner, F., Kronemeyer, N., Tübke, J., Leker, J., Winter, M., Schmuch, R., 2021. Post-lithium-ion battery cell production and its compatibility with lithium-ion cell production infrastructure. Nat Energy 6 (2), 123–134.

[12] Korthauer, R., 2013. Handbuch Lithium-Ionen-Batterien. Springer Berlin Heidelberg, Berlin, Heidelberg.

[13] Heimes, H., Kampker, A., vom Hemdt, Ansgar, Kreisköther, Kim, Michaelis, S., Rahimzei, E., 2019. Komponentenherstellung einer Lithium-Ionen-Batteriezelle. https://www.pem.rwth-aachen.de/global/show_document.asp?id=aaaaaaaaaffplpx.

[14] Kampker, A., Vallée, D., Schnettler, A., 2018. Elektromobilität. Springer Berlin Heidelberg, Berlin, Heidelberg.

[15] Kwade, A., Haselrieder, W., Leithoff, R., Modlinger, A., Dietrich, F., Droeder, K., 2018. Current status and challenges for automotive battery production technologies. Nat Energy 3 (4), 290–300.

[16] Kies, A., Krauß, J., Baum, C., Schmitt, R., 2021. Traceability ermöglicht den digitalen Zwilling: Digitalisierung in der Batteriezellfertigung. IT&Production 3. https://www.it-production.com/wp-content/uploads/dlm_uploads/2021/04/ITProduction_3_April_2021.pdf.

[17] Augustine, P., 2020. The industry use cases for the Digital Twin idea, in: , The Digital Twin Paradigm for Smarter Systems and Environments: The Industry Use Cases, vol. 117. Elsevier, pp. 79–105.

[18] Kaus, D., Singh, S., Wanner, J., Weeber, M., Birke, K.P., 2020. Digitalization in Battery Cell Manufacturing. Symposium Energieinnovation 16, Graz. https://www.tugraz.at/fileadmin/user_upload/tugrazExternal/4778f047-2e50-4e9e-b72d-e5af373f95a4/files/lf/Session_H4/846_LF_Kaus.pdf.

[19] Rohkohl, E., Schönemann, M., Bodrov, Y., Herrmann, C., 2022. A data mining approach for continuous battery cell manufacturing processes from development towards production. Advances in Industrial and Manufacturing Engineering 4 (3), 100078.

[20] Ajit Sharma, 2022. Digital Twin for Scaling up EV Battery Production Using Robots.

[21] Ayerbe, E., Berecibar, M., Clark, S., Franco, A.A., Ruhland, J., 2022. Digitalization of Battery Manufacturing: Current Status, Challenges, and Opportunities. Advanced Energy Materials 12 (17), 2102696.

[22] Wigardt, J., Stauß, G., 2018. Siemens und Northvolt Partner für die Produktion modernster Lithium-Ionen-Batterien, Nürnberg.

[23] Botín-Sanabria, D.M., Mihaita, A.-S., Peimbert-García, R.E., Ramírez-Moreno, M.A., Ramírez-Mendoza, R.A., Lozoya-Santos, J.d.J., 2022. Digital Twin Technology Challenges and Applications: A Comprehensive Review. Remote Sensing 14 (6), 1–25.

[24] Kornas, T., Knak, E., Daub, R., Bührer, U., Lienemann, C., Heimes, H., Kampker, A., Thiede, S., Herrmann, C., 2019. A Multivariate KPI-Based Method for Quality Assurance in Lithium-Ion-Battery Production. Procedia CIRP 81, 75–80.

[25] Schnell, J., Nentwich, C., Endres, F., Kollenda, A., Distel, F., Knoche, T., Reinhart, G., 2019. Data mining in lithium-ion battery cell production. Journal of Power Sources 413, 360–366.

[26] Turetskyy, A., Wessel, J., Herrmann, C., Thiede, S., 2021. Battery production design using multi-output machine learning models. Energy Storage Materials 38, 93–112.

[27] Purdue University Graduate School (Ed.), 2022. Predictive Quality Analytics. Springer, Cham.

[28] Kies, A.D., Krauß, J., Schmetz, A., Schmitt, R.H., Brecher, C., 2022. Interaction of Digital Twins in a Sustainable Battery Cell Production. Procedia CIRP 107, 1216–1220.

[29] Stark, R., Damerau, T., 2019. Digital Twin, in: , CIRP Encyclopedia of Production Engineering. Springer, Berlin, Heidelberg, pp. 1–8.

[30] Sage, K., 2019. Getting into Object Oriented Programming, in: , Concise Guide to Object-Oriented Programming. Springer, Cham, pp. 37–56.

[31] Wagner, C., Grothoff, J., Epple, U., Drath, R., Malakuti, S., Gruner, S., Hoffmeister, M., Zimermann, P., 2017. The role of the Industry 4.0 asset administration shell and the digital twin during the life cycle of a plant, in: 2017 22nd IEEE International Conference on Emerging Technologies and Factory Automation. September 12-15, 2017, Limassol, Cyprus. 2017 22nd IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), Limassol. 9/12/2017 - 9/15/2017. IEEE, Piscataway, NJ, pp. 1–8.

Biography

Robert Ludwigs *(*1993) is research assistant at the Chair of Production Engineering of E-Mobility Components (PEM) at RWTH Aachen University. He studied mechanical engineering with a specialization in production technology at RWTH Aachen University.*

Jessica Schmied *(*1995) is research assistant at the Chair of Production Engineering of E-Mobility Components (PEM) at RWTH Aachen University. She studied mechanical engineering with a specialization in production technology at RWTH Aachen University.*

Henning Clever *(*1992) is research associate at the Chair of Production Engineering of E-Mobility Components (PEM) at the RWTH Aachen University since 2019 and group lead for the research group Battery Production Management since 2021. He studied mechanical engineering specializing in production engineering at the RWTH Aachen University.*

Heiner Hans Heimes *(*1983) studied mechanical engineering with a focus on production engineering at RWTH Aachen University. From 2015 to 2019, he was head of the Electromobility Laboratory (eLab) of RWTH Aachen University and chief engineer of the newly established chair "Production Engineering of E-Mobility Components" (PEM). Since 2019, Dr.-Ing. Heimes has held the role of executive engineer of the PEM facility.*

Achim Kampker *(*1976) is head of the chair "Production Engineering of E-Mobility Components" (PEM) of RWTH Aachen University and known for his co-development of the "StreetScooter" electric vehicle. Kampker also acts as member of the executive board of the "Fraunhofer Research Institution for Battery Cell Production FFB" in Münster. He is involved in various expert groups of the federal and state governments.*

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Proposing A Cyber-Physical Production Systems Framework Linking Factory Planning And Factory Operation

Adrian Langer[1], Christian Ortmeier[1], Tim Abraham[1], Christoph Herrmann[1]

[1]*Institute of Machine Tools and Production Technology / Chair of Sustainable Manufacturing and Life Cycle Engineering / Technische Universität Braunschweig, Langer Kamp 19b, 38106 Braunschweig, Germany*

Abstract

The challenges for industrial companies in the area of factory planning and operation are characterised on the one hand by permanently shortening product life cycles and increasing product diversity. Furthermore, the demand for ecologically sustainable processes is growing and the complexity of production systems is increasing due to higher product complexity. This results in a complex decision-making space for companies within factory planning and factory operation which is difficult to plan. The advancing digitalisation can bring a great opportunity here. Modelling and simulation can create greater transparency in the context of planning and operation, and processes can be designed to be ecologically sustainable and efficient. Currently, research approaches in the context of factory planning and operation are focussing on the application and use of digital methods and tools of the Digital Factory (DF). However, the application is limited to individual areas in factory planning or factory operation.

For this reason, this paper focuses on the design of a framework that addresses both factory planning and factory operation aspects and links them through modelling and simulation. Cyber-physical production systems (CPPS) can help here by mapping the individual modules within planning and operation using individual agents in agent-based simulation (AB). By linking planning and real data, the processes from planning and operation can be taken into account. From this, insights gained from planning can be simulated in an early phase and subjected to optimisation during operation. The cycle-oriented CPPS can be used on an ongoing basis by preparing the generic building blocks on the planning and operational sides through structured data acquisition and implementing them in the real world with the help of decision support from the virtual world.

Keywords

Factory Planning; Factory Operation; Cyber-Physical Production System, Agent-Based Simulation, Framework

1. Introduction

Shorter product life cycles, volatile market conditions, customer demands for individualized products and increasingly stringent environmental regulations in conjunction with growing scarcity of energy and resources are contributing to a turbulent environment with which companies are confronted [1]. The configuration of value chains in factories is additionally subject to an immensely increased complexity of planning tasks. Dynamic and cooperative value networks result in a frequent change of production requirements, which necessitates both an increased planning speed and an increased planning frequency of the production systems [2], [3]. Factory planning and factory operation face these challenges with a targeted, ongoing adaptation of production systems using methods and tools of digitalization, Industry 4.0 and Digital

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Factory (DF). Of great importance in this context are modeling and simulation for decision support in the planning and operating processes of new (greenfield) and rescheduled (brownfield) factories [2], [4]. However, it should be noted that the use of simulation technology often requires expert knowledge and is associated with high time and financial expenditure, which is why such applications are often still limited in companies despite the enormous potential benefits [5]. As a result, manufacturing companies are always faced with the dilemma of potentially reducing planning times on the one hand and the time and financial effort required to create sufficiently accurate simulation models on the other. In addition, the successful and efficient implementation of simulation projects requires a very good and up-to-date data and models representing the current state of production, both are often not yet available [6], [7]. The aspect of the transfer and reuse of models beyond the respective application context also takes on an important role. At the moment, there is still a need for action in industry and research and thus potential for optimization in the process-related, organizational and structural interface between factory planning and factory operation [8].

While a large number of approaches and frameworks exist in the context of production system modeling and holistic factory modeling, a framework for the coupling of planning and operation through the transfer of simulation models for production systems is not yet available in the literature. In particular, the procedure for initializing the models on the basis of planning data and the subsequent extension to the use of real data and thus a real representation of the production system is a central challenge for today's companies. In this context, the data basis should ensure a high degree of topicality, availability as well as quality, so that the input for simulation models is promising. In the area of modeling and simulation, the design of generic, adaptive building blocks (e.g. agent-based simulation (AB)) is a central aspect for the holistic use of simulation models.

In order to support the continuous development up to the further use of the simulation models, a Cyber-physical production systems (CPPS) approach from factory planning to operation is necessary. In the following, a framework is described that, starting from greenfield planning projects, supports the continuous development of simulation models up to operation into a tool that can be used for planning and operation. The cycle of the CPPS is particularly suitable in this framework, since in the later course brownfield changes in the production system follow a recurring cycle. Based on this approach, planners and operators are able to work in a common simulation model and implement changes in the production system in a common network. From this, findings from the planning can be transferred to the operation, but in addition, feedback from the operation to the planning is possible. All in all, the two areas are more closely networked and work more closely together, from which enormous potential can be leveraged.

2. Theoretical Background

2.1 Interface of factory planning to factory operation

In general, the factory is described as a place of corporate value creation and represents a complex system of various elements, such as products, machines and people, and their interrelationships. The relations of the elements to each other can be characterized on a material, informational, energetic, personnel, economic, spatial and temporal level. In addition, the overall system of the factory consists of several subsystems, which are distinguished from each other by a defined system boundary (e.g., production, logistics, etc.). The factory is the subject and object of factory planning and factory operation. [9], [10], [11]

Starting from factory planning, the organizational, process-related and structural design or adaptation of the production system takes place. In the literature, approaches are mainly found which are based on a systematic, goal-oriented and phase-specific planning procedure which builds on each other and links the various planning tasks (e.g., process, resource, structural planning, production operation and control, etc.). Due to the high complexity of factory planning projects, the planning phases are carried out with the involvement of a large number of players from a wide range of specialist areas. In this process, planning always proceeds from the rough to the fine and from the ideal to the real. Of particular importance is the parallelism of the planning phases, i.e., a subsequent phase can already be started when the previous phase has not yet been completed. Basically, the phases can be divided into preparation, structural, detailed, execution planning and execution, GRUNDIG gives a comprehensive overview of existing approaches as well as their differences [12]. In addition to new planning (greenfield), i.e., the completely new construction of a factory from scratch, and the re-planning (brownfield) of an existing factory, there are further planning cases within the life cycle consideration of a factory and its elements in the form of deconstruction and revitalization. Starting from the network and site level, the following levels become more and more detailed, up to the focus on the granular, detailed workplace of a specific area of a factory. The design of the production system, more precisely the arrangement of the production elements, is done taking into account appropriate flow systems. Factory planning involves permanent adaptation in the event of changes in the planning of the factory and factory operations. [9], [10], [11], [12], [13]

In contrast to factory planning, factory operation includes the structuring of the tasks of operating, directing and controlling the processes (including maintenance and service) in the factory. Here, production planning and control, manufacturing, assembly, storage, transport, quality and resource management are particularly important. In this way, the company's objectives are to be safeguarded by a socially, economically and ecologically (resource) efficient organizational structure and process organization in the participatory, transparent interaction of all factory elements. Of particular importance here is also the integration or regulation of the interaction of production, logistics and support processes. The overriding goal of factory operations can therefore be described as the efficient design of a factory's operations and its adaptation to necessary changes, with the creation of value added being a central element of factory operations theory. More precisely, the shortening of the start-up period as well as the operational and continuous improvement of serial production are aimed at. [10], [13], [14], [15]

In total, there are close mutual relationships between the two areas of factory planning and factory operation. Factory operation is strongly influenced by the framework conditions created by factory planning, but this also applies retrospectively, so that findings from factory operation must be reported back to factory planning. A corresponding bidirectional exchange between the two areas leads to an optimization of factory operations, in that adjustments can be made and future planning projects can be improved based on the information fed back. Optimally, factory planning thinks ahead of value creation and provides framework conditions for efficient and error-free processes. The processes, systems, and measures are thought ahead and primarily include the physical material flow, the information and communication system, and the factory's organizational system. Factory operations, on the other hand, are devoted to the real operation of the equipment and the optimal use of the available resources and framework conditions. The problem and task of permanent over-planning of a factory with its production and logistics structures arises. For this reason, the bidirectional exchange of information and data between factory planning and factory operation can be of great benefit for the optimization of planning and operation. [8], [16]

2.2 Simulation models in cyber-physical production systems

For the areas of factory planning and factory operation, simulation models are mainly used as decision support and are part of the concept of DF. In the technical literature, there are a variety of definition approaches for the term of DF, but essentially this summarizes a comprehensive network of digital models, methods and tools, which are integrated by an end-to-end data management and extend from digital planning to operation. The overarching goal of DF is the holistic planning, evaluation and continuous optimization of all relevant aspects of the real factory. [17]. Further goals of the DF consist in the standardization of planning processes as well as in the reusability of planning models, building blocks and results [18]. An important element of digital factory operation is the support or implementation of end-to-end data management. On the basis of end-to-end data management, for example in the form of model databases, planning results from earlier phases of DF can be used and expanded to include operational data, enabling digital models to be updated and reused [19]. Accordingly, the concept of DF is again fundamental for linking factory planning and factory operation through the transfer of simulation models.

CPPS are of great importance, especially with regard to linking the real world with the virtual world. Here, the production system, which consists of a physical component (e.g., machinery and equipment) and a virtual component (e.g., simulation model), is connected at the center with people in focus. The introduction of CPPS in any production system promises economic, social and even environmental benefits. In general, CPPS can be divided into four main elements - physical world (I), data acquisition (II), virtual world (III), and feedback / control (IV). In the physical world, key performance indicators (KPI) are defined in relation to the task to be performed, which should represent the target for analysis and improvement. Via the important element of (continuous) data acquisition, the measured variables are recorded manually or automatically under appropriate requirements for temporal resolution. The virtual world stands for the model-based production system, the digital image, so to speak. The implementation with suitable computationally processing models, which are e.g. data-based, physical, numerical or agent-based / event-discrete nature, is to be considered here. Finally, the feedback/control element ensures the transformation of the processed data into means for decision-supporting action with human involvement. [20]

In the following, the details of the simulation models used in CPPS are briefly described. Models characterize an abstracted representation of a real system and can be classified in the production system context according to their intended use. The main paradigms in simulation modeling are: System Dynamics (SD), Dynamic Systems (DS), Discrete Event (DE) and Agent Based (AB). Technically, SD and DS are mainly concerned with dynamic system behavior, while DE and AB are mainly concerned with discrete system behavior [21]. In the context of factory planning, the necessary main elements usually have a higher degree of uncertainty and thus a higher degree of abstraction. On the side of the factory operation, there is the demand of an image with a low degree of abstraction towards the consideration of procedural, organizational and structural details. The definition of the objectives with respect to the planning and operational tasks is particularly important in order to be able to select a suitable method for simulation. Discrete process chains (such as material flows) can be analyzed using DE or AB simulation. The state is only changed discretely at certain events. In this case the term production system modeling is used. If the context of the production system is extended by energy flows and the technical building services, a holistic factory modeling is possible using DE, AB and DS, i.e., as shown by SCHÖNEMANN. [22] Of great importance, depending on the planning or operational task and objective, is also the possibility to combine several approaches in one model. The combination of models for all elements of a production system within one simulation would make it possible to analyze dependencies between the system elements involved and the effects of local improvement measures on the overall system [22]. In the context of CPPS and linking planning to operations, real-time simulations of the entire factory can help provide immediate results for short-term decision support in parallel with real production operations [23]. With regard to greenfield and brownfield planning, the main difference is in the input data. While only planning data is available for new planning, it is possible to use real, real-time data from the system for an existing production system.

In order to take into account, the different areas within planning and operation in the production system, the design of AB lends itself. One of the fundamental characteristics of AB is decentralization in modeling and with regard to system behavior. Accordingly, in AB, the system behavior is not defined at a central point, but rather the behavior is defined at an individual level of each agent. Each agent acts accordingly individually according to the logic, behavior and attributes assigned to it. The thus independent, individual resources with specific properties enable a mapping of production, logistics, products, employees and other objects. The system behavior then results from the behavior and interaction of these agents. In addition, agent-based models are considered to be generally easier to maintain and modify, since minor model adjustments result in local rather than global changes. Although all presented simulation paradigms are used in different areas of the factory, DE and AB are probably the most important in the context of simulation in the factory and production context. [5], [21]

3. State of Research

The technical literature provides an enormously high number of publications in the context of factory planning and operation. With the aim to present existing approaches for the simulative coupling of factory planning with factory operation, an extensive literature review of relevant publications in different research areas was conducted. First, approaches for linking factory planning and factory operation in general, where this linking does not have to be specifically supported by simulation use, were considered. Furthermore, the research area with approaches to simulation along the value chain, i.e., with end-to-end simulation and data usage, was reviewed. The focus here is particularly on the simulation of production systems. Finally, approaches were considered that specifically address the topic of cyber-physical production systems in this context. The classification and clustering took place in the following categories:

- ***Thematic focus*:** The relevance of the respective approach for the subject area of factory planning represents the first criterion. Analogously, the reference to factory operation or simulation in the factory context represent the two other criteria in this category.
- ***Methodological approach*:** Here, the approaches regarding the coupling of factory planning and operation, simulation models, and several digital tools were considered.
- ***Simulation application*:** In this category, the contents of the consideration of simulation approaches, model reuse and the integration of a model database were of interest.
- ***Data management*:** Here, the interrelationships were examined from a data technology point of view, to what extent this is done bidirectional, consistent and by means of clearly defined interfaces.

The comparative evaluation in Figure 1 illustrates the large number and variety of concepts for the use of simulation in the context of the factory. The analyzed approaches focus preferably on the design of e.g., framework models for the description of the mutability of production systems for planning purposes (ALBRECHT ET AL.), approaches for modeling and simulation of smart production systems, which aim at achieving interoperability of different simulation components (GORECKI ET AL.) or the detailed consideration of flows in the factory by means of production system modeling (KOMOTO ET AL., GOODALL ET AL.). Few approaches, among them MARTIN ET AL., SCHÖNEMANN ET AL., SIEMON ET AL and ZHENG ET AL. integrate components of holistic factory modeling into their approaches, e.g., by modeling parts of the technical building services. While the advantages of the use of simulation along the value chain, the use of CPPS as well as the linking of factory planning and factory operation became clear, no approach could be identified that fulfills all or nearly all criteria used for the evaluation. The majority fulfillment or at least partial fulfillment of the evaluated sources with regard to the three criteria in the category of thematic focus is countered by the only rare fulfillment of other criteria such as the consideration of several simulation approaches. A methodical approach with regard to the coupling of factory planning and factory operation is also only occasionally part of the evaluated publications. Furthermore, the reuse of models and the integration of a model database is only partially included in the approaches considered. The same applies in particular to the support of bidirectional data management and the detailed consideration of the interface between factory planning and factory operation - both are only very rarely addressed.

	Albrecht et al. (2014)	Dér et al. (2021)	Dombrowski et al. (2019)	Dhungana et al. (2021)	Goodall et al. (2018)	Gorecki et al. (2020)	Horler et al. (2019)	Lachenmaier et al. (2017)	Komoto et al. (2019)	Martin et al. (2021)	Meyer (2014)	Schönemann et al. (2019)	Siemon et al. (2022)	Wagner & Brovkina (2020)	Weyer et al. (2016)	Zhang et al. (2018)	Zheng et al. (2018)
Thematic focus																	
Factory planning	●	●	●	●	○	◕	●	◑	●	●	●	●	●	◕	●	●	◕
Factory operation	◑	◔	●	◑	●	◕	○	●	◔	◕	●	◕	◔	◕	◕	○	◕
Production system modeling	◕	◔	○	○	◑	◑	◑	◕	◑	◕	◔	●	◕	○	◑	◑	◑
Holistic factory modeling	○	○	○	○	○	○	○	○	○	◑	○	●	●	○	◔	○	◔
Methodological approach																	
Methodology for coupling factory planning & operation	◔	◕	●	◑	○	○	○	○	◔	◔	●	◕	○	○	●	○	◑
Methodology for coupling simulation models	◕	○	○	◔	◑	●	●	○	◕	●	◔	●	◕	◔	●	◕	●
Methodology for coupling several digital tools	○	○	◔	●	○	◕	●	◔	●	○	◑	◔	○	●	◔	○	◑
Simulation application																	
Consideration of multiple simulation approaches	●	○	○	○	○	◑	○	○	○	●	○	●	●	○	◕	○	○
Model reuse	○	◔	○	◕	◕	◕	○	◔	●	●	◑	●	○	●	●	●	●
Model database integration	○	○	○	◔	◕	◔	○	○	●	●	◔	●	○	●	●	●	●
Data management																	
Bidirectional	◕	◑	●	◕	◕	◕	◕	◕	◕	◔	●	◔	◕	◕	◕	◕	◕
Consistent	◔	◑	●	●	◑	●	◑	◕	◑	●	●	●	◔	◑	●	◕	◕
Data interfaces	◕	◕	◔	●	●	●	◑	◕	◔	●	◑	●	◔	●	◕	◕	●

○ Not fulfilled criteria ◔ Conditionally fulfilled criteria ◑ Partially fulfilled criteria ◕ Mostly fulfilled criteria ● Completely fulfilled criteria

Figure 1: Overview of the state of research

Thus, the evaluated approaches show a multitude of relevant (partial) aspects regarding the coupling of factory planning and factory operation by the transfer of simulation models within CPPS. Nevertheless, there is a need for further research regarding the topic at hand. For example, there is currently a lack of a methodical procedure in the literature for precisely this linking of factory planning with factory operation with regard to the transfer of simulation models of production systems through CPPS.

4. Method

In the following, the approach for linking factory planning with factory operation by means of AB simulation within the framework of a CPPS is shown (cf. Figure 2). Before the framework can be initialized, the preparation and rough planning steps must already be run through in the planning process, so that the approach can be followed from the detailed planning onwards. Based on a normal CPPS, the framework was structured in this case on the side of the real and cyber world into three different layers that build on each other. The cycles running through are to be understood in each case in the arrangements [I-IV], [1-4] as well as [A-D].

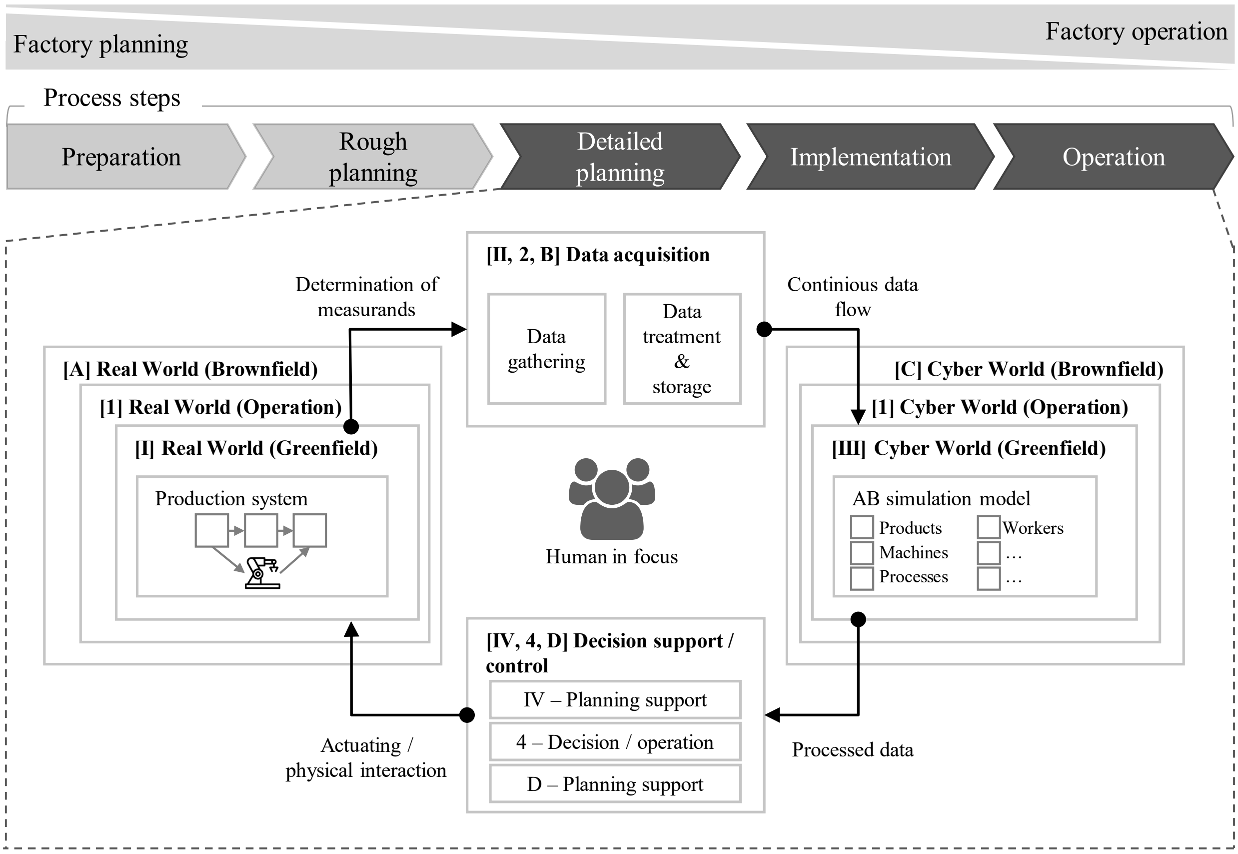

Figure 2: Framework for linking factory planning and operation using AB simulation in the context of a CPPS

- Cycle [I] to [IV]:

This cycle marks the starting point in the application of the framework. Starting from the greenfield planning, the factory planning process takes place in the real world with respect to the design of the production system. Manually, by means of data acquisition, the planning data is collected and transferred to the AB Greenfield simulation model on the cyber side. This model accesses a comprehensive network of agents (such as products, machines, processes, etc.). Based on the planning data, an evaluation of the planning scenarios can be performed. This planning support is transferred to the real world by the human being, who is the central focus, and can thus be used for adjustments in the planning process. The inner cycle is still primarily based on expert estimates and aims at initializing the AB simulation model.

- Cycle [1] to [4]:

After the ramp-up of the production system, the first data acquisition of real-time data is used to establish a quasi-real-time connection between the real and virtual worlds. Here, the agents in the specific executions are provided with the data as input (real / operational data) and thus a mapping and prognosis of the production system can take place. The goal here is the decision support in the operation execution as well as the control and regulation of the production system.

- Cycle [A] to [D]:

The outermost cycle describes the case of brownfield changes. In this concrete planning procedure, changes are to be made to the production system based on the real world. This is where the benefit of continuing to use the simulation model comes into play. A new development is omitted, instead the agents for the respective area (e.g., product) are initialized with a data mix as input. Thus, on the one hand, planning data for the desired changes and real / operational data from the current production system are combined. In this way, important knowledge for detailed planning can be transferred between planning and operation and, conversely, planning support can be designed specifically for the real operation of the production system.

5. Conclusion and outlook

This paper has shown a conceptual approach in the context of the interface between factory planning and operation, how a CPPS can be initialized starting from greenfield planning. Initially, the simulation models are developed on the virtual world side on the basis of plan data, which are acquired manually. In addition, the targets have to be transferred to the generic modules of the AB in the form of planning variables. From this, first simulation runs can be realized and planning scenarios can be evaluated. If the planning is far advanced and the commissioning of the factory elements has taken place, real data of the factory operation can be accessed in the next step and the data acquisition can be carried out via an automated interface. The simulation model, adapted to real operation, can now be used in quasi real-time and supports the operation and control of the production system in the factory. In the last extension step, both sides of factory planning and factory operation can access the virtual world and simulatively evaluate brownfield changes by the combination of plan and real data. Particularly noteworthy at this point is the generic initialization of the AB, so that the simulation modules can be provided with plan or real data. Based on the Greenfield planning approach, the necessary steps for the preparation of a real-time capable CPPS can be taken. In the further course, the interdisciplinary departments can equally bring about forms of decision support by preparing the virtual world for the issues to be solved by simulation in terms of data technology.

In the future, this generic framework can be used and extended. In particular, the focus on an ecologically sustainable design of factory systems could again extend the approach by building blocks of the technical building equipment as well as the factory shell. In addition, the use of the framework is limited to the results from the rough planning, since e.g., changes to the layout etc. are not processed by the simulation model. Further research should be carried out in this interface, since the increase in the degrees of freedom in an early planning phase greatly increases the demands on the simulation models.

References

[1] Martin, N.L., Dér, A.Z., Langer, A., Henningsen, N., Ortmeier, C., Abraham, T., Herrmann, C., 2021. Simulation Based Assessment of Lean and Industry 4.0 Measures in Changeable Production Systems, in: Franke, J., Schuderer, P. (Eds.), Simulation in Produktion und Logistik 2021. Cuvillier Verlag, Göttingen, pp. 21–30.

[2] Bracht, U., Geckler, D., Wenzel, S., 2018. Digitale Fabrik. Springer Berlin Heidelberg.

[3] Stehle, T., Heisel, U., 2017. Konfiguration und Rekonfiguration von Produktionssystemen, in: Spath, D., Westkämper, E., Bullinger, H.-J., Warnecke, H.-J. (Eds.), Neue Entwicklungen in der Unternehmensorganisation. Springer Vieweg, Wiesbaden, pp. 333–367.

[4] Jacobi, H.-F., Landherr, M., 2013. Bedeutung des Treibers Informations- und Kommunikationstechnik für die Wettbewerbsfähigkeit industrieller Produktion, in: Westkämper, E., Spath, D., Constantinescu, C., Lentes, J. (Eds.), Digitale Produktion. Springer Berlin Heidelberg, pp. 41–44.

[5] Schönemann, M., 2017. Multiscale Simulation Approach for Battery Production Systems. Springer International Publishing, Cham.

[6] Langer, A., Ortmeier, C., Martin, N.L., Abraham, T., Herrmann, C., 2021. Combining Process Mining And Simulation In Production Planning. Hannover, publish-Ing.

[7] März, L., Weigert, G., 2011. Simulationsgestützte Optimierung, in: März, L., Krug, W., Rose, O., Weigert, G. (Eds.), Simulation und Optimierung in Produktion und Logistik. Springer Berlin Heidelberg, pp. 3–12.

[8] Meyer, T., 2014. Die Schnittstelle von der Digitalen Fabrik zum Digitalen Fabrikbetrieb. Zeitschrift für wirtschaftlichen Fabrikbetrieb 109 (10), 752–755.

[9] Pawellek, G., 2014. Ganzheitliche Fabrikplanung. Springer Berlin Heidelberg.

[10] Schenk, M., Wirth, S., Müller, E., 2014. Fabrikplanung und Fabrikbetrieb: Methoden für die wandlungsfähige, vernetzte und ressourceneffiziente Fabrik, 2. Aufl. 2014 ed. Springer Berlin Heidelberg, 832 pp.

[11] Verein Deutscher Ingenieure, 2011. Fabrikplanung: Planungsvorgehen. Beuth Verlag, Berlin, 24 pp.

[12] Grundig, C.-G., 2012. Fabrikplanung: Planungssystematik – Methoden – Anwendungen, Hanser Verlag, München, 377 pp.

[13] Bauernhansl, T. (Ed.), 2020. Fabrikbetriebslehre 1. Springer Berlin Heidelberg.

[14] Westkämper, E., Spath, D., Constantinescu, C., Lentes, J. (Eds.), 2013. Digitale Produktion. Springer Berlin Heidelberg.

[15] Verein Deutscher Ingenieure, 2011. Digitale Fabrik: Digitaler Fabrikbetrieb. Beuth Verlag, Berlin, 51 pp.

[16] Westkämper, E., 2014. Fertigungs- und Fabrikbetrieb, in: Grote, K.-H., Feldhusen, J. (Eds.), Dubbel. Springer Berlin Heidelberg, pp. 1468–1489.

[17] Verein Deutscher Ingenieure, 2008. Digitale Fabrik: Grundlagen. Beuth Verlag, Berlin, 52 pp.

[18] Verein Deutscher Ingenieure, 2016. Digitale Fabrik: Datenmanagement und Systemarchitekturen. Beuth Verlag, Berlin, 51 pp.

[19] Sauer, O., Schleipen, M., Ammermann, C. Digitaler Fabrikbetrieb: Virtual Manufacturing, in: Zülch, Stock (Hg.) 2010 - Integrationsaspekte der Simulation: Technik, Organisation und Personal.

[20] Thiede, S., Juraschek, M., Herrmann, C., 2016. Implementing Cyber-physical Production Systems in Learning Factories. Procedia CIRP 54, 7–12.

[21] Borshchev, A., Filippov, A., 2004. From System Dynamics and Discrete Event to Practical Agent Based Modeling: Reasons, Techniques, Tools. The 22nd International Conference of the System Dynamics Society.

[22] Schönemann, M., Bockholt, H., Thiede, S., Kwade, A., Herrmann, C., 2019. Multiscale simulation approach for production systems. Int J Adv Manuf Technol 102 (5-8), 1373–1390.

[23] Fowler, J.W., Rose, O., 2004. Grand Challenges in Modeling and Simulation of Complex Manufacturing Systems. Simulation 80 (9), 469–476.

[24] Albrecht, F., Kleine, O., Abele, E., 2014. Planning and Optimization of Changeable Production Systems by Applying an Integrated System Dynamic and Discrete Event Simulation Approach. Procedia CIRP 17, 386–391.

[25] Dér, A., Hingst, L., Nyhuis, P., Herrmann, C., 2022. A review of frameworks, methods and models for the evaluation and engineering of factory life cycles. Advances in Industrial and Manufacturing Engineering 4.

[26] Dombrowski, U., Wullbrandt, J., Karl, A., 2019. Bidirectional Data Management in Factory Planning and Operation, in: Ameri, F., Stecke, K.E., Cieminski, G. von, Kiritsis, D. (Eds.), Advances in Production Management Systems. Towards Smart Production Management Systems, vol. 567. Springer International Publishing, Cham, pp. 303–311.

[27] Dhungana, D., Haselböck, A., Meixner, S., Schall, D., Schmid, J., Trabesinger, S., Wallner, S., 2021. Multi-factory production planning using edge computing and IIoT platforms. Journal of Systems and Software 182.

[28] Goodall, P., Sharpe, R., West, A., 2019. A data-driven simulation to support remanufacturing operations. Computers in Industry 105, 48–60.

[29] Gorecki, S., Possik, J., Zacharewicz, G., Ducq, Y., Perry, N., 2020. A Multicomponent Distributed Framework for Smart Production System Modeling and Simulation. Sustainability 12 (17), 6969.

[30] Horler, S., Blocherer, T., Spang, F., Riedel, R., 2019. Transformation formaler Systemmodelle in digitale Fabrikmodelle. Zeitschrift für wirtschaftlichen Fabrikbetrieb 114 (10), 679–682.

[31] Lachenmaier, J.F., Lasi, H., Kemper, H.-G., 2017. Simulation of Production Processes Involving Cyber-physical Systems. Procedia CIRP 62, 577–582.

[32] Komoto, H., Kondoh, S., Furukawa, Y., Sawada, H., 2019. A simulation framework to analyze information flows in a smart factory with focus on run-time adaptability of machine tools. Procedia CIRP 81, 334–339.

[33] Martin, N.L., Dér, A.Z., Langer, A., Henningsen, N., Ortmeier, C., Abraham, T., Herrmann, C., 2021. Simulation Based Assessment of Lean and Industry 4.0 Measures in Changeable Production Systems, in: Franke, J., Schuderer, P. (Eds.), Simulation in Produktion und Logistik 2021. Cuvillier Verlag, Göttingen, pp. 21–30.

[34] Siemon, L., Blume, C., Mennenga, M., Herrmann, C., 2022. Multi-scale Simulation for Energy Flexible Factories and Factory Networks: A System of Systems Perspective. Procedia CIRP 105, 404–409.

[35] Wagner, E., Brovkina, D., 2020. Beschreibungsmodell zur Standardisierung von Schnittstellen für Cyber-Physische Module. Zeitschrift für wirtschaftlichen Fabrikbetrieb 115 (5), 352–357.

[36] Weyer, S., Meyer, T., Ohmer, M., Gorecky, D., Zühlke, D., 2016. Future Modeling and Simulation of CPS-based Factories: an Example from the Automotive Industry. IFAC-PapersOnLine 49 (31), 97–102.

[37] Zhang, Z., Wang, X., Wang, X., Cui, F., Cheng, H., 2019. A simulation-based approach for plant layout design and production planning. J Ambient Intell Human Comput 10 (3), 1217–1230.

[38] Zheng, Y., Yang, S., Cheng, H., 2019. An application framework of digital twin and its case study. J Ambient Intell Human Comput 10 (3), 1141–1153.

Biography

Adrian Langer (*1993) studied industrial engineering with a specialisation in mechanical engineering at the TU Braunschweig. Since 2019, he has been working as a research assistant at TU Braunschweig in the sustainable production and factory systems working group of the Institute of Machine Tools and Production Technology (IWF) with a special focus on simulation of production systems.

Christian Ortmeier (*1992) studied industrial engineering with a specialisation in mechanical engineering at the TU Braunschweig. Since 2019, he has been working as a research assistant at TU Braunschweig in the sustainable production and factory systems working group of the Institute of Machine Tools and Production Technology (IWF) with a special focus on data-driven methods and tools in lean administration.

Dr. Tim Abraham (*1987) studied industrial engineering with a specialisation in mechanical engineering at the TU Braunschweig. Since 2014, he has been working at the IST, Fraunhofer Institute for Surface Engineering and Thin Films completing his PhD in 2019. Since 2020, he is head of the sustainable production and factory systems working group of the Institute of Machine Tools and Production Technology (IWF).

Prof. Dr.-Ing. Christoph Herrmann (*1970) is university professor for Sustainable Manufacturing & Life Cycle Engineering and co-director of the Institute of Machine Tools and Production Technology (IWF), Technische Universität Braunschweig as well as director of the Fraunhofer Institute for Surface Engineering and Thin Films IST since November 2018.

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Design Model Of An Ecosystem For Resilient And Sustainable Value Creation Of SMEs In Single And Small Batch Production

Günther Schuh[1], Gerret Lukas[1], Christoph Frey[1]

[1]*Laboratory for Machine Tools and Production Engineering (WZL) of RWTH Aachen University, Aachen, Germany*

Abstract

Today's markets are increasingly dynamic, not only due to shorter product development times and fast changing customer requirements but also unforeseen events. Contemporary crises and wars disrupt entire supply chains and can have existential consequences for manufacturing companies. In these times of uncertainty, it is essential for SMEs to have a resilient business orientation while at the same time fulfil the sustainability aspects demanded by their stakeholders. This paper provides a design model for an ecosystem for a resilient and sustainable value creation of SMEs in single and small batch production to increase competitiveness and to gain a better response to market dynamics. The developed model comprises the elements of ecosystem strategy, configuration and coordination. An adequate partner matching and the underlying business model complement the approach. The model is intended to assist practitioners as a reference framework in developing and managing ecosystems for value creation.

Keywords

Ecosystem; Resilience; Sustainability; SME; Single and small batch production

1. Introduction

Companies in single and small batch production manufacture customer-specific and highly complex products such as machines, engineering components or tools for series production. This is done in close consultation with the customer. In order to meet this very demanding environment, a high degree of specialization of the individual producers is necessary, which is expressed in mostly small and medium-sized enterprises (SMEs) in the mechanical and plant engineering sector focusing on certain technologies. Each company has to compete in the market individually, which leaves it at a disadvantage in the event of major market changes or when handling larger orders due to its low resilience and flexibility. Moreover, SMEs in single and small batch production are far from shaping their value creation sustainably. This is often expressed by poor resource efficiency and a constant trend towards overproduction. In particular, this results from a lack of transparency for sustainable value chains [1]. In contrast to series production, processes in single and small batch production are individual, non-linked manufacturing processes. [1] External contract manufacturers in low-wage countries typically carry out a significant share of the value added. This happens even though the company's own machines are only utilized to 34% on average [2]. Currently, the supplier process for contract manufacturers is controlled manually and very statically. Optimization is required in terms of time, cost and quality. In particular, local sourcing strategies should be given greater consideration in the future to increase sustainability and resilience. Therefore, to overcome these challenges, this paper focuses on the development of a design model of an ecosystem for resilient and sustainable value creation of SMEs in single and small batch production.

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2. Fundamentals

In the following subchapters, fundamentals of overproduction and sustainability, resilience and uncertainty as well as ecosystems and platforms for value creation are described.

2.1 Overproduction & sustainability

In the course of the last century, industry has achieved remarkable things as the industrial revolutions have led to enormous efficiency in production. Everyday products are incredibly inexpensive and everyone can afford them. The manufacturing industry has thus made a major contribution to the prosperity of our society. However, it also has led to an economically sensible overproduction, as existing resources are not being used wisely. For instance, the average utilization of a passenger car is just 4%. [3] Due to the efficient production, large numbers of consumer goods are disposed after a short period of use. This overproduction is partly responsible for the increasing environmental pollution and socio-technological consequences, such as massively increased traffic. Due to the extensive global supply chains in the automotive industry, transport cost accumulate to a share of 12% to 21% of component cost [4]. Greenhouse gas emissions continue to rise steadily (approx. 3 million tons of CO_2 emissions annually), and national savings often only lead to carbon leakage, the outsourcing of greenhouse gas-intensive production steps to other countries [4]. A sustainable economy is therefore indispensable for the future viability of the global economy. To achieve this, the United Nations (UN) regularly refines sustainability goals and obliges manufacturing companies to adopt a more sustainable economic approach. Investors are also increasingly applying ESG factors (Environmental, Social and Governance) in their company valuations [5]. The resulting increase in stakeholder-oriented corporate management has led to a fundamental paradigm shift in industry. German automotive companies, for example, are using sustainability ratings to demand sustainable value creation from their suppliers. Such suppliers are often SMEs in single and small batch production, which struggle to meet these demands.

Sustainability has according to the three-pillar conception an economic, an environmental and a social perspective [6]. All perspectives have to be met in an integrated manner in order to holistically improve sustainability within companies. The central enabler of sustainability is digitization [4]. Production and product data allow lifecycle transparency from engineering through production and product usage to disposal. This includes transparency on transport emissions as well as on resource efficiency. BOOS ET AL. make a proposal to leverage these potentials in single and small batch production. They recommend the four dimensions of resources, process, employee and service portfolio to be addressed for sustainability [7].

2.2 Resilience & uncertainty

The recent SARS-CoV-19 pandemic and the Ukraine war have outlined the importance of resilience in supply chain design. Resilience generally describes the ability to cope with crises and to recover as quickly as possible from their effects. Systematic resilience management can decisively help manufacturing companies to get through crises with only minimal damage and even to emerge stronger from them. [8] Therefore, manufacturing companies have to continuously assess the uncertainty in the markets to configure their value creation in a reliable way. Thus, uncertainty is the lever that determines the necessary degree of resilience [8]. WALKER ET AL. define uncertainty as "any deviation from the unachievable ideal of completely deterministic knowledge of the relevant system" [9]. For model-based decision processes, the distinction between nature, localization and level of uncertainty is particularly relevant. The nature of uncertainty describes its general characteristic, while the localization shows where uncertainty occurs in the decision process. Finally, the level of uncertainty can be determined in the dichotomy between total ignorance and deterministic knowledge. [9] As uncertainty assessment and resilience management are complex tasks that require appropriate resources, the vast majority of SMEs in single and small batch production does not engage in it. This can have existential consequences. The scope of consideration in this paper encompasses the resilience of the ecosystem as a whole. In this context, resilience is defined as the preservation of the functionality of the overall system, which is a function of the companies' individual risks.

2.3 Ecosystems & platforms for value creation

In literature, there are still widely divergent definitions of the term ecosystem. MERTENS AND FAISST describe an ecosystem as a network of companies, which rapidly group together in order to take advantage of an arising market opportunity [10]. Ecosystems are traditionally subject to the field of biology. There, an ecosystem intends to maintain an equilibrium state and describes a complex construct of living resources as well as habitats and inhabitants in a certain area including their interrelations [11]. Ecosystems in industry differ in their target orientation and that they require certain governance [12]. However, the idea of a biologically inspired ecosystem implies resilience and the prevention of overproduction in the sense of an equilibrium sustaining state. Ecosystems describe a network of organizations that are interconnected by a digital platform or a focal firm [13]. Moreover, there are various types of ecosystems, which cannot be clearly distinguished from each other, such as business, innovation, knowledge or platform ecosystems [14]. GRANSTRAND AND HOLGERSSON conducted a broad literature review on ecosystem definitions and identified actors, activities, artifacts and relations as central elements [15]. According to a study of DELOITTE, most SMEs have concerns regarding the disclosure of trade secrets, a lack of data security and unclear liability rules when participating in ecosystems. The highest prospects are seen in improved customer relations through better services as well as a sustainable optimization of business processes. [16] The majority of successful ecosystems are based on digital platforms. Digital platforms take advantage of modern information and communications technology (ICT) to reduce transaction cost and to simplify processes for users. Another advantage can be seen in the high scalability of platforms. [17] SMEs in single and small batch production must use these advantages of digital platforms in order to establish successful ecosystems.

3. Existing approaches

The integrative and systematic approach by ULRICH serves as bases to derive general requirements for the design of an ecosystem model for value creation of SMEs [18]. The approach focuses on social and technical systems in terms of design and management. In this respect, the interdisciplinary approach emphasizes in particular the practical applicability of theoretical concepts to solve real problems. By applying the approach, the problems in practice of SMEs of single and small batch production as well as their industry specific characteristics are taken into consideration. Therefore, the general requirements of applicability, practicability and adaptability have to be considered when designing a model of an ecosystem for value creation of SMEs. [18] First, the design model has to be applicable to the industry specific needs of SMEs in single and small batch production. This includes for instance the suitability to the prevailing (production) processes and certain boundary conditions within these companies. Furthermore, the practicability of the design model has to be ensured. Typically, SMEs have few human and financial resources at their disposal. Therefore, the model should be self-evident and easy to apply in industrial practice. Eventually, the model should be adaptable to external and internal circumstances. This encompasses the model's scalability and modification in terms of number and classification of ecosystem participants. Besides these general requirements, also the ecosystem-specific requirements of resilience, sustainability, systemic partner selection, ecosystem composition and control as well as functioning business model must be fulfilled. In terms of resilience, the ecosystem must adapt in line with the existing uncertainty in markets in order to be either efficient or resilient according to the given circumstances. To address sustainability, the ecosystem should foster a sustainable production due to appropriate measures such as interorganizational capacity leveling. On the one hand, this increases the capacity utilization of individual companies within the ecosystem and on the other hand, it prevents overproduction. Thus, all three pillars of sustainability – economic, environmental and social – have to be considered. A systematic partner selection based on resources, competencies and additional criteria constitutes another relevant requirement. In order to achieve maximum efficiency and thus sustainability in the order fulfilment within the ecosystem, orders have to be assigned to companies having adequate resources and competencies at their disposal. Ensuring an appropriate composition and control of the ecosystem represents another requirement. Adequate companies in suitable numbers have to be selected and integrated within the ecosystem. Moreover, a smooth control of the ecosystem and its inherent orders to be processed has to be ensured. Finally, the ecosystem must provide a functioning business model to achieve practical feasibility and broad acceptance. In addition to defining a suitable value proposition for all ecosystem stakeholders and implementing it through appropriate platform functions, the revenue model must also be given sufficient consideration [19].

Subsequently, relevant approaches from literature on ecosystems and value creation networks are presented. Some of these are biologically inspired. TALMAR ET AL. developed their so-called Ecosystem Pie Model, which is a strategy tool for ecosystem modelling and analysis. The process-oriented tool serves to consider ecosystem properties such as interdependencies, complementarities and alignment risks. One of the main challenges is that this approach does not represent a holistic strategy, but merely an operational tool for ecosystem analysis. [20] HENSEL formulates an approach to network management in the automotive industry. The model pursues the overarching objective of analyzing the effects of network management in order to achieve competitive advantages. However, the approach focuses exclusively on short-term project collaborations and therefore long-term collaborations are not discussed. [21] RITSCH developed a concept focusing on knowledge management in networks. Main subject is an adequate partner selection in the dimensions strategy, culture, cooperation and knowledge management experience. The design of knowledge-based value networks follows a methodology with the steps analysis, design and development. The approach lacks an aggregation of the findings in a superordinate model. [22] TANG ET AL. presents different models and methods based on immune-inspired approaches in the field of manufacturing systems. The collection covers various bio-inspired tools for applications to build production plans and deal with unexpected disruptions at the manufacturing level in an agile manner. Although the approaches are partially transferable into fields of action, there is no explicit consideration of holistic value creation networks. [23] DRESSLER ET AL. provide an overview of the general field of bio-inspired networking, including key concepts and methods. The handling of large networks, their dynamical character, resource constraints and robustness is considered. However, the approach provides almost no context for industrial application. [24] SCHOLZ-REITER ET AL. present a simulation model for system dynamics of production networks with real-world data. The model is used to analyze the behavior and performance of bio-inspired capacity control for production networks with autonomous work systems. The model provides a focused view of scheduling, but the simulation model is not transferable and the adaptation requires further testing. [25]

While the presented approaches fulfill some of the requirements, none of the approaches fully matches the general and specific requirements of an ecosystem for resilient and sustainable value creation of SME in single and small batch production.

4. Design model of an ecosystem for resilient and sustainable value creation

Based on the illustrated deficits from practice and theory, a design model of an ecosystem for resilient and sustainable value creation for SMEs in single and small batch production is developed. The model has to take the before mentioned general and ecosystem-specific requirements into account.

4.1 Derivation of the model

The generic reference framework for network design by FRIEDLI ET AL. serves as theoretical basis of the model to be developed. The scientifically proven framework follows the system approach and is derived from theory on global production networks. As intraorganizational production networks exist for a long time and thus have been extensively researched, the framework is perfectly suitable to the context of ecosystems for value creation. The framework was developed and validated with industrial companies, emphasizing its practical applicability. It analyzes production networks from a holistic point of view by addressing the three layers of strategy, configuration and coordination. Adequately and consistently managing these three design layers through decision variables in different dimensions results in a superior network performance. In this respect, it is essential to provide a consistent fit between all three layers but also between the dimensions within each individual layer. [26] Comparing ecosystems with production networks, the major difference lies in the interorganizational characteristics of ecosystems, which have to be considered additionally in the development of the design model. To develop an ecosystem consisting of several legally independent SMEs, these companies must perceive a distinctive advantage in joining the alliance. Therefore, BLEICHER states that respective networks require the conceptual design of an underlying business model [27]. Moreover, in accordance with GRANSTRAND AND HOLGERSSON, the three most mentioned entities in innovation ecosystem definitions – actors, activities and artifacts – are also considered and integrated within the design model [15]. The resulting model of an ecosystem for resilient and sustainable value creation of SMEs in single and small batch production is illustrated in Figure 1. The different layers of the developed model are described in more detail in the following subsections.

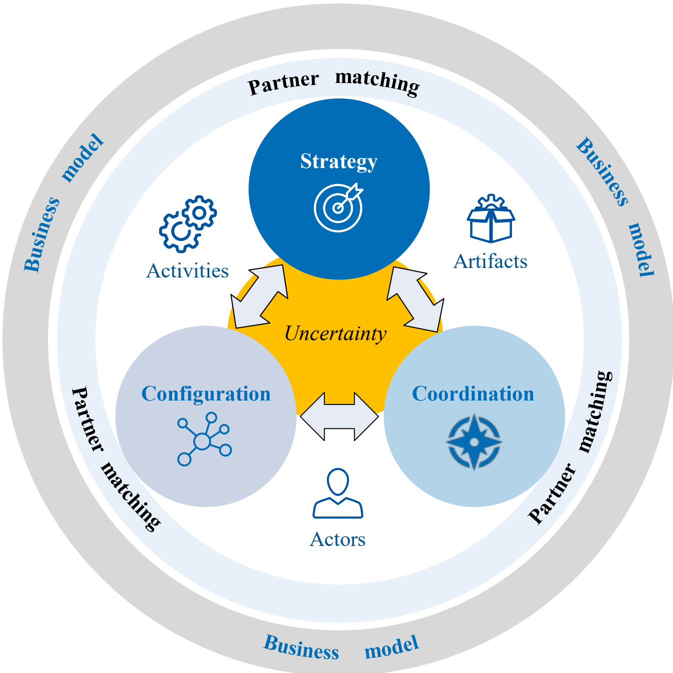

Figure 1: Design model of an ecosystem for resilient and sustainable value creation

4.2 Strategy

Strategy constitutes the first layer within the design model. The layer aims on defining the ecosystem strategy for all participating companies as a whole. The ecosystem strategy represents the business strategy and is composed of the strategic success factors cost, time and quality, which are crucial for the ecosystem's success. Other common differentiating factors for value creation in ecosystems are flexibility and service. These differentiating factors should be based on the competencies of the individual companies as well as of the entire ecosystem. Additionally, the resilience strategy and the sustainability strategy have to be determined. Input to the strategy layer are market requirements and customer needs as well as environmental impacts. All ecosystem stakeholders influence the extent of the sustainability strategy. This includes not only the customers but also the employees of the participating companies. A holistic sustainability strategy covers efficiency, consistency and sufficiency in an integrated manner of the economic, ecological and social dimensions [28]. Efficiency aims at resource efficiency in order to achieve the same results with fewer resources. A lower energy consumption in manufacturing can therefore be seen as an example of an increased eco-efficiency, while socio-efficiency can be seen in fewer negative social impacts per unit produced. [7] Consistency requires a change in the production method, e.g. by recyclable materials or renewable energy. Sufficiency however, aims on minimizing production and consumption in general and thus prevents overproduction. The determinant of the resilience strategy is uncertainty, which is central to the ecosystem model. Environmental impacts, such as the recent SARS-CoV-19 pandemic or the Ukraine war led to large-scale production shutdowns, as many manufacturing companies were not able to adapt and sustain their supply chains in a resilient way. Each of these impacts resulted in a substantial increase in uncertainty. The higher the uncertainty the more resilient the ecosystem should be aligned. To monitor and assess the prevailing uncertainty, sources like the World Uncertainty Index (WUI), providing information on global and country-specific uncertainty, can be utilized [29]. Based on all these preliminary strategic considerations, an adequate value creation strategy for the ecosystem can be derived using the morphological box including dimensions and decision variables in Figure 2. Subsequently, the layers of configuration and coordination can be developed.

Dimensions	Decision variables				
Strategy					
Strategic success factors	Cost	Time	Quality	Flexi-bility	Service
Resilience strategy	Efficiency		Resilience		
Sustainability strategy	Efficiency	Consistency	Sufficiency		
Coordination					
Guidance	Institutionalized	Collective	Hybrid		
Degree of autonomy	Centralized	Decentralized	Neither		
Coopetition	Cooperation	Competition	Neither		
Information flow	Continuous	Discontinuous	Ad hoc		
Resource exchange	Assets	Employees	Neither		
Form of marketing	Centralized	Decentralized	Neither		

Dimensions	Decision variables				
Configuration					
Number of organizations (o)	< 10	10 to 30	30 to 60	60 to 100	> 100
Ø number of employees per o	< 30	30 to 50	50 to 100	100 to 250	
Direction of collaboration	Horizontal	Vertical	Diagonal		
Fields of collaboration	R&D	Design	Service	SCM	HR
Spatial distance	Global	Inter-national	National	Regional	Local
Form of procurement	Global	Centralized	Local		
Form of distribution	Direct supply	Central warehouse	Wareh. near customers	Customer warehouses	

Actors *Activities* *Artifacts*

Figure 2: Morphological box for ecosystem design regarding value creation for SMEs [26]

4.3 Configuration

The configuration layer encompasses the structural design of the ecosystem and its participating SMEs. In contrast to the element-neutral strategy layer, the ecosystem elements from definition apply to the characterizing dimensions in Figure 2. In terms of actors, the average number of employees per organization as well as the total number of organizations within the ecosystem defines the configuration. 40 to 50 companies per ecosystem are considered to be an appropriate number of participants [30]. Additionally, the direction of collaboration has to be determined. A horizontal network is exclusively composed of SMEs in single and small batch production. By adding the vertical direction, suppliers and customers can be included. Diagonal networks supplement organizations from other value chains, e.g. start-ups. The fields of collaboration represent the activities being conducted within the ecosystem. Apart from production, R&D or service partnerships could be initiated. The dimensions of spatial distance as well as the forms of procurement and distribution represent ecosystem artifacts, which are defining the supply chain and the extent of the ecosystem.

4.4 Coordination

Task of the coordination level is the holistic control and management of all partners and activities within the ecosystem. The dimensions of guidance and degree of autonomy refer to the ecosystem element of actors. The ecosystem can either be designed to contain an entity that serves as central orchestrator and thus streamlines all interactions of the participants or define the guidance as a collective task. A hybrid version of certain orchestrating entities serves as another option. Additionally, network decisions and order placements can be centralized, decentralized or a combination of both. Regarding network activities, the participating companies can position themselves in the dichotomy between competition and cooperation. In certain fields, they might compete and in others, they might cooperate. The ecosystem artifacts in the coordination layer focus on the information flow, resource exchange and the form of marketing. Information and communication can occur continuously or only on demand. For increased flexibility and capacity levelling, assets and human resources can be exchanged. Furthermore, the marketing and branding can be centralized or remain in the participating companies. The decision variables of all dimensions have to be consistent with each other and regarding the other layers.

4.5 Partner matching

The partner matching represents a crucial layer in enabling collaboration between SMEs in single and small batch production. It encompasses the strategy, configuration and cooperation layer as it has to take all their dimensions and decision variables into account. As seen in Figure 3, input to the partner matching is information on the internal company characteristics of the order placing company and all potential partners, which should be stored and updated continuously in a common database. Eventually, the trigger of the matching process can be seen in an incoming customer order. Based on the order characteristics in terms of expected quality, cost, delivery time and product complexity as well as the superordinate value creation strategy, a weighting of the matching criteria is carried out. The matching criteria can be classified into two general categories, the categories of interface compatibility and professional competences. In the former, companies should try to achieve the highest possible scores, while in the latter different specifications might be beneficial depending on the boundary conditions. Interface compatibility is divided into criteria for coordination and collaboration compatibility. Coordination compatibility depends on the potential partners' cultural compatibility, coordination and communication competencies as well as technological barriers. Collaboration criteria evaluate potential partners in terms of strategic fit, trust-building factors and the risks of forming a consortium. Resource and competence compatibility represent the general category of professional competences. In terms of resources, financial resources, machinery and intangible assets within each company are analyzed. In the field of competence compatibility, employee qualification, technological and market-oriented competencies as well as innovation capabilities are of importance. Following the assessment, the results and possible project consortiums can be visualized for decision-making purposes.

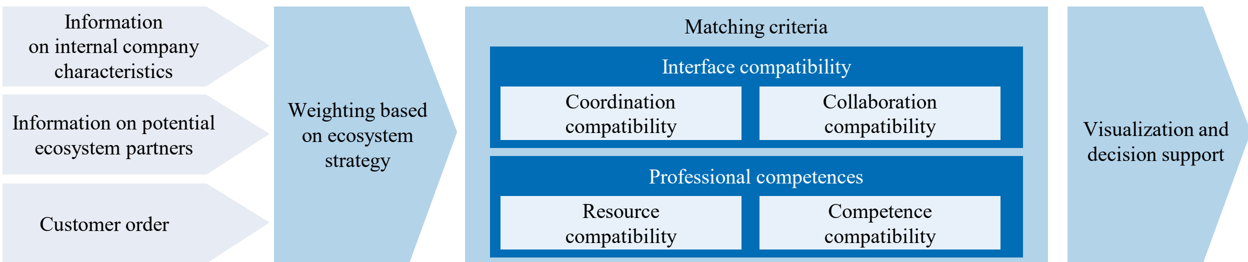

Figure 3: Systematic of partner matching

4.6 Business model

The business model constitutes the outermost layer of the design model, encompassing all other layers. This illustrates the importance of the underlying business model to make an ecosystem for value creation work.

According to STAEHLER, technology-based business models consist of three elements, the value proposition, the architecture of value creation and the revenue model [19]. All three elements have to be considered in depth in order to tailor the ecosystem to the specific characteristics and boundary conditions of SMEs in single and small batch production.

The value proposition reveals the distinctive benefits that the ecosystem provides to its stakeholders. In this respect, it is essential that there exists a sufficient value proposition for each stakeholder or group of stakeholders. Evident groups of stakeholders are SMEs in single and small batch production as well as their customers. However, even within these groups, further distinctions have to be made, e.g. regarding company sizes or industry sectors. Other relevant stakeholders could be orchestrating organizations, which require an appropriate value proposition in order to compensate their coordination efforts. To ensure social sustainability, the ecosystem should be equally beneficial for all kinds of companies.

The primary benefit for the participating companies in single and small batch production is an increase in competitiveness by an optimal use of available manufacturing capacities of a multitude of companies. This includes automated and intelligent order placements and competitive comparisons, partner prioritization, integrated partner management, and capacity alignment to meet on-time delivery commitments. The platform undertakes the time- and resource-consuming search and selection of suitable ecosystem companies for large or highly complex orders through automatic partner matching. Additionally, the ecosystem participants benefit from a free capacity-planning tool, as the majority of SMEs in single and small batch production do not have a planning system. The use of the tool in turn helps the platform with intelligent order placements. Moreover, suitable orders are proposed on the basis of the company's own capacity and technological capabilities. Companies can also achieve economies of scale by intelligently allocating similar orders through the ecosystem to standardize their value creation processes and to increase their margins.

The customers benefit from an automatic supplier assignment based on competencies and specifically selected requirements (e.g. high quality and fast delivery). Customers also gain benefits from a partially automated calculation and the determination of real delivery dates based on real-time capacities. Fast delivery for rush orders is made possible at extra charge by intelligent distribution to several ecosystem companies. The mentioned value propositions and described functions have to be integrated within the platform. Eventually, revenue models can be developed and tested. Suitable concepts could include a transaction-based pricing or membership fees.

5. Summary and outlook

Industrialization has brought prosperity and growth to manufacturing companies. However, it also led to overproduction and a low utilization period of consumer goods. Consequently, more and more stakeholders are demanding for more sustainable value creation in manufacturing companies. In addition, market dynamics recently have been rapidly increasing. These developments pose major challenges, especially for SMEs in single and small batch production. Respective companies are characterized by poor resource efficiency and capacity utilization. Moreover, the individual companies struggle to adapt to changing market requirements or sudden environmental impacts. Resilient and sustainable ecosystems for value creation of SMEs in single and small batch production represent an adequate measure to tackle these challenges. In literature, there exists no suitable approach for ecosystem design, which meets the industry-specific characteristics and boundary conditions. Therefore, this paper presented a design model of an ecosystem for resilient and sustainable value creation of SMEs in single and small batch production. The model is derived from the generic reference framework for network design by FRIEDLI ET AL. and the elements of ecosystem definition by GRANSTRAND AND HOLGERSSON. The developed design model comprises five layers. The strategy layer determines the value creation strategy based on resilience and sustainability objectives. The configuration layer defines the physical structure of the ecosystem, while the coordination layer focuses on ecosystem management and control. The partner matching encompasses the above-mentioned layers and composes optimal project consortiums within the ecosystem. Eventually, the business model defines the value proposition, the architecture of value creation and the revenue model of the platform. The results are more stable, faster and self-configurable value creation systems that ensure rapid and successful adaptation to changing environmental conditions or order volumes. By working together in core business areas, strategic goals can be achieved that are usually outside the capabilities of the individual companies. Future research should focus on the specification of the platform functions as well as the development and testing of reasonable revenue models.

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References

[1] Schuh, G., Kelzenberg, C., & Wiese, J. (2019). Design model for the cost calculation of product-service systems in single and small series production. Procedia CIRP, (84), 296–301.

[2] WZL, & IPT. (2022). Database on companies in single and small batch production.

[3] Schuh, G., Boos, W., Kelzenberg, C., Ebbecke, C., Ochel, T., & Schweins, J. (2021). Sustainable Productivity: Ein neues Produktivitätsverständnis für eine nachhaltige Produktionswende.

[4] Boos, W. (2021). Die Produktionswende - Turning Data into Sustainability: Durch das Internet of Production zu nachhaltiger Produktion und Betrieb.

[5] The Global Compact. (2004). Who cares wins: Connecting financial markets to a changing world.

[6] Purvis, B., Mao, Y., & Robinson, D. (2019). Three pillars of sustainability: In search of conceptual origins. Sustainability Science, 14(3), 681–695.

[7] Boos, W., Kelzenberg, C., Helbig, J., Busch, M., Graberg, T., & Schweins, J. (2020). Competitive Factor Sustainability: A Differentiator for the Tool and Die Industry.

[8] Boos, W., Trauth, D., Arntz, K., Prümmer, M., Niemietz, P., Wilms, M., Lürken, C., & Mayer, J. (2021). Wettbewerbsfaktor Resilienz: Handlungsfelder für den krisensicheren Werkzeugbau.

[9] Walker, W. E., Harremoës, P., Rotmans, J., van der Sluijs, J. P., van Asselt, M.B.A., Janssen, P., & Krayer von Krauss, M. P. (2003). Defining Uncertainty: A Conceptual Basis for Uncertainty Management in Model-Based Decision Support. Integrated Assessment, 4(1), 5–17.

[10] Mertens, P., & Faisst, W. (1997). Virtuelle Unternehmen - Einführung und Überblick. In D. Hahn & B. Taylor (Eds.), Strategische Unternehmungsplanung / Strategische Unternehmungsführung. Physica-Verlag HD., 953–968.

[11] Jackson, D. J. (2011). What is an Innovation Ecosystem? National Science Foundation, Arlington, VA.

[12] Oh, D.-S., Phillips, F., Park, S., & Lee, E. (2016). Innovation ecosystems: A critical examination. Technovation, (54), 1–6.

[13] Autio, E., & Thomas, L. D. W. (2014). Innovation Ecosystems: Implications for Innovation Management? In M. Dodgson, D. M. Gann, & N. Phillips (Eds.), The Oxford handbook of innovation management. Oxford University Press, 204–228.

[14] Thomas, L., & Autio, E. (2019). Innovation Ecosystems. Oxford University Press. Oxford Research Encyclopaedia of Business and Management.

[15] Granstrand, O., & Holgersson, M. (2020). Innovation ecosystems: A conceptual review and a new definition. Technovation, 90–91.

[16] Deloitte. (2015). Digitale Strategien im Mittelstand: Ökosysteme, neue Geschäftsmodelle und digitale Plattformen (Erfolgsfaktoren im Mittelstand).

[17] Choudary, S. P., Parker, G., & van Alstyne, M. (2015). Platform scale: How an emerging business model helps startups build large empires with minimum investment.

[18] Ulrich, P., & Hill, W. (1976). Wissenschaftstheoretische Grundlagen der Betriebswirtschaftslehre. Wirtschaftswissenschaftliches Studium: Zeitschrift Für Ausbildung und Hochschulkontakt, (5),7–8.

[19] Stähler, P. (2002). Geschäftsmodelle in der digitalen Ökonomie: Merkmale, Strategien und Auswirkungen. Dissertation, Eul., (2. Aufl., Vol. 7).

[20] Talmar, M., Walrave, B., Podoynitsyna, K. S., Holmström, J., & Romme, A. G. L. (2020). Mapping, analyzing and designing innovation ecosystems: The Ecosystem Pie Model. Long Range Planning, 101850, 53(4).

[21] Hensel, J. (2007). Netzwerkmanagement in der Automobilindustrie: Erfolgsfaktoren und Gestaltungsfelder. Springer eBook Collection Computer Science & Engineering. DUV.

[22] Ritsch, K. (2005). Wissensorientierte Gestaltung von Wertschöpfungsnetzwerken. Grazer Schriftenreihe Knowledge Management: Vol. 3. Shaker.

[23] Tang, D., Zheng, K., & Gu, W. (2020). Adaptive Control of Bio-Inspired Manufacturing Systems (1st ed. 2020). Research on Intelligent Manufacturing. Springer Singapore Pte. Limited.

[24] Dressler, F., & Akan, O. (2010). Bio-inspired networking: from theory to practice. IEEE Communications Magazine, 48(11), 176–183.

[25] Scholz-Reiter, B., Karimi, H. R., Duffie, N. A., & Jagalski, T. (2011). Bio-inspired capacity control for production networks with autonomous work systems.

[26] Friedli, T., Mundt, A., & Thomas, S. (2014). Strategic management of global manufacturing networks: Aligning strategy, configuration, and coordination. Management for Professionals. Springer.

[27] Bleicher, K. (2003). Integriertes Management von Wertschöpfungsnetzwerken. In N. Bach, W. Buchholz, & B. Eichler (Eds.), Springer eBook Collection Business and Economics. Geschäftsmodelle für Wertschöpfungsnetzwerke. Gabler Verlag, 145–178.

[28] Gunarathne, N., & Lee, K.-H. (2021). The link between corporate energy management and environmental strategy implementation: Efficiency, sufficiency and consistency strategy perspectives. Journal of Cleaner Production.

[29] Ahir, H., Bloom, N., & Furceri, D. (2022). The World Uncertainty Index. Cambridge, MA.

[30] Schuh, G., Millarg, K., & Göransson, Å. (1998). Virtuelle Fabrik: Neue Marktchancen durch dynamische Netzwerke. Hanser.

Biography

Günther Schuh (*1958) holds the Chair of Production Systems at the Laboratory for Machine Tools and Production Engineering WZL at RWTH Aachen University, is a member of the board of directors of the Fraunhofer Institute for Production Technology IPT and director of the Research Institute for Rationalization (FIR) of the RWTH Aachen University.

Gerret Lukas (*1991) holds a master's degree in Industrial Engineering and has been head of the Corporate Development Department at the WZL since 2022. In addition, Gerret is Director of Projects at the Aachen Center for Additive Manufacturing (ACAM) and Head of Consulting at the WBA Tooling Academy.

Christoph Frey (*1992) studied Business Administration and Mechanical Engineering specializing in Production Technologies at the RWTH Aachen University and Tsinghua University. He is research associate at the Corporate Development Department of the WZL as well as Head of Center Development at the ACAM and the WBA Tooling Academy.

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Process-oriented evaluation system for the use of robotic process automation

Christian Ortmeier[1], Adrian Langer[1], Kira Welzel[1], Tim Abraham[1], Christoph Herrmann[1]

[1]*Institute of Machine Tools and Production Technologies / Chair of Sustainable Manufacturing and Life Cycle Engineering / Technische Universität Braunschweig, Langer Kamp 19b, 38106 Braunschweig, Germany*

Abstract

The administrative order processing is confronted with a variety of structural, procedural and organizational changes driven by the increasing demand for shorter delivery times and higher product variances. Thus, business processes become more complex and less transparent having a negative impact on administrative order processing. Studies estimate the waste in indirect areas at around 30 percent. The cause of this waste is, for example, missing information in the process step or interface losses during the transfer to another area of responsibility. This results in queries and coordination efforts that delay the order process. Among other things, robotic process automation (RPA) can be used to reduce waste. This enables the monitoring of administrative processes and the automation of sub-processes (activities). Identifying these automation potentials can be seen as a major challenge in administrative order processing due to the existing complexity. One way to discover automation potential is the use of data-driven tools such as process mining (PM). Using algorithms, a process model can be created on the basis of data from central information systems (e.g. enterprise resource systems), which enables a systematic analysis of causalities. Furthermore, PM can help to identify the relevant indicators for the suitability of the use of RPA in a data-driven way to decisively support the selection process. In the current state of research, most paper applying PM focus on quantifiable indicators for evaluating RPA capabilities. Qualitative criteria for RPA use are rarely considered.

This paper proposes on a qualitative criteria-based and quantitative indicator-based evaluation system for the use of RPA in administrative order processing, with the aim of eliminating waste in the sense of Lean Administration. The approach is validated in a PM software using a data set related to administrative order processing.

Keywords

business administration; lean administration; process mining; robotic process automation; evaluation system

1. Introduction

In recent decades, considerable potential has been leveraged in production by implementing the principles of the Toyota Production System as part of the Holistic Production System in manufacturing companies. These principles are increasingly being adapted to the indirect area as well, through so-called lean administration (LA). [1] Indirect areas are defined as areas which have a supporting function for the direct area, i.e. production, and are not directly involved in the physical production of goods. Examples of indirect areas are development, purchasing and sales. [2]

Administrative processes of indirect areas show significant differences to production processes. While raw materials and materials are processed in production processes, administrative processes generate data / information and intangible services that are far less visible and thus less traceable. Compared to production

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processes, these work contents are subject to high fluctuations in terms of the scope of work and the quality of information. Furthermore, administrative activities are less standardized and documented and therefore more difficult for employees to record. [3] Incidental tasks require flexible action, creative problem solving and a certain degree of freedom to make decisions [2]. As a result, the processing times in these process steps are highly variable. Nevertheless, they are essential for direct areas [4].

Less structured processes, a lack of transparency, a lack of process-related key performance indicators and a high coordination effort due to interdepartmental interfaces thus pose major challenges for the implementation of LA. Furthermore, LA methods are increasingly reaching their limits due to the dynamic environment and the existing complexity in administrative processes. An example of this is the process mapping through Makigami, which is very time-consuming and often only maps a small proportion of all possible process variants. Data-driven process modeling, in combination with the expert knowledge of employees, can compensate those disadvantages. In principle, synergies can be created on both sides by meshing the mindsets of LA and digital transformation. A study by SZEDLAK confirms this positive correlation between the two mindsets. For example, the study identified increased progress in LA among companies that have reached a high level of maturity in digitalization. Further, positive effects on corporate culture, leadership and collaboration were recognized. But also the process-oriented mindset promoted by LA was seen by the participating companies as a support for a sustainable introduction of digital tools. [5]

Despite all the challenges, administrative processes, as well as production processes, are to some extent repetitive, standardizable and measurable. Here, digital transformation tools can help to increase process transparency in order to systematically identify and specifically eliminate waste. In particular, PM and RPA have proven to be effective tools for identifying (through PM) and reducing (through RPA) waste in manual, repetitive activities. However, the identification of suitable processes poses major challenges for companies. Usually, the implementation of one of these technologies is understood as a stand-alone digitization solution. However, the combination of process and technology perspective can help to systematically identify and eliminate waste in administration. In the following, therefore, an approach is outlined which, taking into account the process-oriented mindset of the LA, should enable companies to make a targeted identification of administrative processes for the use of RPA.

2. Process mining and robotic process automation

2.1 Process mining

PM can be seen as a bridging discipline between the disciplines of Process Science and Data Science. The research field of Process Science includes disciplines of Business Process Management (BPM) or Operation Research (OR). These disciplines have a process-oriented character. In contrast, data-oriented approaches can be found in the research field of Data Science, including data mining, stochastics or visual analytics. The approaches of PM are especially related to those of Data Mining. In essence, three types of PM can be distinguished, which are briefly explained below [6, 7]:

- **Process discovery:** Process discovery uses an event log to generate a process model without using a-priori information. It is the most commonly used type of PM [8].
- **Conformance checking:** Conformance checking is characterized by comparing an already known process model with an event log of the same process. It is checked whether the process model corresponds to the reality (event log) or the reality (event log) corresponds to the model. The output generated here is diagnostic information about similarities and differences between the model and the event log.
- **Process enhancement:** In process enhancement (performance analysis), information about the actual recorded process from the event log is used to extend an existing process model and improve it if necessary.

In all types of PM, an event log is required as an input factor, which means that they have a crucial role. Especially in process discovery, the direct influence on the quality of the generated process model becomes clear. In essence, event logs provide information about the systemically recorded process steps. It is necessary that an event log contains at least information about the case, event and timestamp. To create realistic process models, a large number of cases is required. This is the only way to comprehensively map the complexity of the processes. For example, in the context of order processing, a case can be a unique order number. In this example, the events are activities such as order release, order completion, shipping, or invoicing. Accordingly, a case can contain a certain set of events. The timestamp provides a unique reference about the sequence of events. In addition to these minimum requirements, further information can be added to the event logs as attributes. [9,10,11]

With the help of algorithms, so-called miners, process models are generated in PM from the event logs, with the aim of showing the most accurate underlying model that is not invalidated by the next observations. [6] With the help of these process models and the knowledge of all process participants, administrative waste (e.g., process loops due to insufficient information or high inventories) can be identified and measures derived in a targeted manner. In this context, automation potentials can also be identified in order to use RPA.

2.2 Robotic process automation

According to the *Institute For Robotic Process Automation & Artificial Intelligence* (IRPAAI), the term RPA refers to a technological application “that allows employees in a company to configure computer software or a 'robot' to capture and interpret existing applications for processing a transaction, manipulating data, triggering responses and communicating with other digital systems.” [12]. The programmed “software robots” are capable of performing individual process steps in an automated manner. The software robot interacts with the IT systems involved in the process to imitate human user interaction in the process based on explicit if-then rules. In this process, data is extracted, manipulated and entered as input into other applications. Therefore, RPA can be seen as a non-invasive technical application that acts at the presentation layer. [13] An empirical study proves that the use of RPA entails low investment costs, short developing time, an increase in performance and a simultaneous reduction in costs and throughput time [32]. For this reason, RPA makes a wider range of processes lucrative for automation than traditional automation technologies [29].

Since RPA applications can interact with the user in the process and be triggered by certain actions, also partial process automation is enabled. Likewise, RPA applications can be used exclusively for process control, for example, to monitor incoming payments in finance and to improve process quality. In essence, software robots can be characterized as follows [14]: Software robots automate processes originally performed by humans, follow a choreography of technical modules and control flow operators and operate in an IT ecosystem and use existing applications.

3. State of the art

To identify the current state of research, a systematic literature research was conducted. In the process, the current literature databases were searched for existing approaches in the areas of “conventional criteria for identifying automation potential”, “data-based criteria for identifying automation potentials” as well as the “combination of PM and RPA”. After the initial screening, in summary 18 approaches were identified for detailed analysis. These approaches can be found in table 1.

Table 1: Identified approaches of the systematic literature research

Literature	Main focus
Category 1: Conventional criteria for automation potential	
[15] Fung 2014	Literature and interview-based discussion of criteria for the use of Information Technology Process Automation (ITPA)
[13] Smeets et al. 2019	Technical and business criteria for selecting the processes to be automated
[16] Beetz und Riedl 2019	Technical, business and organizational criteria for process selection
[17] Syed et al. 2020	Evaluation of existing literature to identify organizational and process criteria that indicate RPA maturity
[18] Langmann und Turi 2020	Minimum, additional and special criteria for the selection of RPA-suitable processes
[19] Eggert und Moulen 2020	Interview-based identification of practice-relevant criteria for the selection of business processes
[20] Plattfault et al. 2020	Interview-based identification of evaluation criteria for the suitability of a process for an RPA implementation
[21] Wellmann et al. 2020	Reference framework for the evaluation of RPA-suitable process characteristics
[22] Wanner et al. 2019	Multidimensional indicator system for quantifying the automation potential of a process
[23] Viehhauser und Doerr 2021	Identification and weighting of indicators to quantify the automation potential of a process
[24] Jeeva et al. 2021	Literature and interview-based identification of measurable criteria for process selection
Category 2: Data based criteria for automation potential	
[25] Leopold et al. 2018	Automatic recognition of the degree of automation of a process based on textual process descriptions using Natural Language Processing
[26] Van der Aa und Leopold 2021	Automatic recognition of automatable activities based on process models using Natural Language Processing
[24] Jeeva et al. 2021	Classification model for the selection of automatable processes
[27] Urabe et al. 2021	Clustering of user interface logs for the identification of task types and the respective workload as decision support for the selection of automatable processes
[28] Leno et al. 2021	Robotic process mining
Category 3: Combination of PM and RPA	
[29] Van der Aalst 2021	Identification of the interplay between process mining and RPA
[30] Schlund und Schmidt 2021	Challenges and future perspectives of RPA
[22] Wanner et al. 2019	Process mining as a basis for calculating quantitative indicators and optimizing economic benefits
[21] Wellmann et al. 2020	Application of the reference framework with the help of process mining for indicator-based determination of activities that can be automated
[31] Choi et al. 2021	Methodology for process selection by means of process mining

The analysis of existing approaches has shown that no generally valid criteria and indicators for identifying automation potential could be identified. Rather, there is great disagreement about which criteria and indicators are to be classified as relevant. Likewise, the granularity of the indicators and criteria shows great differences. Thus, according to some authors, the evaluation of indicators based on nominal or ordinal scales is sufficient, whereas other authors prefer a clear mathematical description. This reduces subjective influence in the context of scale-based evaluation by process experts. When analyzing the indicators, the differences in granularity also become clear. It can be seen that some of these are defined at the level of processes, subprocesses, or even activity level. Above all, it is striking that different approaches exist to define the same indicator, for example the degree of standardization. Furthermore, there is a lack of a holistic view of qualitative criteria and quantitative indicators. For example, information quality is not sufficiently considered in various approaches, despite its high importance for the application of PM.

This lack of general validity of the indicators and criteria makes it difficult for users to evaluate suitable processes in a targeted manner. In a study conducted by PLATTFAUT, for example, users describe the indicators and criteria available to date as, among other things, “too diffuse,” “not differentiated enough,” and “too intransparent" [22]. As a result, VAN DER AALST, among others, sees a need for further research in the identification of characteristics that describe the suitability of a process for an RPA deployment [29].

A catalog is therefore needed that adequately reflects the current state of research by combining qualitative criteria with quantitative indicators and categorizing them consistently as well as expanding them to include missing aspects. Even if this catalog will not establish general validity over the indicators and criteria, the user can thus fall back on a well-founded holistic tool. In addition to the PM and RPA specific criteria, the aspects of the LA must also be taken into account. This catalog of criteria and indicators is being developed as part of the evaluation system.

4. Development of the evaluation system

The process-oriented evaluation system for the use of RPA contains the catalog described above, including the qualitative criteria and quantitative indicators. The aim of the evaluation system is to provide the user with a defined order for identifying automation potentials in the indirect area, whereby certain degrees of freedom can be taken for individual use. In comparison to key figures, which in accordance with their merely descriptive function condense information and facts quantitatively in the form of a number, indicators do not describe directly measurable variables. Indicators therefore allow conclusions to be drawn about the characteristics and changes in complex processes. As a result, we will continue to refer to indicators. The developed evaluation system is described in detail below.

On the one hand, the event logs extracted from the IT systems (e.g. ERP systems) and, on the other hand, the expert knowledge of the process participants serve as input factors for the evaluation system (see figure 1). Quantitative indicators are determined from the event logs through the targeted use of PM, so that well-founded indicators based on the actual processes can be calculated and incorporated into the subsequent evaluation of RPA potential. This reduces the possibility of spurious accuracy compared to other approaches in the literature that consider purely qualitative criteria. However, as described above, the data quality of the event logs has a significant impact on the process model and thus also on the indicators. So qualitative criteria are added to the evaluation system. At this point, the expertise of the process owners is included. PM can support the process owners by increasing the process transparency through the visualization of the process model. Another advantage of including employee experience and expert knowledge is that the concept can also process information that is not interval-scaled or of high quality, as required, for example, by the approaches of VIEHHAUSER and DOERR, WELLMANN and CHOI (see table 1).

The previous approaches in the literature determine the qualitative criteria and quantitative indicators on the process or activity level. The latter is only pursued in the approaches of WANNER ET AL. and CHOI ET AL. They do not determine the automation potential for complete processes, but for individual activities independent of their process affiliation.

If the automation potential is only determined at the process level, there is a possibility that high or low automation potentials of the activities within the process compensate each other, which consequently leads to a low value of automation potentials for the entire process. Therefore, the determination of the automation potentials of individual activities proves to be advantageous. On the other hand, taking this perspective requires considerable time in practice. The evaluation system presented here takes advantage of both perspectives and therefore includes both the process and the activity level. To limit the analysis effort, a pre-selection of processes apparently suitable for the use of RPA is included. The criteria and indicators can already be consulted. The quantitative indicators are considered at the activity level, since a quick calculation can be made here through the PM. The qualitative criteria are first assessed at the process level in order to use employee experience to evaluate, among other things, higher-level impact relationships. After pre-selection by the quantitative indicators and qualitative criteria, qualitative criteria are used at the activity level to make a final process selection.

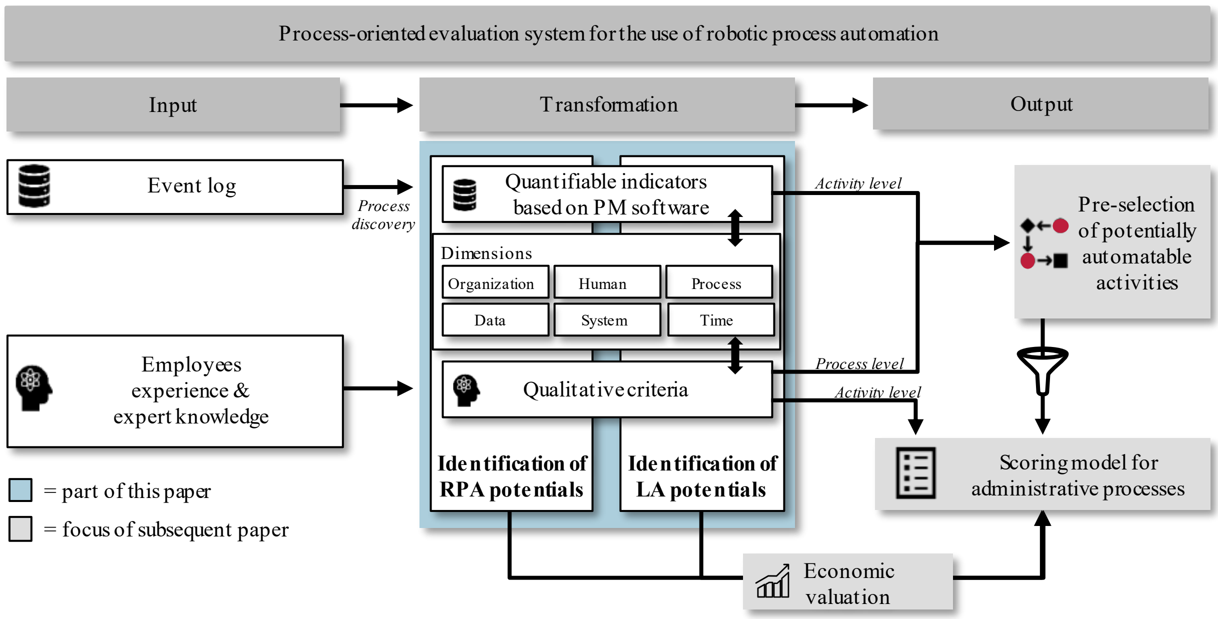

Figure 1: Process-oriented evaluation system for the use of RPA

The criteria and indicators integrated in the evaluation system can be classified into six dimensions (organization, human, process, data, system, time). These are used to determine the automation potential and to determine the LA potential. By determining both potentials, the scoring model prioritizes the ranking so that not only technology-specific requirements but also process-specific impacts on the implementation of LA are considered. In order to gain a better understanding of the structure and content of the criteria and indicators, they are presented in abbreviated form below.

5. Identification of RPA and LA potentials by means of criteria and indicators

The evaluation system is essentially based on two catalogs, which in turn contain assessment objects in the sense of criteria or indicators (see figure 2). If the approaches already discussed (see table 1) provide assessment objects, these are included in the catalogs. If no criteria or indicators are available in the literature for an assessment object, these are developed within the scope of this work. In some cases, qualitative criteria and quantitative indicators are available to the user for the evaluation.

Some assessment objects require a subjective evaluation and are therefore difficult to measure. For this reason, these are only included as criteria. Examples are the repetitive character of an activity, which is perceived by the executing employee, or the influences of automation on customer satisfaction, which are difficult or impossible to measure. [17,18] Here, in addition to the PM-based determination of the indicator, the user can determine the criteria, keeping subjective influences low to ensure objectivity. All criteria and indicators include a brief description and, in the case of the latter, a calculation specification as well. The notation used is based on WANNER ET AL. [22]

The determination of assessment objects with regard to LA potential is based on three building blocks. First, criteria and indicators from the literature were examined and implemented. For example, line efficiency or flow rate are classic lean indicators. [2] Further, criteria could be derived and integrated by analyzing the types of waste. In addition, the connection to the assessment objects of the automation potentials was investigated. Thus, the influences of the criteria and indicators on the LA potential were examined qualitatively. If an influence is suspected, the criteria or indicator is added to the catalog for determining the LA potential. For example, case frequency is included in this catalog because the higher the case frequency of a process, the higher the impact of eliminating waste in that process appears to be. This is also true for cycle time or processing time. Finally, all aspects of data quality are also included in the catalog, since it can be assumed in the course of the digital transformation that efficient process design is increasingly dependent on the quality of the data or information used.

The evaluation system provides for an individual selection of criteria and indicators. This offers the advantage of a situational adaptation to the decision problem at hand and to the associated framework conditions. However, the disadvantage is that individual selection counteracts the standardization and formalization of the decision-making process. For this reason, the freedom of choice is limited by a minimum selection per dimension, which is mandatory. If the possibility of recording exists, the indicator is to be preferred to the criteria even in the case of the minimum selection.

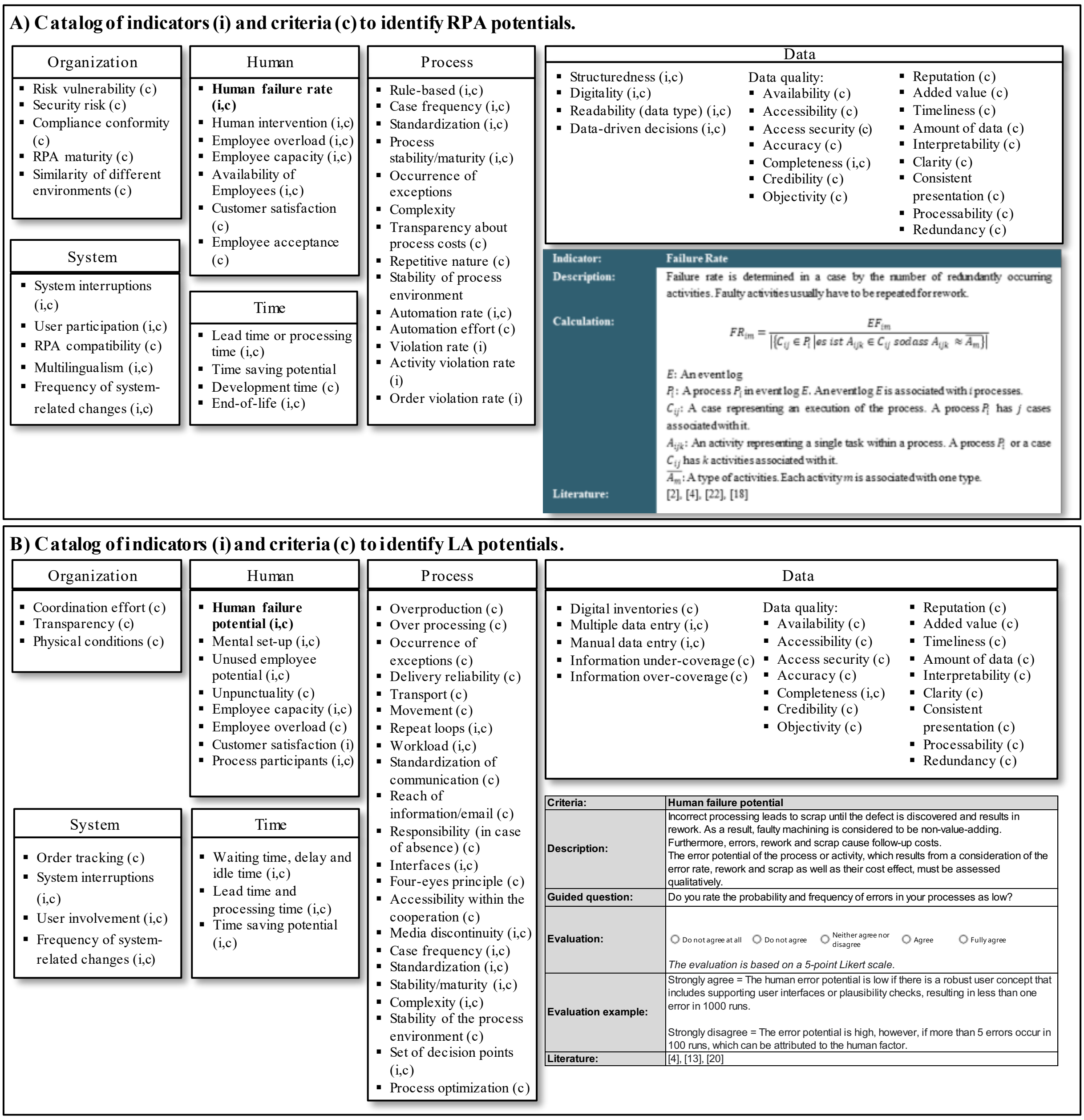

Figure 2: Catalog of indicators and criteria

6. Application, Validation and Outlook

The evaluation system is applied to an exemplary event log representing 1.12 million cases of a Purchase-to-Pay process (P2P) and 988 thousand cases of an Order-to-Cash process (O2C) provided by the PM software Celonis. The P2P process includes all activities to be performed from a good's procurement to the payment of the invoice, while the O2C process is its counterpart at the supplier's site. Since the preselection is trivial due to the given event log, a subset of criteria and indicators to identify the RPA and LA potential is formed based on the catalogs in a first step. This aims to address the most frequently mentioned RPA-criteria as well as all types of waste and to make maximum use of the event log. The extracted process models are then analyzed to determine the indicator values of each activity in Celonis.

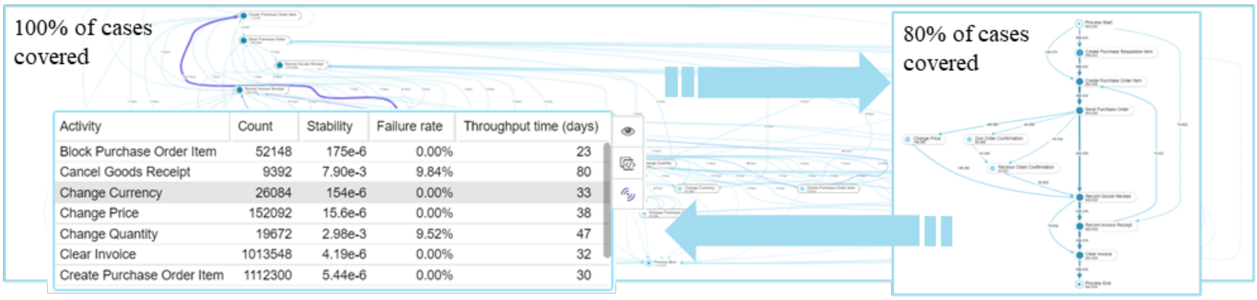

Figure 3: Indicator values of individual activities of the P2P process in Celonis

Due to the lack of deeper process-related knowledge, the criteria values of the activities are estimated on a scale from one to five regarding the respective context, where five is ideal. While the goods receipt, for example, seems to require frequent human intervention, sending an invoice appears to be more suitable for RPA. In terms of aggregation, a normalization and weighting of each criterion and indicator is needed. The lack of empirical knowledge about the ideal indicator values causes that these are normalized regarding the occurred minimum and maximum value. Criteria can be normalized based on the evaluation scale. To align the weighting with the objective of the RPA project, the objective dimensions "costs", "quality" and "time" are ranked and causal connections to the dimensions of the catalogs are qualitatively identified. Those criteria and indicators of the dimensions that are linked to the most important objective dimension are weighted three times higher than those linked to the least important one. This further allows to aggregate the criteria and indicator values to the RPA potential of each activity. The LA potential is calculated the same way, but at the process level. Based on the RPA potential, the decision whether an activity should be included in the partial automation of a process is made. The decision making might be supported by a threshold that in this case is estimated regarding the respective context. The RPA potential of the activities is then aggregated to the process level. The P2P process reaches an RPA potential of 54%, while the one of the O2C process is 69%. In addition, the LA potential of the P2P and O2C process are 58% and 49%. Visualizing the RPA potential, the LA potential and the results of an economic feasibility study, that is not shed light on in this paper, in a portfolio allows to determine the Euclidean distance of each process to the ideal value. Thus, the processes can be ranked and selected by averaging the three decision-making factors. Regarding the RPA and the LA potential only, a partial automation of the O2C process is recommended within the evaluation system application. Finally, a verification of the choice by examining the criteria and indicator values of the chosen activities allows to detect challenging criteria and indicator values that are compensated through the aggregation. For a first step of validation, the calculated RPA potential of each activity is compared to the recorded automation rate in Celonis, because it is assumed that an above-average automation rate correlates with a high actual RPA potential. The reproduction of the decision whether an activity should be automated using the automation rate shows that the calculated RPA potential is 88% in line with the automation rate. The evaluation system seems to be well suited to evaluate the RPA potential of a process.

All in all, this paper presents a process-oriented evaluation system that supports a more impartial multi criteria decision making using PM to identify the RPA and LA potential of administrative processes. The combination of qualitative criteria and quantitative indicators allows maximum use of the given process-related knowledge and event log. Although, the evaluation system needs to be further validated. Considering the catalogs of criteria and indicators future research opportunities arise. Empirical studies might support the determination of ideal indicator values. Moreover, the examination of their relevance and possible effects of multicollinearity might lead to a more sophisticated choice of criteria and indicators.

References

[1] Kubenz, L., Pötters, P., Kamiske, G., 2019. Lean Office. Grundlagen, Methoden und Umsetzungsleitfaden. München: Hanser. P. 5.

[2] Bertagnolli, F., 2020. Lean Management. Einführung und Vertiefung in die japanische Management-Philosophie. 2. Aufl. Wiesbaden: Springer Gabler. P. 224

[3] Schuh G., Potente T., Bachmann F., Nuyken T., 2012. Lean Management in indirekten Bereichen: Methodenunterstützter Wandel der Unternehmenskultur. In: Zeitschrift für wirtschaftlichen Fabrikbetrieb 107 (6). P. 399–403. DOI: 10.3139/104.110776.

[4] Balsliemke, F., Behrens, A., 2019. Einstieg in Lean Administration. Optimierungspotentiale in Büro und Verwaltung erkennen. 1. Aufl. Wiesbaden: Springer Gabler. P. 7.

[5] Szedlak, C., Wagner, K., Leyendecker, B., 2020. Contradictions and Complements of Lean Administration and Digitalization. In: IEOM Society International (Hg.): Proceedings of the 2nd African International Conference on Industrial Engineering and Operations Management. Harare, Zimbabwe, 7.-10. December 2020, P. 582–590.

[6] van der Aalst, W. M. P., 2011. Process Mining. Discovery, Conformance and Enhancement of Business Processes. Berlin, Heidelberg: Springer.

[7] Dumas, M., La Rosa, M., Mendling, J., Reijers, H. A., Grisold, T., 2021. Grundlagen des Geschäftsprozessmanagements. Berlin Heidelberg: Springer Vieweg. P. 489.

[8] Garcia, C. d. S.; Meincheim, A.; Faria Junior, E. R.; Dallagassa, M. R.; Sato, D. M. V.; Carvalho, D. R.; Santos, E. A. P.; Scalabrin, E. E., 2019. Process mining techniques and applications – A systematic mapping study. In Expert Systems with Applications. P. 260–295

[9] Peters, R.; Nauroth, M., 2019. Process Mining. Wiesbaden: Springer Fachmedien Wiesbaden. 2019. P. 15.

[10] Ortmeier, C.; Henningsen, N.; Langer, A.; Reiswich, A.; Karl, A.; Herrmann, C., 2021. Framework for the integration of Process Mining into Life Cycle Assessment. In Procedia CIRP. 2021. P. 163–168.

[11] van der Aalst, W., Adriansyah, A., Medeiros, Ana Karla A., Arcieri, F., Baier, T., Blickle, T. et al., 2012. Process Mining Manifesto. In: Florian Daniel, Kamel Barkaoui und Schahram Dustdar (Hg.): Business Process Management Workshops. Berlin, Heidelberg: Springer Berlin Heidelberg. P. 169–194.

[12] Institute For Robotic Process Automation & Artificial Intelligence (IRPAAI): Definition and Benefits | IRPAAI. URL: http://irpaai.com/definition-and-benefits/

[13] Smeets, M., Erhard, R., Kaußler, T., 2019. Robotic Process Automation (RPA) in der Finanzwirtschaft. Technologie – Implementierung – Erfolgsfaktoren für Entscheider und Anwender. 1. Aufl. Wiesbaden: Springer Gabler.

[14] Hofmann, P., Samp, C., Urbach, N., 2020. Robotic process automation. In: Electron Markets 30 (1), P. 99–106.

[15] Fung, H. P., 2014. Criteria, Use Cases and Effects of Information Technology Process Automation (ITPA). In: Advances in Robotics & Automation 3 (3).

[16] Beetz, R., Riedl, Y., 2019. Robotic Process Automation: Developing a Multi-Criteria Evaluation Model for the Selection of Automatable Business Processes. In: New frontiers in digital convergence. 25th Americas Conference on Information Systems (AMCIS 2019). Cancun, Mexico, 15.-17. August 2019. Association for Information Systems. New York: Red Hook (2), S. 1109–1118.

[17] Syed, R., Suriadi, S., Adams, M., Bandara, W., Leemans, S. J. J., Ouyang, C. et al., 2020. Robotic Process Automation: Contemporary themes and challenges. In: Computers in Industry 115.

[18] Langmann, C., Turi, D., 2021. Robotic Process Automation (RPA) - Digitalisierung und Automatisierung von Prozessen. Voraussetzungen, Funktionsweise und Implementierung am Beispiel des Controllings und Rechnungswesens. 2. Aufl. Wiesbaden: Springer Gabler.

[19] Eggert, M., Moulen, T., 2020. Selektion von Geschäftsprozessen zur Anwendung von Robotic Process Automation am Beispiel einer Versicherung. In: HMD Praxis der Wirtschaftsinformatik 57, P. 1150–1162.

[20] Plattfaut, R., Koch, J. F., Trampler, M., Coners, A., 2020. PEPA: Entwicklung eines Scoring-Modells zur Priorisierung von Prozessen für eine Automatisierung. In: HMD Praxis der Wirtschaftsinformatik 57 (6), P. 1111–1129.

[21] Wellmann, C., Stierle, M., Dunzer, S., Matzner, M., 2020. A Framework to Evaluate the Viability of Robotic Process Automation for Business Process Activities. In: Aleksandre Asatiani et al. (Hg.): Business Process Management: Blockchain and Robotic Process Automation Forum. Cham: Springer International, P. 200–214.

[22] Wanner, J., Hofmann, A., Fischer, M., Imgrund, F., Janiesch, C., Geyer-Klingeberg, J., 2019. Process selection in RPA projects-towards a quantifiable method of decision making. Hg. v. Fortieth International Conference on Information Systems. München.

[23] Viehhauser, J., Doerr, M., 2021. Digging for Gold in RPA Projects - A Quantifiable Method to Identify and Prioritize Suitable RPA Process Candidates. In: Mar-cello La Rosa, Shazia Sadiq und Ernest Teniente (Hg.): Advanced Information Systems Engineering. Cham: Springer International Publishing, P. 313–327.

[24] Jeeva, K. V.; Padmini; Perera, G. I. U. S.; Dilum Bandara, H. M. N.; Silva, R. K. Omega H., 2021. A Decision Support Tool to Select Candidate Business Processes in Robotic Process Automation (RPA): An Empirical Study. In: S. Smys et al. (Hg.): Inventive Computation and Information Technologies. Singapore: Springer Singapore, P. 567–582.

[25] Leopold, H., van der Aa, H., Reijers, H. A., 2018. Identifying Candidate Tasks for Robotic Process Automation in Textual Process Descriptions. In: Jens Gulden et al. (Hg.): Enterprise, Business-Process and Information Systems Modeling. Cham: Springer International Publishing, P. 67–81.

[26] van der Aa, H., Leopold, H., .2021. Automatically Identifying Process Automation Candidates Using Natural Language Processing. In: Agnes Koschmider und Stefan Schulte (Hg.): Blockchain and Robotic Process Automation. Cham: Springer International Publishing, P. 77–86.

[27] Urabe, Y., Yagi, S., Tsuchikawa, K., Oishi, H., 2021. Task Clustering Method Using User Interaction Logs to Plan RPA Introduction. In: Polyvyanyy, A. et al. (Hg.): Business Process Management. Cham: Springer International Publishing, P. 273–288.

[28] Leno, V., Polyvyanyy, A., Dumas, M., La Rosa, M., Maggi, F. M., 2021. Robotic Process Mining: Vision and Challenges. In: Business & Information Systems Engineering 63 (3), P. 301–314.

[29] van der Aalst, W. M. P., 2021. Process mining and RPA. How to pick your automation battles? In: Czarnecki C. und Fettke P. (Hg.): Robotic Process Automation. Management, Technology, Applications. Berlin, Boston: De Gruyter Oldenbourg, P. 223–243.

[30] Schlund, S., Schmidt, M., 2021. Robotic Process Automation in Industrial Engineering: Challenges and Future Perspectives. In: Trzcielinski et al. (Hg.): Advances in Manufacturing, Production Management and Process Control. Cham: Springer International Publishing, P. 320–327.

[31] Choi, D., R'bigui, H., Cho, C., 2021. Candidate digital tasks selection methodology for automation with robotic process automation. In: Sustainability (Switzerland) 13 (16).

[32] Kroll, C., Bujak, A., Darius, V., Enders, W., Esser, M., 2016. Robotic Process Automation - Robots conquer business processes in back offices. Capgemini Consulting. https://www.capgemini.com/consul-ting-de/wp-content/uploads/sites/32/2017/08/robotic-process-automation-study.pdf, checked on 11/03/2022.

Biography

Christian Ortmeier (*1992) studied industrial engineering with a specialisation in mechanical engineering at the TU Braunschweig. Since 2019, he has been working as a research assistant at TU Braunschweig in the sustainable production and factory systems working group of the Institute of Machine Tools and Production Technology (IWF) with a special focus on data-driven methods and tools in lean administration.

Adrian Langer (*1993) studied industrial engineering with a specialisation in mechanical engineering at the TU Braunschweig. Since 2019, he has been working as a research assistant at TU Braunschweig in the sustainable production and factory systems working group of the Institute of Machine Tools and Production Technology (IWF) with a special focus on simulation of production systems.

Kira Welzel (*1998) completed an apprenticeship in mechatronics and a bachelor's degree in industrial engineering as part of a dual study program at Phoenix Contact GmbH & Co. KG. Since then, she has been pursuing a master's degree in industrial engineering with a specialisation in mechanical engineering at the TU Braunschweig. At the Institute of Machine Tools and Production Technology (IWF) she worked as a student assistant in the research field of process mining and lean administration.

Dr. Tim Abraham (*1987) studied industrial engineering with a specialisation in mechanical engineering at the TU Braunschweig. Since 2014, he has been working at the IST, Fraunhofer Institute for Surface Engineering and Thin Films completing his PhD in 2019. Since 2020, he is head of the sustainable production and factory systems working group of the Institute of Machine Tools and Production Technology (IWF).

Prof. Dr.-Ing. Christoph Herrmann (*1970) is university professor for Sustainable Manufacturing & Life Cycle Engineering and co-director of the Institute of Machine Tools and Production Technology (IWF), TU Braunschweig as well as director of the Fraunhofer Institute for Surface Engineering and Thin Films IST since November 2018.

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Investigating The Role Of Digitalization In Operational Excellence Programs – A Case Study From The Pharmaceutical Industry

Lorenzo Pirrone[1], Matteo Bernasconi[1], Thomas Friedli[1]
[1]*Institute of Technology Management, University of St.Gallen, St.Gallen, Switzerland*

Abstract

For years, manufacturing companies have been implementing Operational Excellence (OPEX) programs with the goal of effectively and sustainably improving their performance. Now, companies are also gradually recognizing the possibilities of Digitalization for advancing their operational processes. Even though both OPEX and Digitalization are directed towards the same goal of improved operational performance, there is neither an answer in research nor in practice on how they are or can be interlinked. That is, how processes and the organization to align and reconcile should look like?

To address this question, we conducted 25 interviews with pharmaceutical companies. Thereby we interviewed corporate OPEX functions and Digitalization experts over a timespan of three years. That way we also examine whether companies have adapted and investigate patterns in their development.

Our findings acknowledge that pharmaceutical companies aim to exploit synergies between OPEX and Digitalization for achieving higher operational performance. We further applied a dynamic capabilities perspective to identify how companies align OPEX and Digitalization. Our limitation is that we conducted interviews only within the Pharmaceutical Industry and that each company is unevenly reflected over the duration of the investigation. However, we mitigate that limitation by considering a rather large number of cases reflected in a sample size (16 companies) with a good balance of different company sizes (2.000 – 110.000 employees) and business areas (generics, labelled, and contract manufacturing).

Keywords

Digitalization; OPEX; Dynamic Capabilities; Continuous Improvement; Lean; Pharma Industry

1. Introduction

Operational Excellence (OPEX) can be understood as constant activities to enhance the level of organization-wide performance through targeted, incremental change [1]. Companies have tried to formalize their OPEX activities in programs that consist of organized systems allowing for discovery and implementation of process changes. Despite the need of an infrastructure to support both the execution and coordination of OPEX projects, most organizations perform respective initiatives by running ad-hoc projects and thereby ignore the more difficult part of project coordination [2]. This is particularly undesirable, since it has been shown by several researchers that OPEX deployments with inadequate coordination will become ineffective after generating initial success [3]. On the contrary, there is the potential that Digitalization can enhance OPEX activities as Digitalization efforts facilitate sharing of easily available and distributable information. As a result more informed decisions and greater autonomy for project groups at lower hierarchy levels can

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be taken [4]. Similarly, Alavi et al. [5] argue that Digitalization allows for flatter hierarchies, decentralized information flows, and greater organizational flexibility. However, identifying the right organizational structure is a complex task managers must deal with [6]. It is only possible to achieve higher performance when an organization's structure is tailored to the particular needs of the organization [7]. Based on this understanding, we investigate the organizational alignment process between OPEX and Digitalization. We ground our theoretical background on OPEX and Digitalization literature, and thereby apply the lens of dynamic capabilities [8] as well as the framework of Yeow et al.[9] describing how to align digital and other business departments through sensing, seizing and transforming. We add to literature by identifying specific alignment activities, incorporating the practical perspective and numerous Case Studies from the Pharmaceutical Industry.

2. State of Research

Organizational structures can be defined as patterns of coordination and interaction, by which technology, tasks and humans are synchronized to achieve an organization's purpose. By identifying the right organizational structure, effective coordination-integration and decision making can be facilitated [6]. Organizational structures are dynamic constructs, in fact, they change over the time [10] by adapting to major changes in the organization such as mergers, reallocations, decentralizations, or centralizations [11]. The creation of the right organizational structure around OPEX programs is not an easy task, but it is strategically important to establish a structure to coordinate multiple simultaneously ongoing OPEX initiatives [3]. For example, Anand et al. [12] in their extensive research on CI infrastructures state: "*Infrastructure practices can fulfill the important role of coordination and support of projects and create a culture for continuous improvement to help sustain a CI initiative beyond its immediate gains*" (p.446). However, this structure should not be a static concept as it is rather based on dynamic capabilities that generate the correct environment for integrating lower managerial tiers in strategy deployment and organizational learning [13].

In recent years, digital tools and initiatives have become increasingly prevalent in the manufacturing landscape. However, there is a general lack on how to align new digital strategies with OPEX infrastructures. Literature [14,15] recognizes a positive impact on performance from the alignment of digital and business strategies. Nevertheless, the alignment of digital to other organizational structures presents numerous challenges. For example, organizations have to deal with tensions between formal top-down approaches to exploit existing resources and simultaneously need to take advantage of emergent opportunities applying informal approaches [16]. Moreover, companies often see themselves confronted with organizational inertia [17]. To overcome these challenges, and align digital to other internal organizations, companies must be able to create, extend, and modify their resource base [18]. Yeow et al. [9] use the dynamic capabilities to analyze the alignment of digital and business departments. This approach argues that companies do not only change their resources, as supported by the Resource Based View [19], rather their product, services and organizational structures to survive new challenges [20]. Our unit of analysis, the Pharmaceutical Industry, is considered as process industry facing several challenges, such as, drug products market instability, fixed batch sizes, low modularity, complex product changeovers, and output limitations defined by the equipment [21]. Strategic management literature highlights the contribution of dynamic capabilities in improving firm's productivity [22], and supporting the implementation of new strategic initiatives even in Pharmaceutical Industry [23].

3. Methodology

In order to investigate how dynamic capabilities help pharmaceutical companies to align OPEX and Digitalization, we conducted 25 semi-structured interviews between 2020 and 2022. Semi-structured interviews have been selected as a method of research as they are accompanied by a number of advantages.

These advantages are expressed by e.g., the possibility of spontaneous and guideline-oriented interaction, the clarification of arising questions and the avoidance of incomprehensibilities, which eventually improves the reliability of research. In total we gathered data from 16 different pharmaceutical companies [A-P] with company sizes ranging from 2.000 – 110.000 employees. We rely on the selected sample approach [24] with three evaluation criteria to determinate companies for the interviews. Those criteria were, prior engagement with the authors, diversity of business areas and expertise in OPEX or Digitalization. This in turn assures that the same and transparent understanding of the topic was communicated before conducting the interviews and further allowed to picture a holistic view on Pharmaceutical Industry. Interviewees hold corporate OPEX functions and Digital roles. Transcriptions of interviews were conducted using the commercial transcription program *trint* and coding was done in *Atlas.ti*. The data coding was performed in two steps. First, the companies were clustered according to their alignment level of OPEX and Digital functions. Thereby, three different stages of alignment between OPEX and Digital functions have been identified: no alignment, partial alignment, and full alignment. This guaranteed that the analysis can capture capabilities necessary at different alignment maturity stages and the development of an alignment model can be generalized to all cases [24]. Second, we used a two-step abductive approach to code the interviews. Initially we applied attribute coding technique to consider literature findings of dynamic capabilities (Sensing, Seizing, Transforming) followed by sub-coding technique to account for the explorative, open nature of research [25].

4. Results and Discussion

4.1 Sensing

To gain insight into new opportunities, organizations need to use sensing as described in literature [26]. Especially in digital strategy contexts, where strategy is ongoing and evolving, organizations must develop strategic approaches to identify and understand what changes are needed and how they can be implemented [9]. Sensing is enhanced by the following actions. First, *scanning* action refers to organizations exploring opportunities and markets, gathering information from internal and external sources such as clients or vendors, and filtering relevant information to understand potential opportunities [8]. Second, *learning* action considers efforts to create further knowledge to learn and assess potential opportunities. By monitoring performance this activity helps to gain more insights to eventually identify specific areas for further actions [27,28] . Third, with *calibrating* action, organizations refine their prior actions and determine implications for future actions after probing specific opportunities and identifying implications [29].

Scanning

Numerous interviewees explained that they conduct assessments to identify opportunities from an internal and external perspective. *Internal assessments* were mainly driven by OPEX in order to revise processes and perform analysis on overall performance. In this regard [A] stated "we have observed that the productivity of the company started to decrease […] and we needed to understand why […] [So,] we have decided to perform this digital transformation". Other companies, such as [F; L] indicate that they identify opportunities of digitalized processes by observing the processes at the site. That is why "global transformational leaders […] are spending 80% of their time on the shop floor, […] and start to have a clear view on what could be digital opportunities". Further methods to internally assess and explore opportunities are interviews of internal customers [E], use of digital plant frameworks, playbooks and maturity assessment [B; G; H; I; J]. *External assessments* in contrast are related to adopt an outside-in perspective. Methods mentioned in that case are external Benchmarking [B; F], Ideation workshops, Technology Screening [B; F; G; H; J; L], Hackathons [D] and digital transformation days [H], where digital technology can be showcased and tested. Lastly [E] pointed out that the informal exchange with peer companies is also considered very useful in understanding learnings and experiences with technology implementation. [H] stated in that context: "We have guys that actually just go out there and look at technology and see what might be useful". Company [L] for example mentioned: "We started by looking at what are other companies doing. We had several initiatives, e.g., a workshop […] to see how different teams are improving Digitalization. It was a good opportunity to observe what Digitalization can bring to the strategy and to help us understand what OPEX, IT […] teams could bring in."

The interviews further revealed that pharmaceutical companies approach opportunities regarding their digital transformation and OPEX in a fourfold way. The first approach can be considered as a *Top-Down Approach*. This approach is mainly characterized by a push from digital teams or leadership [B; I]. Company [I] sees the following reasoning: "we're getting pushed [towards] training and awareness training […] to start thinking about where there's opportunities long term to be utilizing". Especially in the case where performance pain points were identified from senior leadership, a top-down approach was followed [F]. Company [E] describes it the following: "So there are some people at management level [who] say here is a clear potential. I cannot live with the lack of transparency in this area. So, I would like to propose a solution, and can we then engage and create a small project?" The second approach, the *Bottom-Up Approach*, was explicitly mentioned by company [F; J]. A *combination of Top-Down and Bottom-Up* Approach was identified for [A; B; F; H; K]. The argumentation at this point was most suitable summarized by Company [J] "It is all so dependent […] on the size of the technology. […] I've seen that […] a particular group will see a gap and they'll say, hey, I want to have some kind of system here to fill this gap […] they'll say, I know about this tool. I want to implement this tool. [K] complementary explanation here was: "We first introduce the processes in paper, and later on we digitalize them. [..] The [OPEX] and the digital team are developing the tools. To bring them to the sites we have a site digital roadmap that has been top-down defined. The roadmap is created from both teams." Lastly, we observed the *Scattered Approach*. Especially in the cases where no formal Digitalization strategy was established, the Scattered Approach based on local initiatives was noticeable [E]. The Scattered Approach can also be explained by directions which are highlighted by [O] when they say: "We digitalize every process, but we don't evaluate if the process is ready for being digitalized or mature enough".

The last activity relating to the Scanning action refers to Decision Making. Decision Making in our understanding is supported by evaluation criteria, which are used to steer through uncertainty. The first evaluation criteria is strongly correlated to what we call *Guiding Principles*. To name a few of them, the interviews revealed performance, decision making support, energy consumption [H], cost reduction [G; H], speed, network distribution, quality improvement, complexity reduction [B], waste elimination [A], supply flexibility [G] or savings [D]. Company [C] indicated, that "[one has to] understand and demonstrate the added value of Digitalization in order to get the financial resources". In that context, Company [J] emphasized to first "focus on the business process […] and then holistically think about a technology solution". As a second evaluation criteria, we identified *Strategic Control.* Company [E] stated that it is important to have a drill-down system of KPIs related to operational goals in order to evaluate process changes due to Digitalization. Company [G] points out that the digital value creation needs to be evaluated from functional areas in combination with cascaded strategies. When we raised the question, Company [A; O] referenced to their vision, which sets a focus on Digitalization and orientation through uncertainty.

Learning

To create knowledge about opportunities, we wanted to understand what pharmaceutical companies have learned and how they learn. We have identified *Organizational Feedback* as a first construct. In that context [N] stressed that digital solutions need to be incorporated, however they shouldn't undermine the OPEX culture. [C] adds: "Start small is the best way […] We started with the most motivated site to proof to other sites the benefits of Digitalization. We also took in consideration the OPEX maturity of each site before starting pilot projects. We cannot start with digital processes with people that are not used to OPEX tools". [P] argues in a similar way, when the interviewee said, "you need people owning the standards, updating them, and so on […]. You need the same element even when implementing digital solutions." Company [F] confirmed that the people aspect is very important, because people tend to react very emotional towards Digitalization. Furthermore, we see that pharmaceutical companies pursue a culture of driven towards more *Agility*. [J] stated that sometimes it happens that parts of processes are not well understood, which can lead to a temporary stop of a digital project. [M] saw it similarly saying that "continuous improvement is constantly changing. We're constantly finding different problems; we're constantly finding better ways of doing things. And technology is continuously improving in the digital side as well".

Calibrating

With respect to the Calibrating action, we have identified the activities of *Challenging* and *Refining*. *Challenging* activity constitutes a basic attitude which can be adopted by both OPEX and Digital teams to question possible changes. [A] asserts the following: "We challenged the digital team last year not to revise the road map, because when they have developed the road map, it was quite centric on the digital. And we said, try to forget that and see what the needs of the company are." [I] generalized at this point: "From our perspective, you know, with the things related to operational excellence, we always kind of go back [and ask] what problem are you trying to solve? Equally Company [A] said "digital also makes the same thing. So, they always challenge the client [and ask] why do you want this?" [G] interprets the role of OPEX as an important part to critical reflection, when saying: "Some people in the organization sometimes just jump into quick [digital] solutions […], but without really looking at the big picture, which is the language of strategy […] I'd say [that is] more so in OPEX side". This is also seen by [L] and exemplified in the context of project organization: "We bring in ourselves, by saying, we suggest here analysis projects, which are conducted before, so that we then can co-determine the direction of those projects". A similar observation can be made for [O]: "We can make projects visible and evaluate the benefits of a certain approach. We then develop visibility studies to the leadership, and they decide if we want to continue with them or not. […] The teams that can present the study can be from OPEX or IT department." *Refining* as a second activity centers around questions like "is this something that is going to be scalable? Is it going to stand in any way implementable in the future?" [B]. Another observation was made by interviewing [J], when the interviewee said, "as far as the project goes, it might not be identified in the beginning, but as the project goes on, there might be elements where it's recognized […] that we need some assessment of the business process processes within the technology implementation that needs more attention". [E] perceives the role of experimentation in the digital environment as particularly important here. [F] specified that they are doing a "return of experience" of everything that was done before including investigations of pitfalls and good practices. [A] adds: "we are becoming more realistic, and we have evolved where to look after one year of implementation of the roadmap". Overall, [M] sums it up well: "[…] sensing is a big part of us understanding what our competitors are doing, understanding what our current problems are, and making sure that the strategy is […] reflective of what challenges we currently have from a digital climate data perspective, from an intelligence perspective and understanding what is the current state? […] And making sure that we're partnering with the right companies […]."

4.2 Seizing

Seizing is the second critical capacity for organizationally aligning to digital strategies. It allows to take advantage of the earlier identified opportunities. Seizing involves going beyond understanding new business opportunities to actually making specific changes across the organization and taking action in order to capture possibilities [28,8]. Seizing comprises *designing*, *selecting* and *committing. Designing* action describes the process of planning and designing new structures and processes within an organization [9]. *Selecting* action refers to organizational activities around selecting between various options available in order to capture opportunities. Different opportunities can e.g., involve the choice of business models, suppliers, platforms, products or services. Decisions for capturing opportunities revolve around their design and further potential solutions. Lastly, *committing* action consists of decisions made by the organization on how to implement the designs and on specific options for partners, services, processes, or business models [26].

Designing

Within the aligning action of Designing, we observed the activity of *Roll-Out Preparation*. Companies like [F] are designing huge transformation programs, which allow cross-functional work and avoid silo-thinking. They argue: **"**If we don't do […] a transformation around the product in terms of new governance and new roles, new trainings to be delivered, […] either people don't use it, or they do use it but extracting a very low value out of the full potential. So, […] the idea is to combine the digital products that are coming from it with the top programs so that we deploy the tool and then we do the transformation around it in a synchronized way". In addition to conducting basic OPEX training, [B] and [J] also see a great importance in training employees to interface and leverage digital tools. [L] argues that more and more waiting times are associated with appointing IT experts. "That is why short-, medium- and long-term cycles are taken into account in various aspects of personnel development, personnel recruitment, plant planning […]". Regarding the design procedures for roll-out across the network, companies usually describe that they target pilot sites in the first place [H; C]. The roll-out preparation strategy of [H] for example foresees the development of a minimum viable product, the creation of lessons learned in small units, e.g., small labs at the site, the roll-out at the same site and then the pilot for two sites at the same time. Overall [H] achieves at least four to five increments and improvements of digital product before rolling out across the whole network.

Selecting

When analyzing the interview data, we ascertained, that the aligning action of Selecting between different options refers to *Use Cases* and *Sites*. *Use Case Selection* describes how companies choose possible applications. [I] holding a OPEX position explained that "we have opportunity to define needs and pass them on to digital and central IT. But we also have of course global [standards] so that we need to align on first of all the use case [and then] also decide on timelines of priorities with respect to processes and products in the site". Moreover, we observe that Use Cases were also selected based on external push. For example, companies like [B] had to change their tier meetings to virtual due to Covid. *Site Selection* explains how companies choose in which sites they deploy their strategy. [C] referenced to a project management office (PMO) which evaluates each project that should be done on the site. [B] described their approach to selecting sites as "socializing" across the network to determine where to start first. The interviewee of [I] specified that OPEX and Digital have ongoing touch points any way. Especially in the case of OPEX strategy deployment projects digital functions are pulled and integrated into project core teams, whenever the need to digitalize at the site was identified before.

Committing

Within the Committing action we identified the *Roadmap Re-Vision* activity. Overall, the interviewed pharmaceutical companies state that they have recently revised their digital strategies and roadmaps. Overall, answers ranged from the year 2015 to 2020. [B] formulated: "It started really from the top with our CEO […] at the time kind of putting it as one of the company's goals and objectives to drive Digitalization". [B] complemented, that shortly after a global team took over to start a digitization strategy discussion the focus on the digital strategy was determined.

4.3 Transforming

Transforming as the third dynamic capacity is critical to aligning resources for a new strategy and adding new resources to fill existing gaps. In addition to the relative novelty of digital strategies and the resources associated with them, many companies don't have the internal expertise, so accessing external resources or creating new resources may be significant in aligning to digital strategies [30]. The first action of *leveraging* is used to reassign resources to new tasks [31]. In that phase especially fungible resources are reassigned [32]. By applying those resources to other products and processes, organizations build new capabilities which are aligned to new digital strategies. The second action of *creating* is thereby used to develop and combine new resources and processes to eventually build new competencies. This expertise can be expressed in e.g., new technological or market competence [31]. The third phase of *accessing* foresees the use of external resources, e.g., from vendors or partners [20], that are complementary to existing resources. Examples in the context of Digitalization refer to web hosting services or business community platforms [33]. The fourth activity of *releasing* includes the reduction of existing resources in circumstances which are found to be not optimal. This may be the case, for example, if it has been analyzed that the existing configuration does not support the digital strategy [20].

Leveraging

Resource Reconfiguration is what we have identified within the Leveraging action. [J] pointed out that, "You can't have the same sort of lean IT group if you've implemented five new systems […]. So operationally we have to support the systems that we've rolled out […], but also by adding more programmers to help when things break and adding more infrastructure people". [J] continued to highlight that skillset and capabilities of people needs to change when digital infrastructures are built differently from classical IT systems. [F] introduced an example of their transformation program, which represents a step-by-step guide to prepare the infrastructure and to build up the team from existing resources at the sites".

Creating

We see that pharmaceutical companies accompany the development of new competencies by building new organizational structures. The most distinct activities we have observed are *Tier Management*, *Communities of Practice* and *Positions*. Fully digitalized *Tier Management* as described by [B; H] will be soon used to connect- and manage the lowest level of operations to the senior level. In that context [F] stated that "all our boards are going to digital format today". Besides digitalized Tier Management structures, pharmaceutical companies create governance and steering structures like Digital Advisory Boards [I], IT Architecture Boards [L], Forums [B; J], Operations Groups [C] or Market Places [G]. What these structures have in common is that they are highly cross functionally staffed. All of them include experts from OPEX and Digitalization. Typical working tasks comprise the identification and harmonization of the IT and tool landscape [L], facilitate exchange for decision making [G] or provide a platform for digital initiatives [G; I; J]. [B] mentioned that their platform facilitates the preparation of digital initiatives which required funding outside the business as long as they drive alignment on the roadmap. Besides those formal structures, the interviewed companies stated that they also leverage *Communities of Practice*. In the case of [I] they are "driven by digital data science" including regional as well as global groups where best practices coming from the sites are shared". In addition [G] explains that they offer webinars, such as one week and one year data science courses as well as one-week trainings for selected people which are installed as digital champions to build digital capabilities across their entire entity. Lastly, the creation of new *Positions* is considered as a further activity to develop new resources. The motivation behind that can be e.g., the idea to centralize Digitalization with a "digital head" [C], merge digital programs with a new "Chief Digital Officer" [F] or to strengthen the company wide perception that activities related to OPEX and Digitalization are aligned, and collaboration will be further enhanced. That is why [P] said: "So far we changed the name of the leader, and in the strategy deployment we use the term lean digital".

Accessing

The use of external resources, especially in the case of *Collaborations* with software providers was also mentioned by some companies [O; E]. Especially when maintaining complex IT-systems, pharmaceutical companies heavily rely on their vendors. However, the interviews revealed that a lot of effort is put into internal digital capability building as they have acknowledged the strategic relevance of Digitalization for their business [A; G; L].

Releasing

Finally, the interviews have also shown that to some degree the release of resources in order to better support the digital strategy has taken place. The first activity was interpreted as *OPEX Support*, which means that OPEX takes over some tasks, which were originally performed by a digital function. [A] for example showed a very pragmatic perspective saying: “I have two persons that work very well in programing […]. So, I have said, I don't need to have digital to create reports or to create basic before they allow us to develop”. [O] commented similarly: “first we make some tests in Excel with some macros and some programing. And then we use that kind of mockup”. [C] has put the before mentioned statements into a broader context: “OPEX took over some goals from IT […] OPEX is informing the IT-roadmap with its values but also integrating Digitalization [within] OPEX roadmap tools. For example, the introduction of digital visual boards.” The second construct of *Digital Support* describes the reverse distribution of roles. Thereby, digital functions are more perceived as service provider. [N] described the situation as following; “OPEX is doing what they need to do, and they're usually in the production area. If they need Digitalization aspects, they call for it”.

Figure 1 summarizes the described alignment process between OPEX and Digitalization.

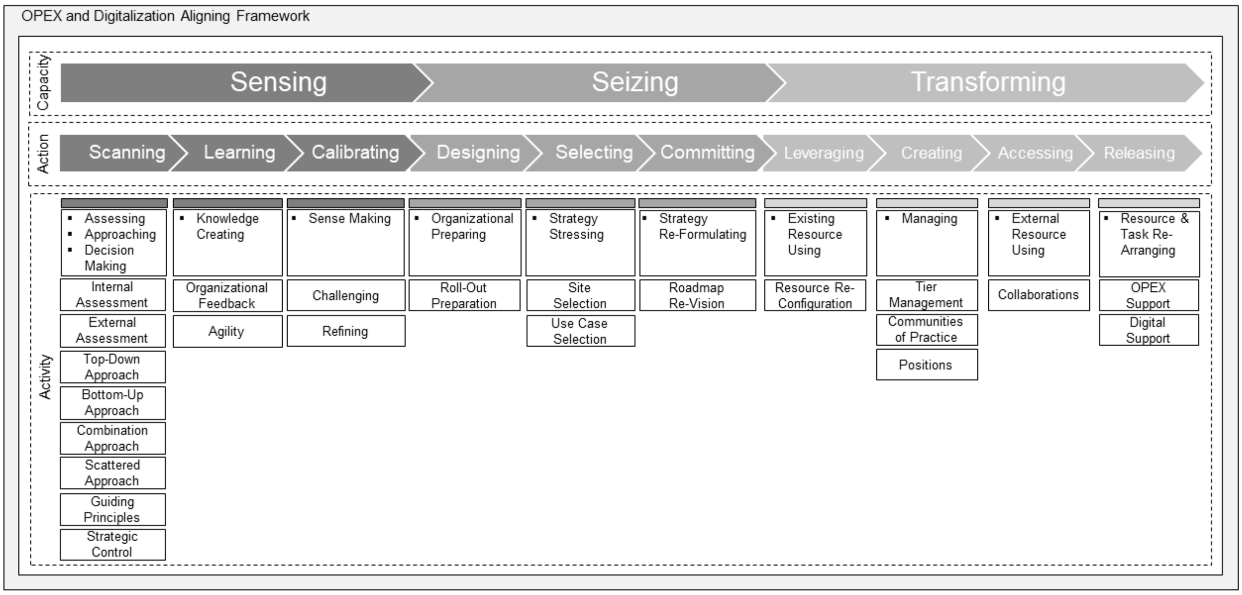

Figure 1: OPEX and Digitalization Aligning Framework

5. Conclusion and Future Research

Companies have acknowledged that they have to combine their Digitalization efforts with OPEX when they want to stay competitive. The question that emerged is how companies align those two and how does the process of alignment look like. We contribute to answering this question by using the dynamic capabilities approach. Our insight driven approach within the Pharmaceutical Industry revealed various aligning activities. We thereby add to literature by presenting a holistic set of activities. Thus, practitioners can reflect upon their current configurations and their status quo of Alignment.

The research at hand offers several future research opportunities. First, an in-depth literature review can reveal further aligning activities, which have not come to light from practice. Second, an in-depth examination of each case's aligning activities including emerging challenges could support the formulation of implications to successfully drive the digital transformation of OPEX programs. Third, a quantitative approach to investigate to what extent Digitalization facilitates the establishment of a Continuous Improvement infrastructure, culture and behaviour could also be investigated. And fourth, a longitudinal study as described by Yeow et al [9] can also be one possible direction for future research.

References

[1] Bessant, J., Caffyn, S., 1997. High-involvement innovation through continuous improvement. IJTM 14 (1), 7.

[2] Anand, N., Daft, R.L., 2007. What is the Right Organization Design? Organizational Dynamics 36 (4), 329–344.

[3] Wruck, K.H., Jensen, M.C., 1998. The two key principles behind effective TQM program. European Financial Management 4 (3), 401–423.

[4] Kuusisto, M., 2017. ORGANIZATIONAL EFFECTS OF DIGITALIZATION: A LITERATURE REVIEW. International Journal of Organization Theory and Behavior 20 (3), 341–362.

[5] Alavi, S., Wahab, Abd, D., Muhamad, N., Shirani, Arbab, B., 2014. Organic structure and organisational learning as the main antecedents of workforce agility. International Journal of Production Research 52 (21), 6273–6295.

[6] Robert Duncan, 1979. What Is the Right Organization Structure? Decision tree analysis provides the answer. Organizational Dynamics 7 (3), 59–80.

[7] Hax, A.C., Majluf, N.S. Organization Design: A Case Study on Matching Strategy and Structure. Journal of Buisness Strategy, 72–86.

[8] Teece, D.J., 2007. Explicating dynamic capabilities: the nature and microfoundations of (sustainable) enterprise performance. Strat. Mgmt. J. 28 (13), 1319–1350.

[9] Yeow, A., Soh, C., Hansen, R., 2018. Aligning with new digital strategy: A dynamic capabilities approach. The Journal of Strategic Information Systems 27 (1), 43–58.

[10] Stanford, N., 2015. Guide to Organisation Design: Creating high-performing and adaptable enterprises. The Economist Newspaper. (Ed. 2).

[11] Laloux, F., 2014. Reinventing organizations – A guide to creating organizations. Nelson Parker, Bruessels.

[12] Anand, G., Ward, P.T., Tatikonda, M.V., Schilling, D.A., 2009. Dynamic capabilities through continuous improvement infrastructure. Journal of Operations Management 27 (6), 444–461.

[13] Neilson, G.L., Martin, K.L., Powers, E., 2008. The secrets to successful strategy execution. Harvard Business Review 86 (6), 60–70.

[14] Bergeron, F., Raymond, L., Rivard, S., 2004. Ideal patterns of strategic alignment and business performance. Information & Management 41 (8), 1003–1020.

[15] Gerow, J.E., Grover, V., Thatcher, J., Roth, P. L., 2014. Looking toward the future of IT-business strategic alignment through the past: a meta-analysis. MIS Quart. 38 (4), 1159–1186.

[16] Marabelli, M., Galliers, R.D., 2017. A reflection on information systems strategizing: the role of power and everyday practices. Info Systems J 27 (3), 347–366.

[17] Hirschheim, R., Sabherwal, R., 2001. Detours in the Path toward Strategic Information Systems Alignment. California Management Review 44 (1), 87–108.

[18] Helfat, C.E., Finkelstein, S., Mitchell, W., Peteraf, M.A., Singh, H., Teece, D.J., Winter, S.G., 2007. Dynamic capabilities: understanding strategic change in organizations. John Wiley & Sons.

[19] Barney, J.B., Wright, M., Ketchen, D.J., 2001. The resource-based view of the firm. Journal of Management 27 (265), 625–641.

[20] Eisenhardt, K.M., Martin, J.A., 2000. Dynamic capabilities: what are they? Strateg. Manage. J. 21 (10–11), 1105–1121.

[21] Abdulmalek, F.A., Rajgopal, J., 2007. Analyzing the benefits of lean manufacturing and value stream mapping via simulation: A process sector case study. International Journal of Production Economics 107 (1), 223–236.

[22] Makadok, R., 2001. Toward a synthesis of the resource-based and dynamic-capability views of rent creation. Strat. Mgmt. J. 22 (5), 387–401.

[23] Narayanan, V.K., Colwell, K., Douglas, F.L., 2009. Building organizational and scientific platforms in the pharmaceutical industry: A process perspective on the development of dynamic capabilities. British Journal of Management 20, 25–40.

[24] Voss, C., Tsikriktsis, N., Frohlich, M., 2002. Case research in operations management. International Journal of Operations & Production Management 22 (2), 195–219.

[25] Saldaña, J., 2013. The coding manual for qualitative researchers, 2nd ed. ed. SAGE, Los Angeles, xix, 303.

[26] Teece, D., 2009. Dynamic Capabilities and Strategic Management: Organizing for Innovation and Growth: Organizing for Innovation and Growth. Oxford University, Oxford, U.K.

[27] Nonaka, I., 1994. A Dynamic Theory of Organizational Knowledge Creation. Organization Science 5 (1), 14–37.

[28] Teece, D.J., 2014. THE FOUNDATIONS OF ENTERPRISE PERFORMANCE: DYNAMIC AND ORDINARY CAPABILITIES IN AN (ECONOMIC) THEORY OF FIRMS. Academy of Management 24 (4), 328–352.

[29] Weick. Karl E., Sutcliffe, K.M., 2006. Mindfulness and the Quality of Organizational Attention. Organization Science 17 (4), 514–524.

[30] Rindova, V.P., Martins, L.L., Yeow, A., 2016. The Hare and the Fast Tortoise: Dynamic Resource Reconfiguration and the Pursuit of New Growth Opportunities by Yahoo and Google (1995–2007), in: Folta, T.B., Helfat, C.E., Karim, S. (Eds.), Resource Redeployment and Corporate Strategy, vol. 35. Emerald Group Publishing Limited, pp. 253–284.

[31] Danneels, E., 2002. The dynamics of product innovation and firm competences. Strat. Mgmt. J. 23 (12), 1095–1121.

[32] Teece, D.J., 1982. Towards an economic theory of the multiproduct firm. Journal of Economic Behavior & Organization 3 (1), 39–63.

[33] Markus, M.L., Loebbecke, C., 2013. Commoditized Digital Processes and Business Community Platforms: New Opportunities and Challenges for Digital Business Strategies. MIS Quart. 37 (2), 649–654.

Biography

Lorenzo Pirrone (*1994) has been a research associate in the operational excellence group at the Institute of Technology Management (ITEM) in the division of production management of the University of St.Gallen since 2021. He previously studied Industrial Engineering (M.Sc.) at the TU Dortmund University.

Matteo Bernasconi (*1994) has been a research associate in the operational excellence group at the ITEM in the division of production management of the University of St.Gallen since 2020. He previously studied business innovation (M.A., B.A.) at the University of St.Gallen.

Prof. Dr. Thomas Friedli (*1971) is a director at the ITEM and became professor in 2004. He leads a division of 14 PhD students and one post-doc. His research areas include strategic management of production companies, management of industrial services, and operational excellence.

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Data-driven Prediction of Internal Turbulences in Production Using Synthetic Data

Jan Schuhmacher[1,2,3], Thomas Bauernhansl[1,2]

[1] *Fraunhofer Institute for Manufacturing Engineering and Automation IPA, Nobelstrasse 12, 70569 Stuttgart, Germany*

[2] *University of Stuttgart, Institute of Industrial Manufacturing and Management IFF, Nobelstrasse 12, 70569 Stuttgart, Germany*

[3] *Reutlingen Center Industrie 4.0, Fraunhofer IPA & ESB Business School (Reutlingen University), Alteburgstraße 150, 72762 Reutlingen, Germany*

Abstract

Production planning and control are characterized by unplanned events or so-called turbulences. Turbulences can be external, originating outside the company (e.g., delayed delivery by a supplier), or internal, originating within the company (e.g., failures of production and intralogistics resources). Turbulences can have far-reaching consequences for companies and their customers, such as delivery delays due to process delays. For target-optimized handling of turbulences in production, forecasting methods incorporating process data in combination with the use of existing flexibility corridors of flexible production systems offer great potential. Probabilistic, data-driven forecasting methods allow determining the corresponding probabilities of potential turbulences. However, a parallel application of different forecasting methods is required to identify an appropriate one for the specific application. This requires a large database, which often is unavailable and, therefore, must be created first. A simulation-based approach to generate synthetic data is used and validated to create the necessary database of input parameters for the prediction of internal turbulences. To this end, a minimal system for conducting simulation experiments on turbulence scenarios was developed and implemented. A multi-method simulation of the minimal system synthetically generates the required process data, using agent-based modeling for the autonomously controlled system elements and event-based modeling for the stochastic turbulence events. Based on this generated synthetic data and the variation of the input parameters in the forecast, a comparative study of data-driven probabilistic forecasting methods was conducted using a data analytics tool. Forecasting methods of different types (including regression, Bayesian models, nonlinear models, decision trees, ensemble, deep learning) were analyzed in terms of prediction quality, standard deviation, and computation time. This resulted in the identification of appropriate forecasting methods, and required input parameters for the considered turbulences.

Keywords

Data-driven Prediction; Probabilistic Forecasting; Turbulences; Synthetic Data; Flexible Production;

1. Introduction

Not only since the outbreak of the Corona pandemic, have companies been subject to numerous unplanned events or turbulences that hinder economic production [1], [2]. A difference is made between internal turbulences originating in the company itself, such as resource failures and missing parts at the workplace, and external turbulences originating outside the company, such as delivery failures and delivery delays [3].

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The capacity for change describes the ability of a production system to respond to external and internal changes. According to *Erlach et al.* [4], a distinction must be made between short-term turbulences, medium-term trends, and long-term disruptions. Due to the short-term effect of turbulences requiring a short-term (low reaction time) and reversible action in the production system, the change capability of flexibility fulfills these requirements best [4]. The built-in flexibility of flexible production systems with defined boundaries (flexibility corridors) allows production systems to deal with turbulences without having to change the structure of the system, experiencing only minor losses in terms of time, effort, costs, or performance [5] [6]. The detection and prediction of turbulences offers huge potential for target-optimized handling of turbulences using existing flexibility corridors [7]. For example, using the operation and routing flexibility of flexible production, a predicted internal turbulence of a production resource failure or process delay can be countered by allocating the production order to an alternative production resource [8].

To address the challenge of generating the required database for identifying suitable probabilistic forecasting methods, an experimental research design has been applied to predict internal turbulences [9]. Starting with analyzing the state of science of data-driven forecasting and synthetic data generation, a simulation study to generate synthetic data has been conducted based on a minimal system with defined turbulence events. Then, the synthetic data was used for a comparative study of data-driven probabilistic forecasting methods to predict internal turbulences by splitting the data into training data for the forecasting models and test data to validate the forecasting models.

2. Analysis of the state of the science

In the following, the state of science in the fields of data-driven forecasting and synthetic data generation is analyzed to set the theoretical base for the simulation study and comparative study of data-driven probabilistic forecasting methods and to highlight the limitations of existing approaches.

2.1 Data-driven forecasting

Forecasting methods can be model-driven or data-driven [10], [11]. Model-driven approaches use classical statistical methods and assume that the data-generating process is known and that an explicit stochastic behavior can be assumed. In data-driven approaches, the data-generating process is considered unknown, and algorithms are used to meet specific analysis or prediction goals based on input data [11]. For the prediction of turbulences, a data-driven approach was chosen, since the data-generating, turbulence-triggering process is considered unknown.

A probabilistic forecast represents an estimate of the corresponding probability of all possible future outcomes of a random variable. Unlike single-value forecasts, such as time series averages, or quantile forecasts, probabilistic forecasts represent a probability density function considering future quantities or events [12], [13]. For predicting turbulence events in production systems, these probabilistic forecasting methods are particularly suitable since they allow the determination of the probabilities of occurrence of all turbulence events considered, taking into account the selected parameters and not only one particular event. By using simulators, a probabilistic forecast can also be carried out with deterministic forecast methods by varying the attribute values and/or combining different forecasting scenarios, as in the case of ensemble forecasts.

Major types of data-driven probabilistic forecasting methods are ensemble methods, deep learning methods, methods based on Bayes' theorem, and methods using regression [7].

Standard ensemble methods are random forests and gradient boosted trees. They combine many weak deterministic predictors (decision trees in the case of random forests and gradient boosted trees) to create a superior deterministic predictor. To turn ensemble methods into probabilistic forecasting methods, the mixing or combining process is adapted to consider probabilities instead of a single aggregated outcome [12].

Deep learning methods are based on a multi-layer feedforward artificial neural network trained with stochastic gradient descent [14]. The input data is processed through the neuronal network and afterwards the determined output is compared to the desired output [15]. Deep learning methods are probabilistic because the gradient descent converges faster when the loss function reflects a probabilistic forecast [12].

The method of the naïve Bayes classifier is a probabilistic classification method based on the Bayes' theorem. The main assumption is that given the value of the class, the value of any attribute is conditionally independent of the value of any other attribute [16], [17]. Although this independence of input attributes and target attributes is given only in rare cases, this method often allows good (prediction) results even in cases where this condition is not fulfilled [16], [17].

Methods using regression, such as logistic regression, support vector machines and fast large margin, can also be applied for probabilistic forecasts. They provide particularly good results when there are strong relationships or correlations between a target categorical variable and one or more input variables [15].

A major challenge is identifying the suitable forecasting method for a specific application. A common approach to selecting an appropriate forecasting method for a particular use case is to analyze the state of the art and science to determine which forecasting methods have provided good results in the past for that use case. For probabilistic forecasting of internal turbulences, no existing prior work could be identified in the analysis of the state of the art and science. Discussions with experts as well as literature sources led to the result that a parallel test of different forecasting methods (considering forecast quality and computation time) and a variation of the input parameters (add, replace or remove) must be performed [18], [19]. However, data-driven forecasting methods require a large database that is not always available in industrial practice. Synthetic data generation offers huge potential to build up the required database of different input parameters.

2.2 Synthetic data generation

Synthetic data is used when real data is difficult to access, real data sets are not detailed enough or not of the right scale (amount of data), or if real data sets are incomplete [20]. Synthetic data can be divided into the three main types of dummy data, rule-based generated synthetic data, and synthetic data generated using artificial intelligence [21].

Dummy data is randomly generated data created, for example, by means of a mock data generator. Due to the random data generation, features, relationships, and statistical patterns of the original data are lost, so the representativeness of dummy or mock data is minimal compared to the original data [21].

Rule-based generated synthetic data can be generated by defining specific rules for generating the data, e.g., by using simulation tools [21], [22]. The use of simulation methods to generate (or "grow") and analyse synthetic data to gain specific insights is part of the research field of data farming [23], [24]. This requires the definition of all features, relationships, and statistical patterns to be reproduced in the generated synthetic data. Therefore, the data quality of the synthetic data strongly depends on the quality of the predefined set of rules. Nevertheless, rule-based synthetic data generation is useful, especially when no data are available (yet) [21].

Another way to generate synthetic data is to use artificial intelligence algorithms. This involves training the AI model with real data to learn appropriate features, relationships, and statistical patterns of the data set. The trained AI algorithm then generates entirely new data points and models them to replicate the training data's features, relationships, and statistical patterns [21]. This AI-based generation of synthetic data can be used when sufficient data is available for training the AI algorithms.

Since no real data on production systems' internal turbulences is available, but the effects of turbulence on the production system are known, a rule-based approach for the simulative generation of synthetic data is pursued to generate synthetic data based on a simulation study described in the next section.

3. Simulation study for the generation of rule based synthetic data

Following VDI 3633, seven steps must be considered to perform a simulation study [25]. The procedure starts with the task definition, followed by the systems analysis, model formalization, implementation, execution of simulation experiments, and analysis of the results. In parallel, the phases of data collection and data preparation have to be considered. In the following, the major steps of the simulation study preparation, implementation of the simulation model, and generation of synthetic data are described.

3.1 Preparation of the simulation study

For simulating an existing or planned system, its transformation into a model that can be experimented with is required. According to VDI 3633 [25], the mapping accuracy of the model should not be as detailed as possible but detailed enough to meet the specific objective. For the generation of synthetic data based on turbulence scenarios of a production system, a minimal system with reduced structural complexity was defined by reducing the number and variants of elements, relations, and properties in the system and by applying the modeling principles of abstraction and representation [26], [27], [28].

The minimal system model is based structurally and process-wise on an actual work system for the assembly of a product at two alternative workstations supplied with pre-picked component sets from the warehouse via automated guided vehicles (AGV). For the considered work system, there is an insufficient database regarding quantity, quality, and granularity of real process and turbulence data. By transferring this working system into a simulation model, synthetic data is generated as input data for the investigation of suitable data-driven forecasting methods. It is also used for predicting turbulences and their effects on process and throughput times.

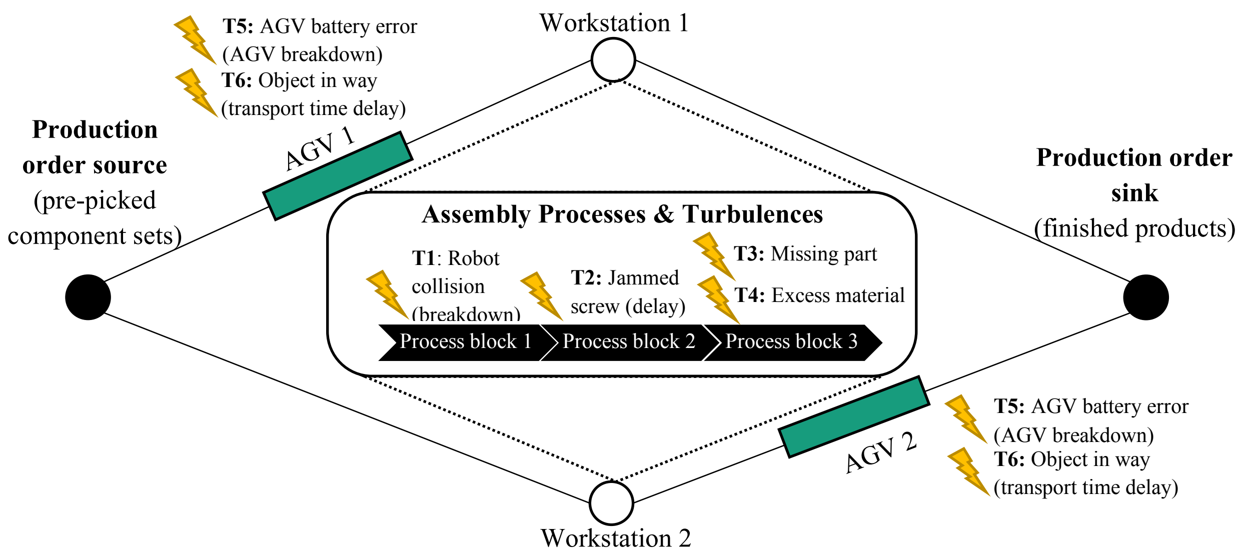


Figure 1: Concept of defined minimal system with turbulence events (T)

The minimal system (see Fig. 1) consists of one source (entry point for production orders in the form of pre-picked component sets into the system), two production resources (2 alternative assembly workstations), two intralogistics transport resources (2 alternative AGVs), and one sink (exit point of completed production orders). For the model implementation, the turbulences (T1-T6) to be considered were defined, specified in terms of their effect within the minimal system, and located in the model according to their locations of occurrence. The results of this analysis are summarized in the following section, together with the implementation of turbulence modeling.

3.2 Implementation of the simulation model

Previous work has already shown that negative effects of internal turbulences on lead time and delivery reliability can be countered by measures of intralogistics' autonomous control using the flexibility corridors of flexible production systems [29]. To model the defined minimal system, a multi-method simulation with agent-based modeling of the transport resources' autonomous behavior and event-oriented modeling of the turbulence scenarios with stochastic turbulence events is required. MATHLAB/Simulink, SimPy and AnyLogic were investigated as potentially suitable tools for this multi-method simulation [30], [31]. The simulation tool AnyLogic was selected due to its comprehensive method library for material flow simulations and agent modeling [31].

3.2.1 Modelling of resource breakdowns (T1 and T5)

The technical availability as a measure of a technical system's ability to meet the requirements placed on it is a major measure in the context of resource breakdowns [32]. The technical availability of production resources, like industrial robots, is specified over 99 % [33], [34] and the technical availability of AGVs is indicated with 98 % [35]. In industrial practice, also mean time between failures (MTBF) [33], [34] and mean time to repair (MTTR) [33] are important parameters for system availability. The MTBF for industrial robots is on average 40,000 hours (approx. 4.5 years) and more [33], [36]. Since these very high MTBFs would result in very long periods by the time, a purely technical failure of the corresponding production and logistics resources occurs, resource failures caused by human error are assumed for T1 and T5. Thus, for T1, a collision of the robot manipulator and the assembly fixture caused by the human operator is assumed resulting in the assembly fixtures' replacement and the robot's recalibration. For T5, a missed replacement of the AGV battery by the logistics employee is assumed. So, a warning message on the AGV fleet manager dashboard is ignored by the employee. For the modeling, a failure probability of 1 % for T1 and 3 % T5 has been assumed. Due to the lack of actual data, a uniform distribution as proposed by [37], [38] is assumed for the MTTR to solve the resource breakdowns.

3.2.2 Modelling of Process delays (T2 and T6)

For process-related delays or lead time delays in production systems with unknown delay reason, exponential distributions are usually assumed [39], [40]. For process times with some time dispersion, usually triangular [37], uniform [38], [41], [42], [43], and normal distributions [42], [44] are used in simulation models. A triangular distribution is frequently used for service and operation times where not enough samples are available for a more specific distribution, but some information about minimum, maximum, and mean values are available [37], [45]. Therefore, a narrowly set triangular distribution was used for modeling the target process times of assembly (without turbulence) with a certain tolerance due to the insufficient database of real data. For T2, as an assembly-related process delay with the specific reason "jammed screw", a triangular distribution was chosen because the error removal process (similar to the actual assembly process) requires loosening and re-screwing the jammed screw. This approach of splitting the process time and delay goes in line with *Wiendahl* [46], who states that turbulence occurs when the current actual value of a parameter deviates significantly from its mean value. For the representation of a time delay of the transport process due to an unknown obstacle on the transport path (T6), an exponential distribution was assumed in the model based on the literature [39], [40].

3.2.3 Modelling excess supply and missing part (T3 and T4)

For T3 and T4, no common comparative values could be found in the literature. The probabilities of occurrence of the turbulence were, therefore, modeled with assumed probabilities of 5 % (T3) and 4 % (T4).

Like the other process times in the model, the process times for the required picking, transport, and waiting times for the subsequent delivery of the missing material (T3) or return of the excess material were represented in the simulation model by a triangular distribution with minimum, maximum, and mean values.

The considered turbulences, turbulence attributes, and considered values and distributions as described above are summarized in table 1.

Table 1: Turbulences, turbulence attributes, distributions, and probabilities of the minimal system

Turbulence	Turbulence attributes	Distribution and probabilities
T1	Probability of occurrence	Probability: 1 %
	Mean time to repair (MTTR)	Uniform distribution [37], [38]
T2	Process delay	Triangular distribution [37], [45]
T3	Probability of occurrence	Probability: 5 %
	Process delay	Triangular distribution [37], [45]
T4	Probability of occurrence	Probability: 4 %
T5	Probability of occurrence	Probability: 3 %
	Mean time to repair (MTTR)	Uniform distribution [37], [38]
T6	Delay of transport time (AGV)	Exponential [39], [40]

3.3 Generation of synthetic data

By executing the simulation model, synthetic data for more than 5,000 production orders for 20 working days with two shifts was generated. All turbulences considered are independent of each other so that several of these turbulences can occur randomly during the processing of a production order within the defined minimal system. The results of the probabilistic forecasting comparing different forecasting models based on the generated synthetic data are described in the following chapter.

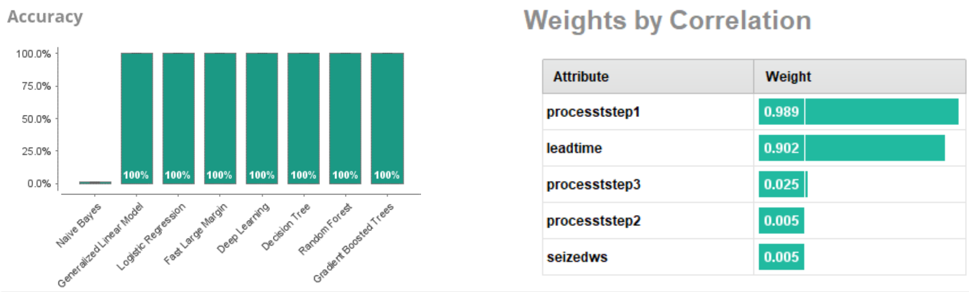
4. Probabilistic forecasting

To perform comparative studies of the selected forecasting methods and models, the data analytics tools RapidMiner, SPSS, Python (Pandas), R (CRAN-Project), and Minitab were analyzed based on the previous work of *Flückiger* [47]. The tool "RapidMiner" was chosen for the comparative investigation of the different probabilistic forecasting methods due to the available method library, the low effort for data import and the creation of the (forecasting) models as well as the high usability.

The synthetic data has been divided into training data (60 %) for training the data-driven prediction models and test data (40 %) for determining the prediction accuracies of the models. The investigated models and methods of different types (Naïve Bayes, generalized linear model, logistic regression, fast large margin, deep learning, decision tree, random forest, gradient boosted trees) were compared in terms of prediction accuracy for the respective turbulence, standard deviation and computation time. The results of the probabilistic forecasting are described in more detail on the two examples of the prediction of T1 as a production-related turbulence and T6 as an intralogistics-related turbulence.

4.1 Probabilistic forecasting of T1

The comparison of the investigated probabilistic forecasting methods to predict the occurrence of T1 of a resource breakdown due to a robot collision caused by the worker shows that most of the investigated forecasting methods lead to a 100 % accuracy to forecast the turbulence based on the generated synthetic training data (see Fig. 2). A major reason for this high forecasting accuracy of this turbulence (apart from the idealized data quality of the synthetic data) is that the occurrence of this turbulence is highly correlated to an increase of overall lead time. More precisely the robot defect has a negative impact on process block 1 where this turbulence is affecting the actual processing time of the production order. The probabilistic forecasting based on the naïve Bayes model leads to an accuracy of less than 1% since the main assumption of this model is that the value of any attribute is conditionally independent of the value of any other attribute [16], [17]. Considering the accuracy, standard deviation, and total computational time, the generalized linear model (GLM) led to the best overall performance for the forecasting of this turbulence considering the seized workstation, the process times of the workstations, and the overall lead time of the production order. By detecting this turbulence, the process-related delay can be predicted probabilistically and, using the flexibility corridors of flexible production, the negative effects (e.g., extended lead times) of this turbulence on subsequent orders can be reduced. For example, subsequent orders can be preventively allocated to an alternative production resource by tapping the routing flexibility of flexible production systems.



Model	Accuracy	Standard Deviation	Gains	Total Time	Training Time (1,000 ...
Naive Bayes	0.9%	± 0.2%	-2,808	13 s	12 ms
Generalized Linear Model	100.0%	± 0.0%	26	12 s	21 ms
Logistic Regression	100.0%	± 0.0%	26	12 s	27 ms
Fast Large Margin	100.0%	± 0.0%	26	14 s	12 ms
Deep Learning	100.0%	± 0.0%	26	24 s	58 ms
Decision Tree	100.0%	± 0.0%	26	12 s	11 ms
Random Forest	100.0%	± 0.0%	26	36 s	16 ms
Gradient Boosted Trees	100.0%	± 0.0%	26	29 s	34 ms

Figure 2: Major results of probabilistic forecast T1

4.2 Probabilistic forecasting of T6

For the prediction of T6 of a transport time delay of an AGV due to an object on the driving path, the comparison of the probabilistic forecasting methods showed again that the GLM is the most favorable forecasting method, with a forecasting accuracy of 100 % and fastest overall computation time (see Fig. 3).

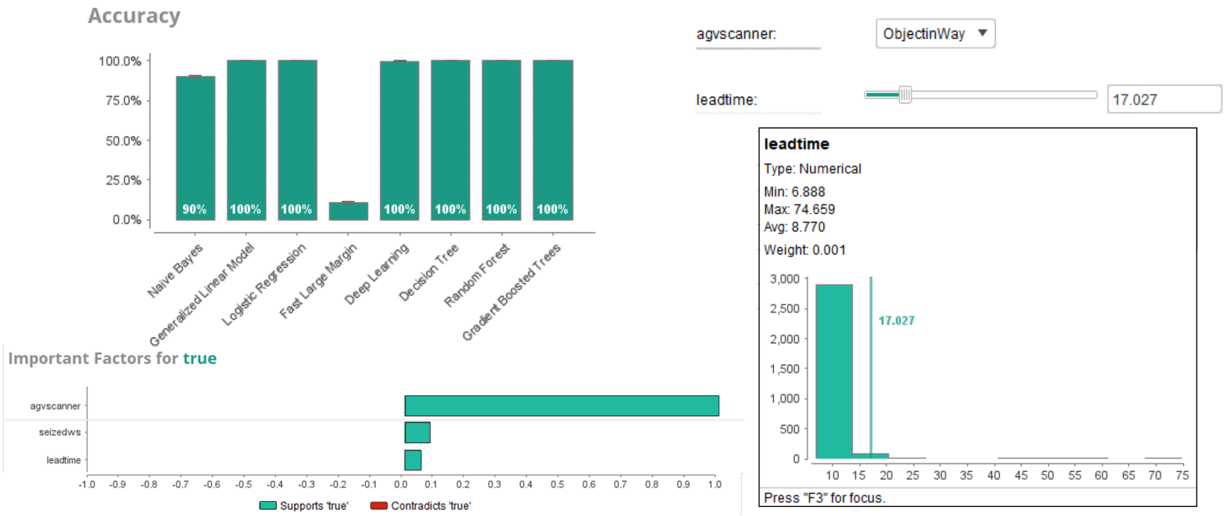


Figure 3: Major results of probabilistic forecast T6

As input parameters for this prediction AGV scanner alerts, the seized workstation, the process times of assembly as well as the overall lead time have been considered. Since not all input parameters correlate with the occurrence of T6, the fast large margin model leads to a poor forecasting accuracy of 11 % that can be increased to over 99 % by limiting the input parameters to the relevant factors. The analysis shows that the most important factors for the occurrence of T6 are the notification of the AGV scanner "object in way" and the seized workstation serviced by the AGV. The probabilistic forecast states that in the most likely case the lead time of the affected production order is expected to increase from an average of 8.770 minutes to 17.027 minutes. This probabilistic information can be used, for example, to transport subsequent orders to their destination on an alternative transport route using the material handling flexibility of the flexible production system, or to allocate subsequent production orders to alternative production resources (routing flexibility) which are not blocked by an obstacle.

4.3 Results of the comparative analysis

For the comparative analysis (also see table 2) of probabilistic, data-driven forecasting methods, different combinations of input parameters and forecasting models have been tested to predict the defined turbulences, as described above on the example of the turbulences T1 and T6. The comparative analysis using synthetic training data to train the prediction models and synthetic test data to validate the models showed that for most of the turbulences considered, the GLM is particularly suitable in terms of prediction accuracy and computational time. Nevertheless, some of the other forecasting methods showed comparable forecasting results. Therefore, a parallel comparison of different forecasting methods for the envisaged data-driven forecasting of turbulences based on real production will be maintained.

Table 2: Overview of the used input parameters to forecast turbulences

Turbu-lence	**Input parameters for forecast**							**Forecasting model with highest accuracy**
	AGV Battery warning	AGV scanner alert	Seized work-station	Lead time	Process time step 1	Process time step 2	Process time step 3	
T1			X	X	X	X	X	GLM (100 %)
T2			X	X	X	X	X	Decision tree (97.8 %)
T3			X	X	X	X	X	GLM (100 %)
T4			X	X	X	X	X	Naïve Bayes (96.2 %)
T5	X		X	X	X	X	X	GLM (100%)
T6		X	X	X	X	X	X	GLM (100%)

5. Conclusion

It has been shown and validated that a data-driven, probabilistic prediction of internal turbulences can be achieved through a simulative generation of synthetic data. In a further step, the findings regarding the identified models are to be validated with real data from the Werk150 – The Factory of the ESB Business School (Reutlingen University). The focus must be on the acquisition of manual process times for predicting possible assembly process delays since these frequently occur in practice and, therefore, offer great potential for reducing the negative influences of this turbulence on the lead time and delivery reliability of production orders. In the future, more potential arises from the inclusion of digital twins, which can provide additional input parameters for probabilistic forecasting of technical defects (e.g., through wear models of the corresponding resources) and other stochastic derivations in the production system. Future work is also intended to investigate how much forecasting methods can contribute to the exploitation of flexibility corridors in combination with autonomous control of intralogistics and, thus, to increase flexible production systems' resilience.

References

[1] Gruszczynski, L., 2020. The COVID-19 Pandemic and International Trade: Temporary Turbulence or Paradigm Shift? European Journal of Risk Regulation 11 (2), 337–342.

[2] Kupers, R. (Ed.), 2014. Turbulence: A corporate perspective on collaborating for resilience.

[3] Wiendahl, H.-H., 2006. Auftragsmanagement im turbulenten Umfeld – Teil 1 – Anforderungen. WT Werkstatttechnik online 96, 183–189.

[4] Erlach, K., Berchtold, M.-A., Gessert, S., Kaucher, C., Ungern-Sternberg, R., 2022. Flexibilität, Wandlungsfähigkeit und Agilität in der Fabrikplanung. ZWF 117 (7-8), 442–447.

[5] ElMaraghy, H.A., 2005. Flexible and reconfigurable manufacturing systems paradigms. International Journal of Flexible Manufacturing Systems 17 (4), 261–276.

[6] Andersen, A.-L., ElMaraghy, H., ElMaraghy, W., Brunoe, T.D., Nielsen, K., 2018. A participatory systems design methodology for changeable manufacturing systems. Intern. Journal of Production Research 56 (8), 2769–2787.

[7] Hill, R., Berry, S., 2021. An Introduction to Industrial Analytics, in: Hill, R., Berry, S. (Eds.), Guide to Industrial Analytics. Springer International Publishing, Cham, pp. 3–20.

[8] Schuhmacher, J., Hummel, V., 2022. Training Module on Probabilistic Forecasting of Production and Intralogistics Turbulences within Learning Factories. SSRN Journal.

[9] Leavy, P., 2022. Research Design: Quantitative, Qualitative, Mixed Methods, Arts-Based, and Community-Based Participatory Research Approaches. Guilford Publications.

[10] Breiman, L., 2001. Statistical modeling: The two cultures. Statistical science 16 (3), 199–231.

[11] Freitag, M., Kück, M., Ait Alla, A., Lütjen, M., 2015. Potentiale von Data Science in Produktion und Logistik: Teil 1 – Eine Einführung in aktuelle Ansätze der Data Science. Industrie 4.0 Management 31 (5), 22–26.

[12] Vermorel, J., 2020. Probabilistic Forecasting. https://www.lokad.com/probabilistic-forecasting-definition.

[13] Gneiting, T., Katzfuss, M., 2014. Probabilistic Forecasting. Annual Review of Statistics and Its Application. 1 (1), 125–151.

[14] H2O.ai, 2021. Deep Learning (Neural Networks). https://docs.h2o.ai/.

[15] McCarthy, R.V., McCarthy, M., Ceccucci, W., Halawi, L., 2019. Applying predictive analytics. Springer, 205 pp.

[16] RapidMiner, 2021. Operator Reference Guide - Naive Bayes. https://docs.rapidminer.com/latest/studio/operators/modeling/predictive/bayesian/naive_bayes.html.

[17] Maimon, O.Z., Rokach, L., 2005. Decomposition methodology for knowledge discovery and data mining: Theory and applications. World Scientific, Hackensach, NJ, 323 pp.

[18] Kieu, L.-M., Malleson, N., Heppenstall, A., 2020. Dealing with uncertainty in agent-based models for short-term predictions. Royal Society open science 7 (1), 191074.

[19] Lloyd, D.J.B., Santitissadeekorn, N., Short, M.B., 2016. Exploring data assimilation and forecasting issues for an urban crime model. European Journal of Applied Mathematics 27 (3), 451–478.

[20] Mannino, M., Abouzied, A., 2019. Is this Real?, in:Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology. ACM, New York, NY, USA, pp. 549–561.

[21] Syntho, 2022. Was sind synthetische Daten? https://www.syntho.ai/de/what-is-synthetic-data/.

[22] AnyLogic, 2023. Synthetic data. https://www.anylogic.de/features/artificial-intelligence/synthetic-data/.

[23] Lechler, T., Sjarov, M., Franke, J., 2021. Data Farming in Production Systems - A Review on Potentials, Challenges and Exemplary Applications. Procedia CIRP 96, 230–235.

[24] Sanchez, S.M., 2020. Data Farming. ACM Transactions on Modeling and Computer Simulation 30 (4), 1–30.

[25] Verein Deutscher Ingenieure, 2014. Simulation of systems in materials handling, logistics and production: Fundamentals. Beuth Verlag GmbH, Berlin ICS 03.100.10.

[26] Kuzgunkaya, O., ElMaraghy, H.A., 2007. Assessing the structural complexity of manufacturing systems configurations. International Journal of Flexible Manufacturing Systems 18 (2), 145–171.

[27] Windt, K., Philipp, T., Böse, F., 2008. Complexity cube for the characterization of complex production systems. International Journal of Computer Integrated Manufacturing 21 (2), 195–200.

[28] Swarup, S., 2019. Adequacy: What Makes a Simulation Good Enough?, in: 2019 Spring Simulation Conference (SpringSim). Tucson, AZ, USA. 29.04.2019 - 02.05.2019. IEEE, pp. 1–12.

[29] Schuhmacher, J., Hummel, V., 2021. Development of an Intelligent Warehouse and Autonomously Controlled Intralogistics Scenario to Investigate the Mastering of Short-Term Turbulences at Werk150. SSRN Journal, 1–6.

[30] SimPy, 2020. Discrete event simulation for Python. SimPy. https://simpy.readthedocs.io/en/latest/.

[31] AnyLogic, 2022. Multimethod Simulation. https://www.anylogic.de/use-of-simulation/multimethod-modeling.

[32] Signoret, J.-P., Leroy, A., 2021. Reliability Assessment of Safety and Production Systems. Springer International.

[33] Automationspraxis, 2012. Roboter machen weniger Fehler. Automationspraxis. https://automationspraxis.industrie.de/allgemein/roboter-machen-weniger-fehler/.

[34] publish-industry Verlag GmbH, 2020. Ein Roboter für alle Einbaulagen. publish-industry Verlag GmbH. https://www.industr.com/de/ein-roboter-einbaulagen-2468562.

[35] Balyo, 2022. AGV Installation. https://www.balyo.us/success/your-savings/how-do-you-generate-savings.

[36] Raviola, A., 2020. Diagnostics and Prognostics of Industrial and Collaborative Robots. https://www.dimeas.polito.it/content/download/2772/18711/file/35_Raviola_a.pdf.

[37] Grigoryev, I., 2021. AnyLogic in Three Days: Modeling and Simulation Textbook, 5th ed.

[38] Yu, A.J., Seif, J., 2016. Minimizing tardiness and maintenance costs in flow shop scheduling by a lower-bound-based GA. Computers & Industrial Engineering 97, 26–40.

[39] Gudum, C.K., 2002. On the distribution of lead time delays in supply chains. København.

[40] Mathematics Stack Exchange, 2022. statistics - What density distribution could be used for time delays? https://math.stackexchange.com/questions/3146378/what-density-distribution-could-be-used-for-time-delays.

[41] Aramon Bajestani, M., Beck, J.C., 2015. A two-stage coupled algorithm for an integrated maintenance planning and flowshop scheduling problem with deteriorating machines. Journal of Scheduling 18 (5), 471–486.

[42] Dodin, B., 1996. Determining the optimal sequences and the distributional properties of their completion times in stochastic flow shops. Computers & Operations Research 23 (9), 829–843.

[43] Wang, L., Zhang, L., Zheng, D.-Z., 2005. A class of hypothesis-test-based genetic algorithms for flow shop scheduling with stochastic processing time. The International Journal of Advanced Manufacturing Technology 25 (11-12), 1157–1163.

[44] Heydari, M., Mahdavi Mazdeh, M., Bayat, M., 2013. Scheduling stochastic two-machine flow shop problems to minimize expected makespan. 10.5267/j.dsl, 163–174.

[45] Fairchild, K.W., Misra, L., Shi, Y., 2016. Using Triangular Distribution for Business and Finance Simulations in Excel. Journal of Financial Education 42 (3-4), 313–336.

[46] Wiendahl, H.-H., 2011. Auftragsmanagement der industriellen Produktion. Springer Berlin Heidelberg.

[47] Flückiger, I., 2015. Data Analytics in Organisations and Business: 5.5 Selection of Software Tools. ETH Zürich. https://stat.ethz.ch/education/semesters/as2015/analytics/Data_Analytics_2015-11-25.pdf.

Jan Schuhmacher (*1987) has been a research associate at the Fraunhofer Institute for Manufacturing Engineering and Automation IPA since 2017 and doctoral student at the Institute of Industrial Manufacturing and Management IFF at the University of Stuttgart since 2020. His major field of research is the design and optimization of changeable, autonomously controlled intralogistics systems.

Thomas Bauernhansl (*1969) has been the director of the Institute of Industrial Manufacturing and Management IFF at the University of Stuttgart and the Fraunhofer Institute for Manufacturing Engineering and Automation IPA since 2011. He is a member of the WGP, the Scientific Society for Production Technology as well as Deputy Chairman of the Steering Committee of Allianz Industrie 4.0 BW.

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Development Of Data-based Business Models To Incentivise Sustainability In Industrial Production

Felix Hoffmann[1], Tobias Koch[1], Markus Weber[1], Matthias Weigold[1], Joachim Metternich[1]
[1]TU Darmstadt, Institute of Production Managaement, Technology and Machine Tools (PTW), Darmstadt, Germany

Abstract

Recent environmental catastrophes highlight the need to curb global climate change. Carbon dioxide (CO_{2e}) is responsible for the majority of the anthropogenic greenhouse effect. Politicians and society already exerted pressure for some time on industry and companies as major emitters. Despite continuously decreasing emissions, the savings achieved in the industrial sector fall short of the politically set targets. This is mainly due to the fact, that the combination of economic and ecological interests for companies is not promoted sufficiently. As a result, there is a lack of incentives for production companies to reduce their emissions. By incorporating economic aspects, data-based business models can create such incentives and thus support current and future regulatory measures.

This paper presents an approach of developing data-based business models to incentivise sustainability in industrial manufacturing. For this purpose, existing and potential future incentive mechanisms for the reduction of CO_{2e} are first identified and discussed. Subsequently, the business model approach for "CO_{2e} reduction in product creation" from the Gaia-X lighthouse project EuProGigant is presented. Finally, this approach is discussed in consideration of possible emission savings and the compatibility of economical and ecological company interests.

Keywords

Business Models; Sustainability; Digitalization; Data Analysis, GAIA-X

1. Introduction

The anthropogenic climate change and the resulting global warming cause a multitude of problems for humans and the environment. This becomes evident not only in the recent increase in extreme weather events, which have led to considerable economic damage around the globe [1]. Estimates suggest that the global economy will lose up to 18% of its GDP in 2050 due to climate change if no countermeasures will be taken [2]. For this reason, politics and society have already been working for decades to slow down or stop global climate change. Policymakers have set ambitious climate targets with the adoption of the Paris Climate Agreement [3] and the implementation of the European Green Deal [4] at European level. The reduction of climate-damaging greenhouse gas emissions is a key lever in this context. Along with increasingly strict regulatory measures, the pressure on companies to systematically reduce their emissions thus continues to grow.

For companies, though, switching to more sustainable production poses a number of problems and risks, as they primarily operate in a profit-oriented manner [5]. However, switching to sustainable production can mean a high level of effort and investment in new technologies and equipment. Such a changeover and

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investment must therefore be justifiable in terms of measurable benefits and return on investment. If competitors do not act similarly, they could achieve decisive advantages in the market through e.g. lower costs and thus displace more sustainable players [6]. In this context, data-driven business models can provide a way of unlocking additional potential benefits for companies that operate sustainably. By creating additional savings and revenue potential, they create incentives for manufacturing companies to reduce their emissions within current and future regulatory measures. Thus, the combination of economic and ecological interests of the companies is promoted [7].

Research on data-based sustainable business models in industrial production and the accompanying empowerment of companies is still in its infancy [8]. This includes both a structured and systematic approach to developing appropriate business cases and the practical demonstration of the potential in industrial use cases. In addition, there is a lack of approaches on how to enable the value creation mechanisms in these business cases to convert the additional value created into revenue [9]. The following remarks highlight future possibilities of data-based sustainable business models in production. First, the concept of a sustainable, data-based business model and current and future regulatory measures are discussed. Then, a possible approach for the structured development of corresponding business models in the context of Gaia-X is presented. Subsequently, the business model approach for "CO_{2e} reduction in product creation" from the Gaia-X lighthouse project EuProGigant is presented. Finally, this approach is discussed with regard to possible emission savings and economic potentials.

2. Related Work

2.1 Data-based sustainable business models

A business model captures the generated value proposition of a service offering and produces profitable outcomes through the application of a particular technology. In doing so, it represents a link between a technology and its economic value. It consists of the three complementary dimensions of value generation, value proposition and revenue structure [10]. The value proposition dimension represents the benefits that a company provides to its customers with a particular product or service. The value generation dimension captures the required key processes and competencies to fulfill the value proposition. Finally, the revenue structure dimension describes the composition of cost and revenue mechanisms. It thus determines the value generated from the business [11]. Data-driven, digital business models represent a special form and distinguish by their customer-centric, service-oriented value creation based on data and a fully digitized implementation [12]. In value creation, a data value chain significantly shapes the interactions in the ecosystem of such a business model [13]. The data used in this way is obtainable from various internal and external data sources [14]. In manufacturing, data often roots from the use of machinery and equipment. This is not least due to the ongoing transition from physical products to product-service systems and software-as-a-service models. Thus, the importance of dematerialized values is continuously increasing [15].

According to the United Nations Brundtland Commission, sustainability is defined as “meeting the needs of the present without compromising the ability of future generations to meet their own needs” [16]. Sustainable business models thus do not primarily aim for economic success, but complement an ecological and social target dimension. The resulting service offerings must therefore also contribute to an improvement in social and ecological performance indicators in the company and in society [8]. This creates an additional field of tension for the operating companies. The company's own positioning in the target system is largely determined by maintaining its competitiveness in the market [17]. In the context of Industrie 4.0, sustainable data-based business models can make a significant contribution to uniting economic and ecological interests. At research level, and to a lesser extent at industry level, technical approaches already exist to increase sustainability in production by leveraging data. These extend across different areas of the value chain [7]. By using data in maintenance, for example, it is possible to extend the useful life of machines and systems and their components. This enables to avoid emissions from the production of unnecessarily installed spare parts and non-optimal use of energy and resources as a result of wear-related degradation [18,19]. In the field of quality management, data-based applications are used for the early detection of production defects. As a result, emissions can be avoided by using energy and resources in the further processing of defective components and the destruction or costly recycling of scrap parts [20,21]. Finally, data is also used to optimize processes in terms of their demand for energy and resources and thus to make them more sustainable. In this context, operators are supported in the parameterization of the machines in order to generate an operationally optimal state [22].

2.2 Regulatory mechanisms

In recent years, an increasing number of regulatory measures were introduced in order to emphasize the demands of the climate protection agreements and to curb industrial emissions of greenhouse gases. These laws and regulations intend to provide companies with incentives to switch to sustainable technologies of their own accord and in accordance with market principles. They thus have a direct influence on the viability of sustainable business models. In addition to bans and verification requirements, incentives can also be subsidies or advantages, e.g. in taxation. The EU Commission is currently planning to introduce a digital product passport as an instrument for recording sustainability data along the entire product life cycle [23]. A possible tool in this context is the introduction of a CO_{2e} price, in which the emission of greenhouse gases is financially sanctioned [24].

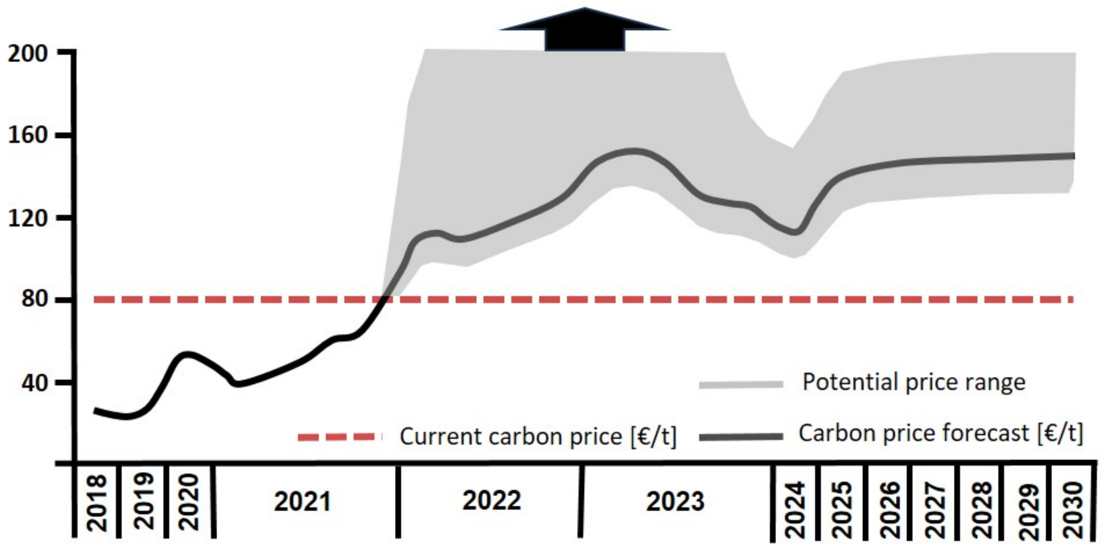

Figure 1: Price development for carbon emission certificates as forecast by [26]

The principle behind the CO_{2e} price are as follows: The emission of CO_{2e} causes damage to society in the long term. If the pricing of emitted CO_{2e} matches the amount of damage, an equilibrium is reached. At the same time, the incentive to emit CO_{2e} will decrease as the price of CO_{2e} increases. This financially sanctions every emitted amount of CO_{2e} and indirectly rewards every saved amount. One possibility is a simple CO_{2e} tax, where every emitted amount is taxed directly and with a fixed price. This creates a direct economic incentive to save CO_{2e}. An alternative concept is trading with so-called emission certificates. Here, the total amount of CO_{2e} that may be emitted at the reference level over a period is first determined. At the beginning of a commitment period, participants are allocated a number of emission certificates equal to their permitted emissions. At the end of the commitment period, emitters must demonstrate that their actual emissions do not exceed the number of emission allowances. Surplus allowances can be sold or stored, and missing allowances can be purchased from other participants. In Germany, a CO_{2e} tax or trading in emission certificates already exists for some industries through the European Union Emissions Trading System (EU ETS). This includes power generation, iron and steel production, glass, ceramics, paper and cellulose production, refineries and other subsectors of the chemical industry. Accordingly, there is no overall certificate trading system for the entire manufacturing industry, resulting in only indirect impacts in broad areas. In recent years however, the trading system has been steadily extended to other sectors [25]. Figure 1 shows the development of the EU ETS carbon price. It shows that the price has roughly tripled in the last 3 years and is expected to double further in the near future until 2023 [26]. In the future, a "Carbon Boarder Adjustment Mechanism" is intended to prevent CO2e emissions from being shifted on balance to countries outside the EU, which are monitored less strictly. This means, for example, that the location and energy mix of raw material production must be taken into account. In this course, it is then no longer permissible to calculate an average CO2e value for raw material supply. The emission content of raw materials will thus play a stronger role [23].

Pressure on the manufacturing industry is also increasing outside of legislative regulatory measures. Many large OEMs increasingly require their downstream suppliers to report certain sustainability parameters and to comply with defined threshold values. The OEMs hope that increased transparency throughout the supply chain will enable them to identify processes with particularly high emissions and to take countermeasures. Manufacturers who do not comply with these requirements may run the risk of losing their status as a preferred supplier [27].

3. Methodology

The overall objective of the underlying sub-research project is to develop a prototypical use case for data-driven reduction of greenhouse gas emissions in industrial production. A sustainable business model is needed to commercialize the technical solution as a marketable application. The project itself integrates into the research project EUProGigant, which is one of the lighthouse projects of the European Gaia-X initiative. Gaia-X aims to create an innovative data infrastructure based on European values. Thus, it also focuses on the aspect of sustainability. In their paper, Hoffmann et al. propose a funnel-shaped, iterative process for the development of data-based business models in the context of Gaia-X (see Figure 2) [28]. In this process, a problem is transformed into a commercially viable and executable application through the three phases of problem selection, solution design, and solution development. In the next chapter, the functionality and development of the business model based on the described approach will be explained in detail. A special focus is placed on the solution development phase. Subsequently, the economic and ecological potentials of the business model approach will be discussed.

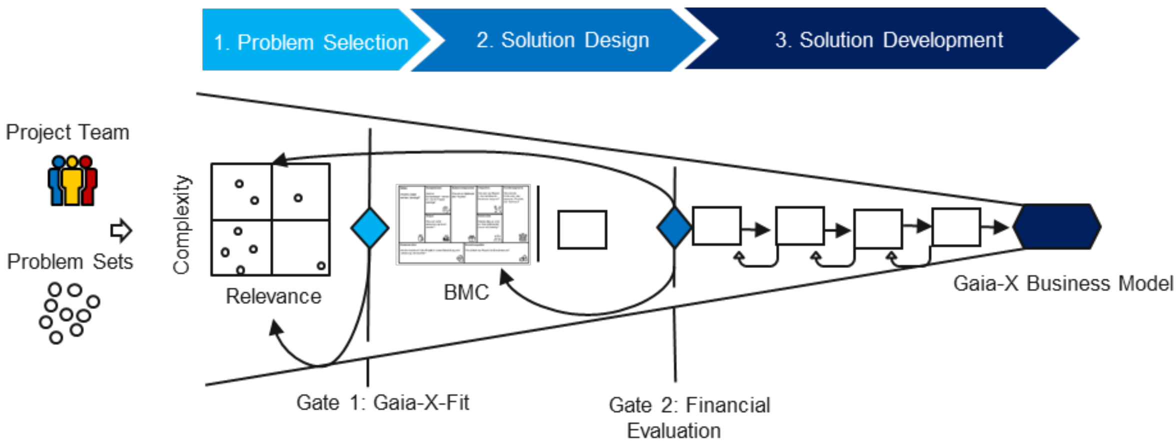

Figure 2: Development process of data-based business models according to [28]

4. Application

This section presents the current work on the "CO_{2e} footprint in product creation" use case within the EuProGigant project [29]. Due to the status of the project and the limited scope of the paper, the application is focused on the area of solution design. For this purpose, the use case is first described, and then the business architecture is depicted. The results presented were developed within interdisciplinary workshops with project participants. Domain experts from the fields of polymer processing, data scientists, as well as software developers were among the participants.

As illustrated in section 2.1, a number of different approaches to improve sustainability in production by leveraging data already exist. However, these approaches mostly focus on the product manufacturing phase. In order to develop innovative sustainable business model approaches, it is thus necessary to have fundamental transparency over the entire product life cycle. According to a recent study by Fuchs et al., „up to four-fifths of a product's lifetime emissions are determined by decisions made at the design stage" [30]. If these potentials are only identified in later phases, their implementation may involve considerable and, in the worst case, unrealizable effort. For this reason, the effects of subsequent phases should be implied as early as possible in the product design phase or as early as possible in the product development process. A clever design can then reduce CO_{2e} emissions without limiting the actual functionality of the product.

In the production of components in the mechanical engineering sector, there are various levers for influencing lifecycle CO_{2e} emissions [31]. In the present application, these were identified by experts specifically for the area of plastics processing. The first lever identified is the selection of materials for the product. It becomes apparent that materials with similar properties require significantly different CO_{2e} footprints for their production. This effect is reinforced by the increasing spread of organic-based polymers designed for particularly low emissions [32]. It is also evident that different polymers have different processing properties. The temperatures required to melt plastics and the injection pressure needed to form them differ significantly from one another. This impacts not least on the energy required to carry out the manufacturing process and thus on CO_{2e} emissions. The emissions generated during transport and the energy and resources required for recycling are further influencing factors. Another lever is the selection of the underlying manufacturing process. In the industrial context, injection molding, machining and additive manufacturing are the predominant processes used to manufacture functional components from thermoplastics [33]. Each process brings different specific properties that affect CO_{2e} emissions. In the case of machining, a key factor is that components are mostly machined from the solid. This results in a relatively high volume of machined material, which in turn has to be recycled or destroyed [34]. With injection molding, this process-related waste is much less pronounced. On the other hand, a high level of energy and material input is required for the production of the injection mold itself [35]. Depending on the exact process, there is no waste in additive manufacturing. However, due to the significantly longer processing times, the manufacturing of a single component is much more energy-intensive. Within manufacturing processes, there

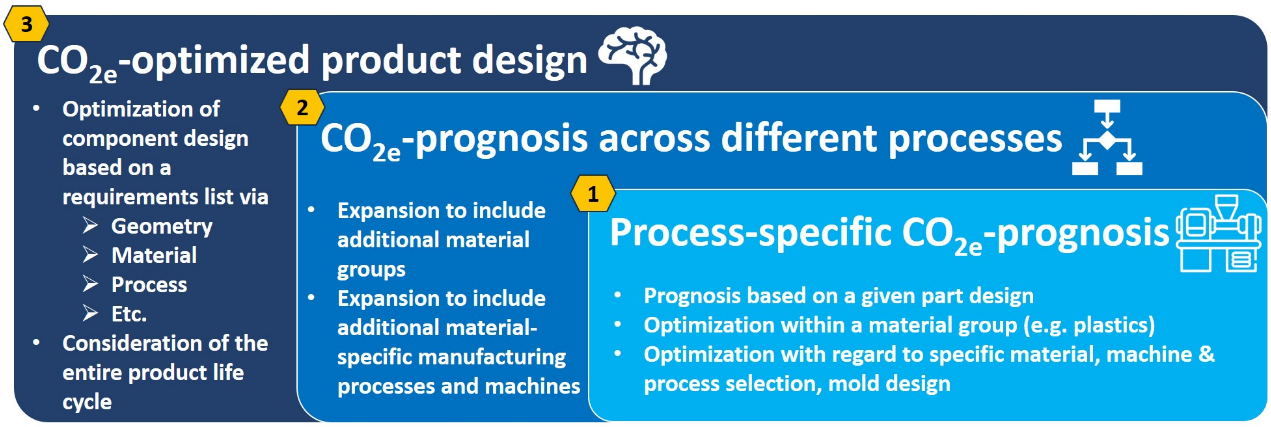

Figure 3: Development stages of the business model "CO_{2e} footprint reduction in product creation"

are again further opportunities to influence lifecycle CO_{2e} emissions. Here, the injection molding process acts as an example: It often happens that machines are over-dimensioned, which increases the energy consumption to carry out the process. The design of the mold determines the number of components that can be produced in one shot and simultaneously the volume to be heated.

Industrial practice shows that optimization efforts often fail because there is no exchange between the relevant actors. In order to exploit the emission saving potentials identified, EUProGigant develops an approach for optimizing the "CO_{2e} footprint in product creation". The concept builds on the Gaia-X data infrastructure, which conforms to European values. It aims to promote exchange between the relevant players in product creation to minimize CO_2 emissions. Figure 3 shows different expansion stages of the business model approach in relation to the value proposition. In the first stage, an existing component design is optimized - e.g. with regard to material and machine selection - within a certain type of manufacturing process. In the second stage, the value proposition includes a comparison of different types of manufacturing processes. The third and final stage finally enables to generate a CO_{2e} optimized product design based on a requirements list.

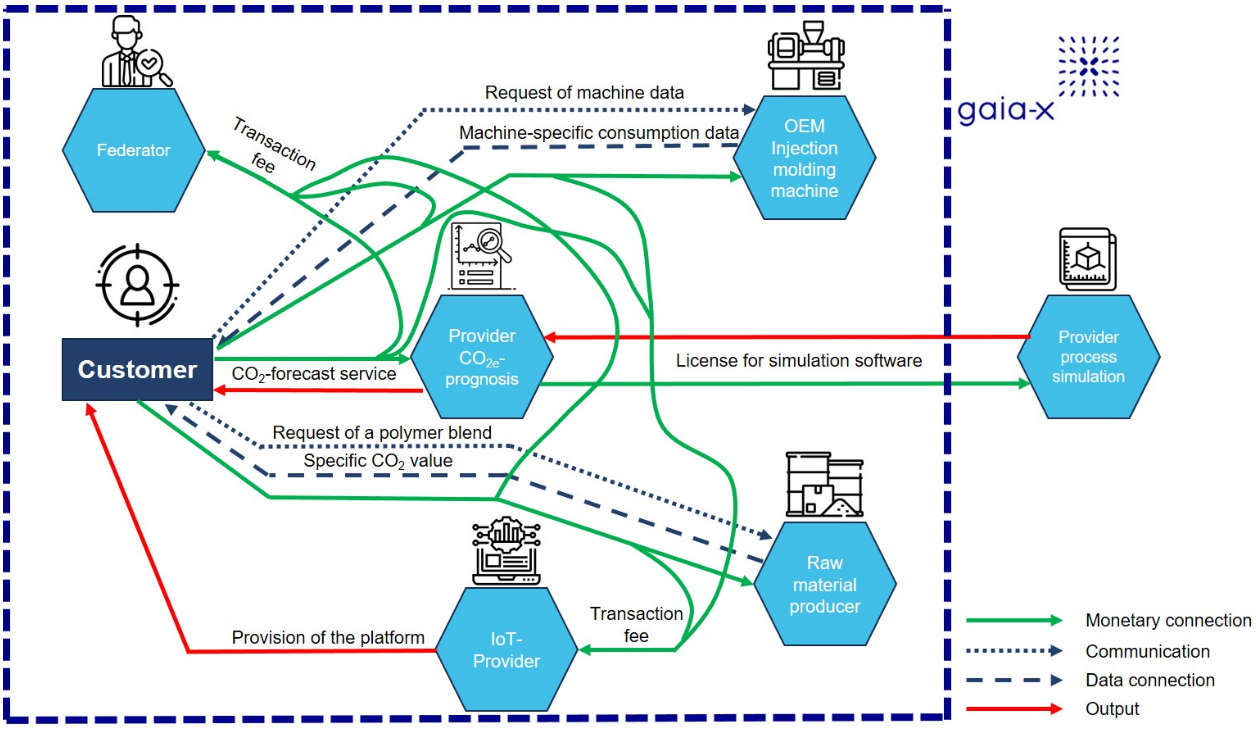

Figure 4: Business model architecture of the "CO_{2e} footprint prognosis in product creation"

Figure 4 shows the developed business model architecture of the first stage with the representation method according to Kölsch et al. [36]. It shows the players involved within the business model and their relationships to each other for the case of plastic injection molding. The key players in the business model are injection molding machine manufacturers, raw material producers, process simulation providers, IoT providers, a Federator, the customer, and finally the CO_{2e} prognosis service provider himself. The relations divide into data connections, communication, monetary connections, and outputs. The OEM and the raw material supplier provide data to the customer and are financially compensated by him. In the case of an OEM, this is precise data on the energy and operating material consumption of its machines, and in the case of the raw material manufacturer, information on the CO_{2e} footprint and the processing properties of its materials. The provider of the CO_{2e} prognosis provides the customer with its digital service for processing his component data and the purchased data for a charge. To enrich its service, the CO_{2e} prediction provider uses simulation software from the process simulation provider. Here, it is also conceivable that the simulation provider itself is simultaneously the provider of the CO_{2e} prognosis. The IoT provider offers its platform for interaction between the aforementioned players. He charges a transaction-based fee for this. The same applies to the so-called Federator. The federator verifies that all parties involved are compliant with the Gaia-X standard and that only approved parties exchange data.

5. Discussion

The procedure was adapted to an exemplary use case in order to analyze the effectiveness of the business model. A holding bracket was selected as an example component, which is manufactured by one of the application companies within the EUProGigant project. Table 1 shows the comparison of different materials, manufacturing processes and machine concepts for one bracket. With all combinations mentioned, the component produced meets its functional requirements. In the initial state, the component is manufactured from polyamide on a hydraulic injection molding machine. This serves as a baseline for the calculated relative emission savings.

Table 1: Evaluation of the effects of a CO_{2e}-optimization in product creation

Machine	Material	Emissions/ part [%]	Share of Energy [%]	Share of Material [%]	Energy cost* [€]	Emissions cost** [€]
HIM	PA	100	16	84,0	0,0024	0,0096
HIM	PP	25,1	4,4	95,6	0,0022	0,0024
EIM	PA	76,9	12,8	87,2	0,0023	0,0074
EIM	PP	18,2	4,4	95,6	0,0019	0,0017
3D-Printer	PA	1897,2	99,2	0,8	1,0349	0,1827
3D-Printer	PP	517,4	85,8	14,2	0,2442	0,4983
HIM = hydraulic injection molding				EIM = electronic injection molding		
*considering an energy price of 0,35€/kWh						
**considering an emission price of 150€/tCO_{2e}						

The evaluation shows that by applying the proposed solution in the present case, considerable potentials for saving greenhouse gas emissions can be realized. A changeover from PA to PP, for example, already leads to a reduction of around 75% when using the existing machine. By switching to a modern electrically driven injection molding machine, another 7% of emissions can be saved compared to the initial state. Broken down to a single component, the use of a 3D printer leads to drastically higher emissions than injection molding. However, this does not take into account that for the injection molding process, significantly more emissions are caused during the production of the mold. From an economic point of view, potential improvements can also be expected. The changeover from PA to PP while using the existing machine results in a reduction of energy costs by approx. 10%. An additional conversion to the electric injection molding machine saves a total of 20% of the energy costs. Despite the relatively small amounts of energy costs in absolute terms for the production of a component, this can lead to significant savings in the company if a very large number of produced units is taken into account.

As already explained in chapter 2.2, politically initiated regulatory measures can lead to a significant change in the viability of sustainable business models. For this reason, the evaluation also considered the hypothetical scenario of introducing a CO_{2e} price for discrete component manufacturing. The price of 150€/tCO_{2e} predicted by [26] was assumed here. Based on the greenhouse gases emitted in the machining process of a component, this leads to additional costs as much as four times the energy costs of the initial scenario. In the optimum scenario with PP on an electric injection molding machine, these costs can be reduced by approx. 80%.

6. Conclusion and Future Research

This paper presents an approach for developing sustainable data-based business models in the context of industrial production. First, the necessity of such approaches was motivated and the fundamentals were described. In this course, the profound influence of regulatory measures on the viability of business models was revealed. Finally, an exemplary business model was developed using an existing method. Its potential in terms of profitability and sustainability was finally evaluated by applying it to a practical use case. It was shown that the solution presented in the considered case achieves significant savings in terms of greenhouse gas emissions and energy costs. In addition to these cost savings, companies can thus also be supported in complying with the limits imposed by legislators or customers. In the case of an extension of CO_{2e} pricing to the sector of discrete production of machine components, this effect would be significantly enhanced.

In the current state of development, some simplifying measures have been adopted, allowing opportunities for future research in this context. The consideration of quantity-related effects offers a point for further elaboration. This includes e.g. the impact of emissions due to the production of tools or repair measures. Furthermore, great potential is expected by extending the method to other materials and manufacturing processes. This represents a fundamental prerequisite for ultimately enabling sustainability-optimized product design based on component requirements.

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References

[1] European Environment Agency, 2022. Economic losses and fatalities from weather and climate- related events in Europe. https://www.eea.europa.eu/publications/economic-losses-and-fatalities-from/economic-losses-and-fatalities-from. Accessed 26 October 2022.

[2] Swiss Re Institute, 2021. The economics of climate change: no action not an option. https://www.swissre.com/media/press-release/nr-20210422-economics-of-climate-change-risks.html. Accessed 26 October 2022.

[3] United Nations, 2016. Paris Agreement.

[4] Sikora, A., 2021. European Green Deal – legal and financial challenges of the climate change. ERA Forum 21 (4), 681–697.

[5] Corsten, M., Corsten, H., 2019. Betriebswirtschaftslehre, 2. Edition ed. Franz Vahlen, München.

[6] Bengtsson, J., Dellborg, E., Hanicke, M., Huemer, Y., 2022. Mastering the dual mission: Carbon and cost savings, Hamburg. https://www.mckinsey.com/capabilities/operations/our-insights/mastering-the-dual-mission-carbon-and-cost-savings. Accessed 26 October 2022.

[7] Koch, D., Lentes, J., Schuseil, F., Waltersmann, L., 2022. Nachhaltigkeit durch KI: Potenziale und Handlungsleitfaden für produzierende Unternehmen. Fortschrittszentrum Lernende Systeme und Kognitive Robotik, Stuttgart. https://www.ipa.fraunhofer.de/de/Publikationen/studien/nachhaltigkeit-durch-kI.html. Accessed 26 October 2022.

[8] Muller, J., 2020. Data-based sustainable business models in the context of Industry 4.0, in: International Conference on Information Systems 2020, Hyderabad, pp. 1–8.

[9] Bocken, N., Boons, F., Baldassarre, B., 2019. Sustainable business model experimentation by understanding ecologies of business models. Journal of Cleaner Production 208 (7), 1498–1512.

[10] Gassmann, O., Frankenberger, K., Choudury, M., 2014. The business model navigator: 55 models that will revolutionise your business. Pearson, München.

[11] Chesbrough, H., 2007. Business model innovation: it's not just about technology anymore. Strategy & Leadership 35 (6), 12–17.

[12] Sharp, M., Sexton, T., Brundage, M.P., 2017. Toward Semi-autonomous Information, in: Lödding, H., Riedel, R., Thoben, K.-D., Cieminski, G. von, Kiritsis, D. (Eds.), Advances in Production Management Systems. The Path to Intelligent, Collaborative and Sustainable Manufacturing, vol. 513. Springer International Publishing, Cham, pp. 425–432.

[13] Otto, B., Jürjens, J., Schon, J., Auer, S., Menz, N., Wenzel, S., Cirullies, J., 2016. Industrial Data Space: Digitale Souveränität über Daten, München. https://www.fraunhofer.de/content/dam/zv/de/Forschungsfelder/industrial-data-space/Industrial-Data-Space_whitepaper.pdf. Accessed 21 October 2022.

[14] Hartmann, P.M., Zaki, M., Feldmann, N., Neely, A., 2016. Capturing value from big data – a taxonomy of data-driven business models used by start-up firms. IJOPM 36 (10), 1382–1406.

[15] Khan, M.A., Wuest, T., 2019. Upgradable Product-Service Systems: Implications for Business Model Components. Procedia CIRP 80 (43), 768–773.

[16] Brundtland, G.H., 1987. Report of the World Commission on Environment and Developmen: Our Common Future. Report of the World Commission on Environment and Development, New York.

[17] Cesinger, B., Vallaster, C., Müller, J.M., 2022. The ebb and flow of identity: How sustainable entrepreneurs deal with their hybridity. European Management Journal 40 (1), 77–89.

[18] Brockhaus, B., Hoffmann, F., Metternich, J., Weigold, M., 2022. Predictive Maintenance for Flexible Protective Covers in Machine Tools, in: Behrens, B.-A., Brosius, A., Drossel, W.-G., Hintze, W., Ihlenfeldt, S., Nyhuis, P. (Eds.), Production at the Leading Edge of Technology, vol. 79. Springer International Publishing, Cham, pp. 177–185.

[19] Cheng, Y., Zhu, H., Wu, J., Shao, X., 2019. Machine Health Monitoring Using Adaptive Kernel Spectral Clustering and Deep Long Short-Term Memory Recurrent Neural Networks. IEEE Trans. Ind. Inf. 15 (2), 987–997.

[20] Lee, S.Y., Tama, B.A., Moon, S.J., Lee, S., 2019. Steel Surface Defect Diagnostics Using Deep Convolutional Neural Network and Class Activation Map. Applied Sciences 9 (24), 5449.

[21] Susto, G.A., Beghi, A., McLoone, S., 2017 - 2017. Anomaly detection through on-line isolation Forest: An application to plasma etching, in: 2017 28th Annual SEMI Advanced Semiconductor Manufacturing Conference (ASMC). 2017 28th Annual SEMI Advanced Semiconductor Manufacturing Conference (ASMC), Saratoga Springs, NY, USA. 15.05.2017 - 18.05.2017. IEEE, pp. 89–94.

[22] Willenbacher, M., Wohlgemuth, V., 2018. Einsatzmöglichkeiten von Methoden der Künstlichen Intelligenz zur Optimierung von Stoff- und Energieströmen und prototypische Umsetzung auf der Basis von Stoffstromnetzen,

in: Arndt, H.-K., Marx Gómez, J., Wohlgemuth, V., Lehmann, S., Pleshkanovska, R. (Eds.), Nachhaltige Betriebliche Umweltinformationssysteme. Springer Fachmedien Wiesbaden, Wiesbaden, pp. 97–108.

[23] European Commission. Green Deal: New proposals to make sustainable products the norm and boost Europe's resource independence, Brussels.

[24] Bundesministerium für Umwelt, Naturschutz, nukleare Sicherheit und Verbraucherschutz, 2021. CO2-Preis: Anreiz für einen Umstieg auf klimafreundliche Alternativen. https://www.bmuv.de/WS5734. Accessed 20 June 2022.

[25] Frankovic, I., 2022. The impact of carbon pricing in a multi-region production network model and an application to climate scenarios. Deutsche Bundesbank, Frankfurt am Main, 49 pp.

[26] Steele, L., Fisher, A., Gleeson, A., Ip Tat Kuen, M., 2022. Raising power prices by 50%; carbon to EUR150/t. Utilities, Hamburg.

[27] Deloitte, 2021. Sustainable manufacturing: From vision to action, London. https://www2.deloitte.com/content/dam/Deloitte/global/Documents/Energy-and-Resources/gx-eri-sustainable-manufacturing-2021.pdf. Accessed 26 October 2022.

[28] Hoffmann, F., Weber, M., Weigold, M., Metternich, J., 2022. Developing GAIA-X Business Models for Production. Hannover : publish-Ing.

[29] Weber, M., Weigold, M., Koch, T., 2022. The European Production Gigane: Towards a Green and Digital Manufacturing Ecosystem, in: Smart and Networked Manufacturing. Conference Proceedings. Wiener Produktionstechnik Kongress, Wien. new academic press, Wien, pp. 95–100.

[30] Fuchs, S., Mohr, S., Öreback, M., Rys, J., 2022. Product sustainability: Back to the drawing board. Operations Practice. McKinsey & Company, New York. https://www.mckinsey.com/capabilities/operations/our-insights/product-sustainability-back-to-the-drawing-board. Accessed 31 October 2022.

[31] Su, J.C.P., Chu, C.-H., Wang, Y.-T., 2012. A decision support system to estimate the carbon emission and cost of product designs. Int. J. Precis. Eng. Manuf. 13 (7), 1037–1045.

[32] Amulya, K., Katakojwala, R., Ramakrishna, S., Venkata Mohan, S., 2021. Low carbon biodegradable polymer matrices for sustainable future. Composites Part C: Open Access 4 (1), 100111.

[33] Schwarz, O., Ebeling, F.-W., Furth, B., 2009. Kunststoffverarbeitung, 11. Auflage ed. Vogel Buchverlag, Würzburg.

[34] Agrawal, G., Khare, M., 2013. Material and Energy Wastes Minimization in a Machining System: A Review. Jounral of Materials and Environmental Science 4 (2), 251–256.

[35] Elduque, A., Elduque, D., Javierre, C., Fernández, Á., Santolaria, J., 2015. Environmental impact analysis of the injection molding process: analysis of the processing of high-density polyethylene parts. Journal of Cleaner Production 108, 80–89.

[36] Kölsch, P., Herder, C.F., Zimmermann, V., Aurich, J.C., 2017. A Novel Concept for the Development of Availability-Oriented Business Models. Procedia CIRP 64 (2), 340–344.

Biography

Felix Hoffmann, M. Sc. is a research assistant and PhD student at the Institute of Production Management, Technology and Machine Tools (PTW) at the Darmstadt University of Technology since 2019. His research interests are ML-driven Business Models in manufacturing and Predictive Maintenance. Since 2022 Mr. Hoffmann is head of research at the Production Management department of PTW.

Tobias Koch, M.Sc. is a research assistant and PhD student at the Institute of Production Management, Technology and Machine Tools (PTW) at the Darmstadt University of Technology since 2022. His research interest focuses on cyber-physical systems in climate-neutral production.

Markus Weber, M. Sc. is a research assistant and PhD student at the Institute of Production Management, Technology and Machine Tools (PTW) at the Darmstadt University of Technology since 2017. Mr. Weber was head of research at the Manufacturing Technology department of PTW from Jan. 2021 until May 2022 and he is project coordinator of EuProGigant.

Prof. Dr.-Ing. Matthias Weigold is the head of the Institute for Production Management, Technology and Machine Tools (PTW) at the Darmstadt University of Technology with responsibility of the manufacturing and energy efficiency research groups since 2019. Prof. Weigold contributes many years of industrial experience from management positions at Heidelberger Druckmaschinen AG and SAP SE.

Prof. Dr.-Ing. Joachim Metternich is the head of the Institute for Production Management, Technology and Machine Tools (PTW) at the Darmstadt University of Technology since 2012. In addition, Prof. Metternich is the spokesman for the Center of Excellence for Medium-Sized Businesses in Darmstadt and president of the International Association of Learning Factories.

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Extended Production Planning of Reconfigurable Manufacturing Systems by Means of Simulation-based Optimization

Sebastian Behrendt[1], Marco Wurster[1], Marvin Carl May[1], Gisela Lanza[1]

[1]*wbk Institute of Production Science, Karlsruhe Institute of Technology, Karlsruhe, Germany*

Abstract

Reconfigurable manufacturing systems (RMS) are capable of adjusting their operating point to the requirements of current customer demand with high degrees of freedom. In light of recent events, such as the covid crisis or the chip crisis, this reconfigurability proves to be crucial for efficient manufacturing of goods. Reconfigurability aims thereby not only at adjust production capacities but also for fast integration of new product variants or technologies. However, the operation of such systems is linked to high efforts concerning manual work in production planning and control. Simulation-based optimization provides the possibility to automate processes in production planning and control with the advantage of relying on mostly existing models such as material flow simulations. This paper studies the capabilities of the meta heuristics evolutionary algorithm, linear annealing and tabu search to automate the search for optimal production reconfiguration strategies. Two distinct use cases are regarded: an increase of customer demand and the introduction of a previously unknown product variant. A parametrized material flow simulation is used as function approximator for the optimizers, whereby the production system's structure as well as logic are target variables of the optimizers. The analysis shows that meta-heuristics find good solutions in a short time with only little manual configuration needed. Thus, metaheuristics illustrate the potential to automate the production planning of RMS. However, the results indicate that the performance of the three meta-heuristics considering optimization quality and speed differs strongly.

Keywords

Reconfigurable manufacturing systems; simulation-based optimization; material flow simulation; meta heuristics; production planning

1. Introduction

Reconfigurable manufacturing systems (RMS) are characterized by a high degree of adjustability concerning the structure of the system and the structure of machines associated to the system [1,2]. Whilst the design of flexible manufacturing systems aims to plan for all possible upcoming demands, RMS are designed to fit the current requirements with its provided functionality and capacity and, thus, allow to be more cost efficient in the long run [3]. The ability to reconfigure a manufacturing system to a more efficient operating point gets increasingly important with regard to disruptive and highly volatile markets in a VUCA-world [4]. Moreover, new use cases, such as remanufacturing, increase the demand for highly adjustable and scalable manufacturing systems [6,5]. By providing the changeability enablers – modularity, scalability, compatibility, universality and mobility – a manufacturing systems is enabled to adjust its functionality and capacity to the current requirement [8,7]. Today there are several technical solutions available that provide the changeability enablers for production and logistical processes, such as modular automated assembly stations, autonomous guided vehicles and reconfigurable material handling systems. However, frequently

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reconfiguring a manufacturing system results in increased planning efforts and cost, since associated tasks are currently performed in practice manually by experts [9]. A solution to automate reconfiguration planning is the use of optimization methods [10].

There exist numerous examples in the literature that show how optimization is successfully utilized in planning tasks associated to manufacturing system reconfigurations. Uribe et al. present a simulation-based optimization approach for capacity planning in agile manufacturing [11]. Based on a two-stage stochastic integer programming under budget constraints they configure their system while taking multiple products, flow paths and tool types into consideration. Finally, they test their approach on a semiconductor manufacturing use case. Youssef & Elmaraghy propose an approach for the configuration of RMS taking into account the arrangement of the machines, selection of the equipment and the assignment of operations [12]. Besides cost and availability of the system, they also consider the reconfiguration effort between production periods within the evaluation. Genetic algorithms as well as a reactive tabu search algorithm had been developed for the formulated optimization problem. The authors prove that the reconfiguration effort plays a vital role if the total cost of a system is considered over multiple planning periods. Stähr et al. propose a foresighted planning method for RMS with a scalable degree of automation [13]. The aim of the method is to determine optimal scaling paths for the system catering for evolving requirements such as a rise in demand or increasing labour costs. The planning uncertainties are reduced and a decision support is granted by the integration of Monte-Carlo chains and stochastic scenario analysis. Further approaches on the optimization of RMS configuration had been recently summarized by Sabioni et al. [14]. The authors divide existing approaches by the configuration level in system, machine and hybrid approaches as well as into exact and approximate methods.

Existing approaches have in common that either only a subset of the planning tasks associated to a reconfiguration are considered or that their underlying model is bound to many assumptions. Therefore, the following optimization approach aims to extend previous approaches by considering the following requirements: (1) include all tasks associated to a system reconfiguration [1,2] and (2) utilize a model with a high degree of model accuracy and detail compared to previous approaches. In order to satisfy requirement (1), structural as well as logical reconfigurations are possible on a machine and system level. While structural reconfigurations affect the hardware used, logical reconfigurations affect the control logic of the machines and system by changing the decision process for sequencing, i.e. the control policy, and allocation of jobs to resources, i.e. the routing policy. The selection of decision variables of the optimization problem is thereby based on a real-world testbed for the approach, as shown in [15]. Requirement (2) considering model accuracy and detail is met by using a digital twin represented by a discrete-event simulation (DES) as a model of the RMS [16–19]. DES are generally applicable in the manufacturing domain and allow specific modelling enhancement, such as extending a material flow simulations with consideration of machine failures and repair [20], activity based costing [21] or energy consumption of production processes [22]. Considering the combinatorial complexity of the reconfiguration of a manufacturing system, global optimization methods, such as meta-heuristics, are advisable [24,23]. This is based on the general applicability, simplicity and good behaviour of meta-heuristics concerning global optimization in large and discrete search spaces [14]. Therefore, this paper aims to investigate the suitability of simulation-based optimization with meta-heuristics for manufacturing system reconfiguration planning by assessing and comparing the performance of three distinct meta-heuristics: evolutionary algorithms, simulated annealing and tabu search. The paper is structured as followed: the optimization problem and the used meta-heuristics are described in chapter 2. Chapter 3 shows, explains and discusses the results of the experiments. Lastly, the paper concludes with a summary and an outlook in chapter 4.

2. Methods

2.1 Optimization Problem Description

The description of the optimization problem is oriented towards the description of a complex job-shop scheduling problem [25] and the formalization of RMS [12]. There is a set of n jobs $J = \{J_1, J_2, \dots, J_n\}$, that need to be processed on m resources, where the set of m resources is $R = \{R_1, R_2, \dots, R_m\}$. Each job J_j consists thereby of a sequence of n_j operations $(O_{j,1}, O_{j,2}, \dots, O_{j,n_j})$. The execution of each operation i of job j $(O_{j,i})$ requires a resource $R(i,j)$ that is capable to perform this process. Each resource R_k is thereby equipped with a set of c_k process modules $M_k = \{m_1, \dots, m_{c_k}\}$, where each process module $m_s \epsilon M_k$ enables the resource to perform a distinct subset O_{m_s} of all possible operations $O_{i,j}$. The set of all c process modules will be called $M_a = \{m_1, \dots, m_c\}$ in the following. The sequence of performed operations of a resource R_k is determined by a control policy $u_k \in U$, where $U_a = \{u_1, \dots, u_q\}$ defines the set of all q possible control policies. The configuration of resource R_k is then defined by the tuple (M_k, u_k).

Each resource R_k is located in the RMS at location $l_k = (x_k, y_k) \in L$, where $L_a = \{l_1, \dots, l_p\}$ is the set of all possible p locations. By introducing the set L= $\{l_1, \dots, l_m\}$ that includes the locations of all m resources, the system configuration S is defined by the tuple $S = (R, L)$.

In the problem of the reconfiguration of a RMS from configuration $S = (R, L)$ to $S' = (R', L')$ several degrees of freedom concerning the structure and logic of the manufacturing system exist [1,2]. At first, due to the mobility and compatibility, a resource R_k can be added ($R' = R \cup R_k$), removed ($R' = R \setminus R_k$) or relocated in the manufacturing system ($l_k{}' \neq l_k$). Moreover, it is possible to add ($M_k{}' = M_k \cup m_s$) or remove ($M_k' = M_k \setminus m_s$) a process module m_s from a resource R_k and, furthermore, move a process module from one resource to another ($m_s \in M_k'$ and $m_s \in M_g$ where $k \neq g$). Lastly, the control policy u_k of a resource R_k can be altered ($u_k{}' \neq u_k$).

The objectives of the optimization problem at hand are minimal reconfiguration cost C, minimal inventory I in the RMS and a maximum throughput λ. Although lead time or throughput time T is an important performance measure in practice, it is neglected in regard of its correlation with inventory level I and throughput λ, according to Little's Law ($T = \frac{I}{\lambda}$) [26]. The mentioned objectives describe a conflict of objectives, since they describe independent and contradictory goals. For example, increasing the throughput of a production system requires a larger production capacity, that is only reached by increased cost. Therefore, the optimization problem yields a set of pareto-optimal configurations. Identification of a particular optimum can only be achieved by knowing the weighting of the objectives.

2.2 Specific use case

In order to investigate the performances of the three meta-heuristics to solve a reconfiguration problem, a representative benchmark use case of an RMS is used. In the benchmark use case, an initial configuration is chosen as the initial state S_I and reconfiguration cost is evaluated by a comparison of the reconfigured and the initial configuration. The initial configuration S_I is described in Table 1.

The task of the manufacturing system is the completion of jobs that require the operation sequence $O_p = \{o_1, o_2, o_3, o_4, o_5\}$ to be finished. Since all jobs require the same process sequence, the second index is omitted for sake of simplicity. Moreover, every operation is performed by a distinct process module in the use case, for which reason a differentiation of operations and process modules is in this case unnecessary.

Table 1: Initial configuration S_I of the manufacturing system in the studied benchmark use case

Resource	Operations	Location	Control policy
Machine 1	o_1, o_3	(5, 5)	FIFO
Machine 2	o_2, o_5	(5, 10)	SPT
Machine 3	o_4	(10, 5)	FIFO
Machine 4	o_5	(10, 10)	FIFO
Transport resource 1	-	(5, 0)	SPT
Source	-	(0, 0)	-
Sinks	-	(35, 35)	-

Table 2: Overview of the distribution parameters of the time of processes in the benchmark use case

Process	Distribution type	Mean	σ
o_1	Normal distribution	50 s	5 s
o_2	Normal distribution	250 s	25 s
o_3	Normal distribution	40 s	4 s
o_4	Normal distribution	180 s	18 s
o_5	Normal distribution	40 s	4 s
Product arrival	Exponential distribution	150 s	150 s
Machine TTF	Exponential distribution	700 min	700 min
Transport resource TTF	Exponential distribution	1100 min	1100 min

Individual jobs are released into the manufacturing system by the source with exponentially distributed interarrival times. Each performed operation takes a normal distributed process time. The transport time required to transfer products from one machine to another is calculated by considering the transport distance by the Manhattan distance and assuming a velocity of 1 m/s and a constant reaction time of 2 s. Moreover, machine and transport resources fail in exponentially distributed time to failure (TTF) and the associated repairs require 15 min. An overview of the parameters of the time distributions of the individual processes can be found in Table 2.

The reconfiguration of the benchmark use case is also constrained by some restrictions. These restrictions aim to represent real planning situations, where only a limited amount money is available, additional equipment is related to some expenditure and infrastructure and hardware can only be used in some defined boundaries. Table 3 presents the constraints in the benchmark use case.

The degrees of freedom specified by the reconfiguration problem are realized by the benchmark use case. Machines, transport resources and process modules can be added and removed in the reconfiguration in the defined boundaries of the constraints. Moreover, machines can be relocated, control policies can be changed and process modules can be transferred to other machines. However, there are some special assumptions made in the use case. At first, transport resources do not require a process module for the transport and they always start at position $l = (5, 0)$. Additionally, if a machine is added to the manufacturing system, the process modules and location of the machine are selected randomly. Machines and transport resources can only perform a single operation at a time.

Table 3: Overview of the distribution parameters of the time of processes in the benchmark use case

Constraint type	Constraint
Maximum reconfiguration cost	100.000
Buying a machine	30.000
Buying a transport resource	15.000
Buying a process module	5.000
Maximum number of machines	6
Maximum number of transport resources	3
Machine TTF	3
Maximum process modules per machines	3
Possible machine positions	(5, 5), (5, 10), (10, 5), (10, 10), (15, 10), (10, 15), (20, 25), (25, 20), (25, 25), (30, 25), (30, 30)
Possible control policies	FIFO, LIFO, SPT [27]

For the evaluation of the configurations with the DES, a time range of 10.000 minutes (approx. 7 days) is simulated. This simulation time is long enough to neglect stochastically induced effects. The output of the system, which represents the system throughput since a constant time range is simulated, is determined by the number of individual products that arrived at the sink and the inventory is calculated as the average number of products in the system. For the calculation of the inventory, the first quarter of simulation results is discarded to neglect the impact of the warm-up phase within the DES.

2.3 Meta-heuristics

Meta-heuristics are approximative optimization techniques that use high-level algorithms, that do not rely on any domain knowledge, which results in their wide applicability across optimization problems. This class of optimization techniques can be divided in population-based and trajectory-based methods. [28]

Evolutionary algorithm (EA) is a population-based method that relies on Darwin's principle of natural selection. The algorithms rely thereby on three basic operations that are repeated for every generation: selection, crossover and mutation. Each individual, i.e. a possible solution, of a population is evaluated and a selection of the best individuals is done according to the objective values of the individuals. Subsequently in crossover, pairs of individuals are combined to generate new individuals. Lastly, individuals are randomly modified in mutation. The sequence of these three operations is repeated until a predefined number of generations is evaluated.

In the presented approach, each individual in the population represents a configuration of the RMS. The population is randomly initialized at start of the optimization. As the reconfiguration optimization problem has multiple objectives, NSGA-II [29] is used for selection, because of its good behaviour in finding a pareto-optimal front and no need to weight the different objectives. In crossover, the individuals are combined by exchanging a random number of machines or transport resources. Lastly, in mutation, an individual is randomly altered by one of the earlier defined degrees of freedom.

Contrarily, simulated annealing (SA) is a trajectory-based method that is motivated by the cooling process of metals. The algorithm is started with an initial solution and an initial temperature that decreases over time. At first, a candidate solution is generated by altering the initial solution and both solutions are evaluated and the compared to each other. With a certain acceptance probability, the candidate solution is accepted although it has a lower performance. This acceptance probability decreases with temperature and allows SA to leave local minima. This process is repeated until a stop criterion is met. [30]

Similar to the implementation of EA, a solution in the SA approach is a distinct configuration of the RMS and the altering of solutions is done randomly according to the degrees of freedom of the RMS. Instead of starting with a random configuration, as in EA, the initial solution of SA is the earlier mentioned initial configuration S_I. As SA requires a single objective, a weighted sum of the objectives, in the following referred to as fitness, cost ($w_C = -0.001$), throughput ($w_\lambda = 0.025$) and WIP ($w_I = -1.0$) is used. The parameter choice of the weights is thereby done according to the magnitude of the objectives.

The last evaluated meta heuristic, tabu search (TS), is also a trajectory-based method introduced by Glover [31]. In each iteration of TS, the best nonvisited solution is selected from the neighbourhood of the previously selected solution. The memory of visited solutions, also called tabu list, has a maximum length and gets updated if a new best nonvisited solution is found. If the tabu list reaches its maximum length, the oldest solutions get removed when adding new solutions. Similar to SA, TS allows worsening moves with the help of the tabu list. The algorithm iterates until a stop criterion is reached.

With regard to the benchmark use case, TS starts optimization with the initial configuration S_I. Since the concept of neighbourhood is not obvious for an RMS, we define a neighbourhood as 10 configurations that can be reached from the starting configuration by randomly using one degree of freedom. Similar to SA, TS requires a single objective for performance comparison of solutions, which is defined in this case as the previously described weighted sum of objectives.

3. Results and Discussion

The analysis of the three meta-heuristics for the presented benchmark use case is performed by comparing their performance on the same hardware (Intel Core i7 1185G7, 4,8GHz) within a limited optimization time range of 180 minutes. In order to evaluate the solutions more precisely, we define an interesting region of solutions by a minimum throughput $\lambda_{min} = 3000$ and a maximum inventory $I_{max} = 150$. The hyperparameter selection of all three algorithms is done based on a similar grid search and choosing the best parameter set. The hyperparameter sensitivity of SA can be observed to be much higher than that of TS and NSGA-II.

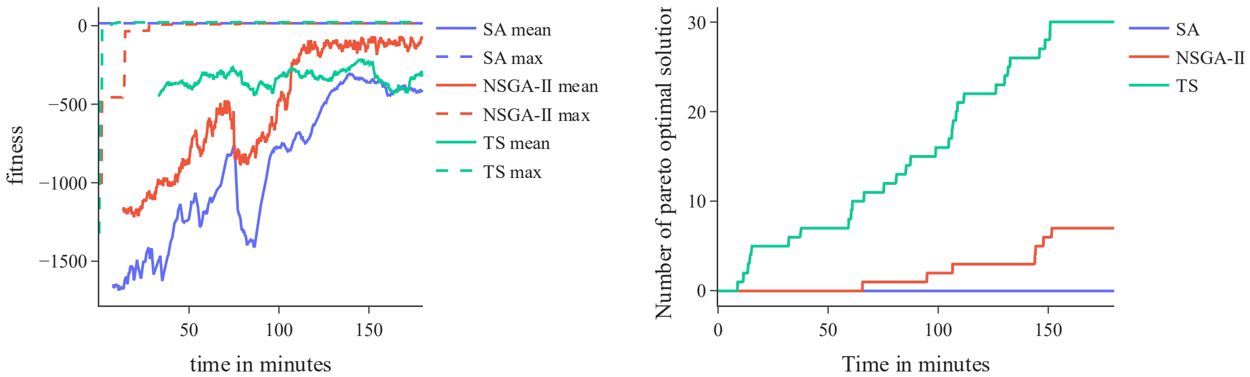

Figure 1: Maximum and rolling average performance of the three meta heuristics over time (left) and number of found pareto-optimal solutions per meta heuristic over time (right)

In the left diagram of Figure 1, the max and rolling average of the fitness of the three heuristics over optimization time is displayed. All three algorithms manage to improve their best fitness over time and NSGA-II and SA improve their average dramatically. It is also visible that all algorithms reach a steady fitness level, where TS reaches this steady state very early. When comparing the rolling average fitness, NSGA-II reaches a higher fitness than SA and TS.

The right diagram of Figure 1 shows the number of found pareto-optimal solutions for the three algorithms over time. As the combinatorial complexity of the benchmark use case is too big to evaluate all possible configurations, the pareto-optimal solutions are only derived from all evaluated configurations of the three

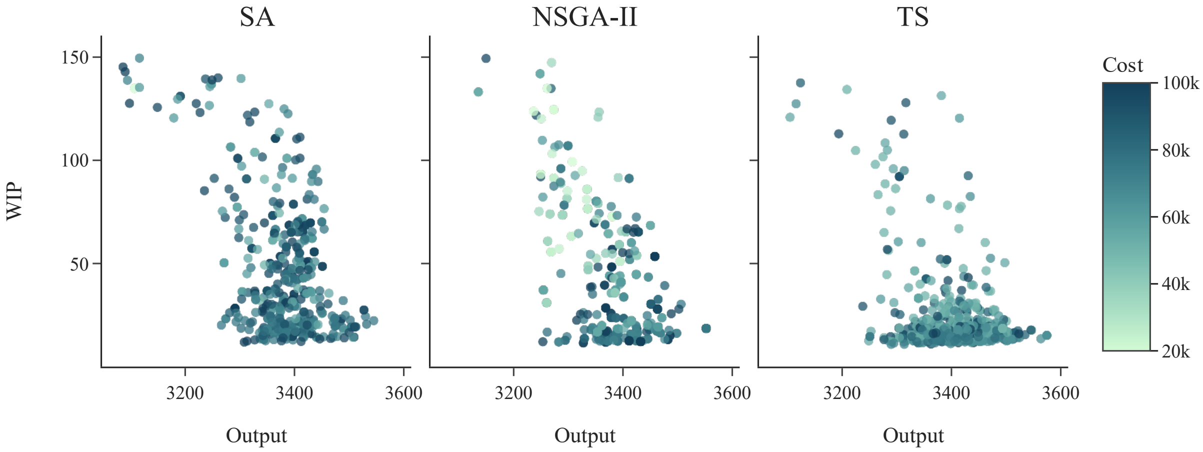

Figure 2: Output, inventory and cost distribution of found configurations per meta heuristic in the interesting region.

optimization runs. The diagram indicates that SA finds no pareto-optimal solution and TS finds much more pareto-optimal solutions than NSGA-II. Similarly, to the left diagram of Figure 1, TS finds good solutions fast when compared to SA and NSGA-II. Although TS is based on fitness optimization and NSGA-II on multi-objective optimization, TS finds more pareto-optimal solutions and NSGA-II has a higher average fitness.

As the reconfiguration problem is a multi-objective optimization problem, we want to consider how the found configurations are distributed in the earlier defined interesting region. Figure 2 shows this by displaying the three objectives cost (colouring), output and inventory for the analysed three meta heuristics. It is visible that NSGA-II and SA has a very broad distribution of found configurations in the interesting region but especially solutions of SA with high inventory are on average costlier than the ones found by NSGA-II and TS. Contrastingly, TS has the narrowest search, focusing heavily and low inventory, medium cost configurations.

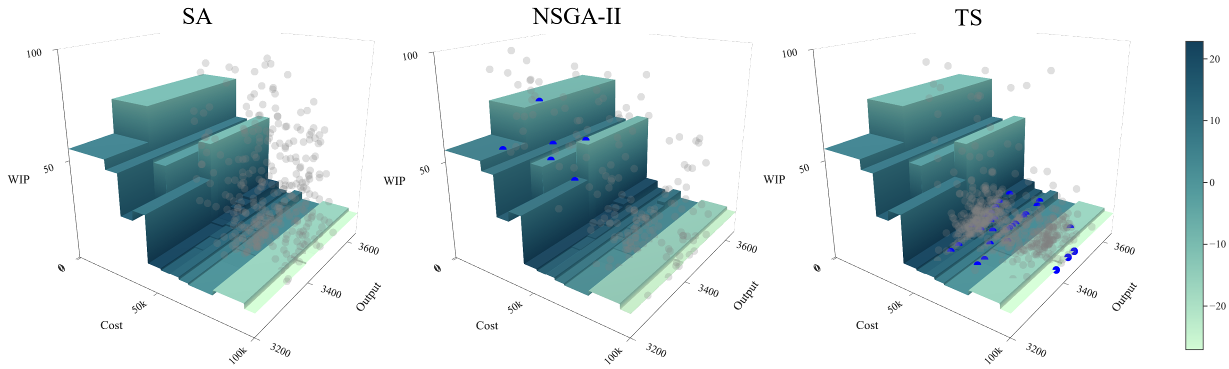

Figure 3: Output, inventory and cost distribution of found configurations per meta heuristic in the interesting region with an interpolation of the pareto-front and display of pareto-optimal points.

In order to evaluate, where the pareto-optimal configurations are found in the search space per algorithm, Figure 3 can be regarded. The three diagrams show 3D plots of the three objectives cost, output and inventory where all configurations of the interesting region are displayed in grey and pareto-optimal solutions are displayed in blue. The pareto-front is thereby displayed as an interpolated surface with a colour according to the fitness. The pareto-front can be divided into two distinct regions: low cost with high inventory (I) and low inventory with high cost (II). Interestingly, the pareto-optimal solutions of region I are exclusively found by NSGA-II and the solutions of region II exclusively by TS. It is visible that the configurations found by TS have a very high focus in the region with high fitness values whereas configurations found by NSGA-II are much broader distributed. This can be explained by the fact, that TS optimizes fitness whereas NSGA-II optimizes all objectives. The fact that NSGA-II finds no pareto-optimal solutions in region II is due to the fact that TS exploits this region more strongly and finds better solutions there. The previous observation that TS finds more pareto-optimal solutions but has a lower average fitness compared to NSGA-II can be explained by two facts. At first, the pareto-optimal solutions are much more densely packed in region II than in region I as TS searched this region very exhaustively. Secondly, the selection method of NSGA-II leads to redundant but good solutions in a population which explains the high average fitness.

In summary, TS and NSGA-II show a better performance in optimization than SA while SA showed to be much more instable and hyperparameter sensitive. This limits the use of SA for practical applications. TS and NSGA-II exhibit a good performance for different objectives. If a multi-objective search space of an RMS has to be evaluated, NSGA-II is more suited. Contrarily, if a designated operating point considering the objectives is given, TS shows a better behaviour. As combinatorial complexity increases strongly with the size of the RMS, fast optimization gets more important. This motivates again the use of TS. Future research should examine how this approach is applicable to larger problem settings. However, as TS is not as easily parallelizable as population-based optimization methods, the potential of parallelization and combination of TS with a population-based method should be evaluated. Lastly, future research could evaluate how this approach can be extended with more degrees of freedom in order to represent a more generalizable production planning approach.

4. Conclusion

The paper at hand evaluates the capability of the meta-heuristics SA, TS and NSGA-II for the optimization of a RMS. After reviewing state-of-the-art literature from the domain of RMS optimization, it is motivated that recent approaches either lack high model accuracy and detail or many degrees of freedom considering the reconfigurations. Therefore, we formulate an optimization problem description of an RMS that considers structural as well as logical changes on the machine and system level. To evaluate the capability of SA, TS and NSGA-II optimization experiments are performed with use of discrete-event simulation as evaluation model. The results indicate that all meta-heuristics are able to find good configurations of the RMS in a defined amount of time. However, SA shows an inferior performance than TS and NSGA-II. As a conclusion, the approach demonstrates that reconfiguration planning of RMS is possible to automate by simulation-based optimization with only little need for manual meta-heuristic configuration. These insights motivate to conduct further research that assesses how this approach is applicable to larger problem settings, how parallelization can be used to reduce optimization time and how the degrees of freedom of the RMS could be extended to a broader, more general production planning approach.

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References

[1] Koren, Y., Heisel, U., Jovane, F., Moriwaki, T., Pritschow, G., Ulsoy, G., van Brussel, H., 1999. Reconfigurable Manufacturing Systems. CIRP Annals 48 (2), 527–540.

[2] Mehrabi, M.G., Ulsoy, A.G., Koren, Y., Heytler, P., 2002. Trends and perspectives in flexible and reconfigurable manufacturing systems. Journal of Intelligent Manufacturing 13 (2), 135–146.

[3] ElMaraghy, H.A., 2006. Flexible and reconfigurable manufacturing systems paradigms. International Journal of Flexible Manufacturing Systems 17 (4), 261–276.

[4] Mack, O., Khare, A., Krämer, A., Burgartz, T. (Eds.), 2016. Managing in a VUCA world. Springer, Cham, Heidelberg, New York, Dordrecht, London, 259 pp.

[5] Wurster, M., Häfner, B., Gauder, D., Stricker, N., Lanza, G., 2021. Fluid Automation — A Definition and an Application in Remanufacturing Production Systems. Procedia CIRP 97, 508–513.

[6] Lanza, G., Asfour, T., Beyerer, J., Deml, B., Fleischer, J., Heizmann, M., Furmans, K., Hofmann, C., Cebulla, A., Dreher, C., Kaiser, J.-P., Klein, J.-F., Leven, F., Mangold, S., Mitschke, N., Stricker, N., Pfrommer, J., Wu, C., Wurster, M., Zaremski, M., 2022. Agiles Produktionssystem mittels lernender Roboter bei ungewissen Produktzuständen am Beispiel der Anlasser-Demontage. at - Automatisierungstechnik 70 (6), 504–516.

[7] Wiendahl, H.-P., Reichardt, J., Nyhuis, P., 2014. Handbuch Fabrikplanung: Konzept, Gestaltung und Umsetzung wandlungsfähiger Produktionsstätten, 2., überarb. und erw. Aufl., [elektronische Ressource] ed. Hanser Verlag, München.

[8] Wiendahl, H.-P., ElMaraghy, H.A., Nyhuis, P., Zäh, M.F., Wiendahl, H.-H., Duffie, N., Brieke, M., 2007. Changeable Manufacturing - Classification, Design and Operation. CIRP Annals 56 (2), 783–809.

[9] Oluyisola, O.E., Sgarbossa, F., Strandhagen, J.O., 2020. Smart Production Planning and Control: Concept, Use-Cases and Sustainability Implications. Sustainability 12 (9), 3791.

[10] Tempelmeier, H., 2003. Practical considerations in the optimization of flow production systems. International Journal of Production Research 41 (1), 149–170.

[11] Uribe, A.M., Cochran, J.K., Shunk, D.L., 2003. Two-stage simulation optimization for agile manufacturing capacity planning. International Journal of Production Research 41 (6), 1181–1197.

[12] Youssef, A.M.A., ElMaraghy, H.A., 2007. Optimal configuration selection for Reconfigurable Manufacturing Systems. Int J Flex Manuf Syst 19 (2), 67–106.

[13] Stähr, T., Englisch, L., Lanza, G., 2018. Creation of configurations for an assembly system with a scalable level of automation. Procedia CIRP 76 (9), 7–12.

[14] Sabioni, R.C., Daaboul, J., Le Duigou, J., 2021. Optimization of Reconfigurable Manufacturing Systems Configuration: A Literature Review, in: Roucoules, L., Paredes, M., Eynard, B., Morer Camo, P., Rizzi, C. (Eds.), Advances on Mechanics, Design Engineering and Manufacturing III, vol. 48. Springer International Publishing, Cham, pp. 426–435.

[15] M. Vorderer, S. Junker, A. Lechler, A. Verl, 2016. CESA3R: Highly versatile plug-and-produce assembly system, in: 2016 IEEE International Conference on Automation Science and Engineering (CASE). 2016 IEEE International Conference on Automation Science and Engineering (CASE), pp. 745–750.

[16] Kritzinger, W., Karner, M., Traar, G., Henjes, J., Sihn, W., 2018. Digital Twin in manufacturing: A categorical literature review and classification. IFAC-PapersOnLine 51 (11), 1016–1022.

[17] May, M.C., Overbeck, L., Wurster, M., Kuhnle, A., Lanza, G., 2021. Foresighted digital twin for situational agent selection in production control. Procedia CIRP 99, 27–32.

[18] Smith, J.S., Wysk, R.A., Sturrock, D.T., Ramaswamy, S.E., Smith, G.D., Joshi, S.B., 1994. Discrete event simulation for shop floor control, in: 1994 Winter Simulation Conference proceedings. Lake Buena Vista, Florida, December 11 - 14, 1994. Winter Simulation Conference, Lake Buena Vista, FL, USA. 11-14 Dec. 1994. Assoc. for Computing Machinery, New York, NY, pp. 962–969.

[19] Turner, C.J., Hutabarat, W., Oyekan, J., Tiwari, A., 2016. Discrete Event Simulation and Virtual Reality Use in Industry: New Opportunities and Future Trends. IEEE Trans. Human-Mach. Syst. 46 (6), 882–894.

[20] Valet, A., Altenmüller, T., Waschneck, B., May, M.C., Kuhnle, A., Lanza, G., 2022. Opportunistic maintenance scheduling with deep reinforcement learning. Journal of Manufacturing Systems 64, 518–534.

[21] Spedding, T.A., Sun, G.Q., 1999. Application of discrete event simulation to the activity based costing of manufacturing systems. International Journal of Production Economics 58 (3), 289–301.

[22] Kohl, J., Spreng, S., Franke, J., 2014. Discrete Event Simulation of Individual Energy Consumption for Product-varieties. Procedia CIRP 17, 517–522.

[23] Law, A.M., McComas, M.G., 2002. Simulation-based optimization, in: Exploring new frontiers. 2002 Winter Simulation Conference, San Diego, CA, USA. 8-11 Dec. 2002. IEEE, pp. 41–44.

[24] Gansterer, M., Almeder, C., Hartl, R.F., 2014. Simulation-based optimization methods for setting production planning parameters. International Journal of Production Economics 151, 206–213.

[25] Chaudhry, I.A., Khan, A.A., 2016. A research survey: review of flexible job shop scheduling techniques. Intl. Trans. in Op. Res. 23 (3), 551–591.

[26] Little, J.D.C., Graves, S.C., 2008. Little's Law, in: , Building Intuition. Springer, Boston, MA, pp. 81–100.

[27] Pinedo, M.L., 2012. Scheduling. Springer US, Boston, MA.

[28] Ahmed, Z.E., Saeed, R.A., Mukherjee, A., Ghorpade, S.N., 2020. Energy optimization in low-power wide area networks by using heuristic techniques, in: , LPWAN technologies for IoT and M2M applications; Ed. by Bharat S. Chaudhari. Elsevier Academic Press, London, pp. 199–223.

[29] Deb, K., Pratap, A., Agarwal, S., Meyarivan, T., 2002. A fast and elitist multiobjective genetic algorithm: NSGA-II. IEEE Trans. Evol. Computat. 6 (2), 182–197.

[30] Zhan, S., Lin, J., Zhang, Z., Zhong, Y., 2016. List-Based Simulated Annealing Algorithm for Traveling Salesman Problem. Computational Intelligence and Neuroscience 2016 (5), 1712630.

[31] Glover, F., 1990. Tabu Search: A Tutorial. Interfaces 20 (4), 74–94.

Biography

Sebastian Behrendt (*1997) is a research associate at the Institute of Production Science (wbk) at the Karlsruhe Institute of Technology (KIT) and works in the group of production system planning. He studied mechanical engineering with a specialization in production systems, data analysis and machine learning at the Karlsruhe Institute of Technology (KIT).

Marco Wurster (*1993) is a research associate at the Institute of Production Science (wbk) at the Karlsruhe Institute of Technology (KIT) working in the group of production system planning. In his research he focuses on production planning and control of agile production systems in environments with a high degree of uncertainty such as remanufacturing and product disassembly.

Marvin Carl May (*1994) is a researcher at the Institute for Production Science (wbk) at the Karlsruhe Institute of Technology (KIT). His research concerns production system optimisation on strategical, tactical and operational levels by means of intelligent algorithms. The focus lies on discrete manufacturing, in close cooperation with industry, e.g. semiconductor manufacturing, and aims at researching and implementing innovative and application-oriented solutions to technological problems.

Gisela Lanza (*1973) is member of the management board at the Institute of Production Science (wbk) of the Karlsruhe Institute of Technology (KIT). She heads the Production Systems division dealing with the topics of global production strategies, production system planning, and quality assurance in research and industrial practice. Her research focus is on the holistic design and evaluation of production systems. The methodological approach includes the use of quantitative methods to increase efficiency. In addition, a special focus is placed on data-driven planning and control of production networks in order to translate corporate strategy into tactical and operative network design.

4th Conference on Production Systems and Logistics

Towards Factory Location Planning Using GIS

Justin Hook[1], Chris Macdonald[1], Peter Nyhuis[1]

[1]Institute of Production Systems and Logistics/ Leibniz University Hannover

Abstract

Today, companies face continuously increasing competitive pressure resulting from highly volatile markets, globalisation and constantly growing customer requirements. Against this background, the location of a factory has a significant influence on competitiveness. The process of location planning is crucial for future success, as the choice of location can determine competitive aspects such as the distance to customers and suppliers or the attractiveness for employees for decades. At present, location decisions are often derived heuristically by gradually narrowing down the object of consideration starting from the global level. In the future, geo-information systems (GIS) shall help to make a more holistic and future-proof factory location decision, which is less dependent on subjective feelings and takes less time and costs. In this paper, the necessary fundamentals for factory location planning with GIS are presented, and it is explained which factory planning information can support location planning using GIS.

Keywords

Factory Planning; Geo-Information Systems; Location Strategy; Supply Chain; Online Map Services

1. Introduction

In recent decades, the market situation of manufacturing companies has been shaped by the influence of change drivers such as advancing digitalisation, volatile internal and external requirements, environmental impacts and several others [1]. In addition, supply shortages and new regulations pose significant challenges to companies' global production networks [2]. Uncertainties of this kind lead companies to question whether the long-term success of a company's location is sustainable in terms of ecological and social aspects [1]. If a company's current location situation is no longer benefiting its strategic goals, a location planning process is triggered that can determine the company's future competitiveness. Location planning strongly influences the future, as the location decision has a long-term character of up to 30 years and determines the company's success [3,1]. It is, therefore, necessary to carry out location planning according to specific requirements to ensure future performance [4]. Among other things, a location decision may be influenced by the distance to customers and suppliers and the connections to inland ports or motorways [5,1]. A future-based solution for site planning could be to use geo-information systems (GIS) in this process. Depending on the context, GIS means either software systems or the basic conceptual idea underlying these systems, which is geographically based [6]. GIS is used today as a tool for performing tasks. In addition to routine tasks such as navigation in traffic, GIS also includes a deeper level of support. In this context, a GIS provides predictive support in decision-making in line with requirements, e.g. for a planning task [7]. With the help of this link, the planning process could show greater transparency, be made more efficient and increase the quality of the results. This paper presents current approaches and challenges and discusses premises and data requirements regarding the use of GIS in factory location planning.

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2. State of the Art

In this chapter, the basics of factory location planning are explained, including location factors and their subdivision, influencing factors in location planning, current considerations on the use of GIS in location planning and challenges in implementation.

2.1 Factory Location Planning

How exactly a location is selected usually depends on the production strategy as well as the reason for and scope of the planned relocation. Figure 1 shows how external and internal factors influence decisions regarding a factory location. Internal weaknesses can create certain motives for changing a location and perhaps influence strategic goals. The figure shows an example of a company having high production costs leading to the motive of cost reduction that can ultimately conclude in aiming for cost leadership in a market due to new circumstances and possibilities deriving from a new factory location.

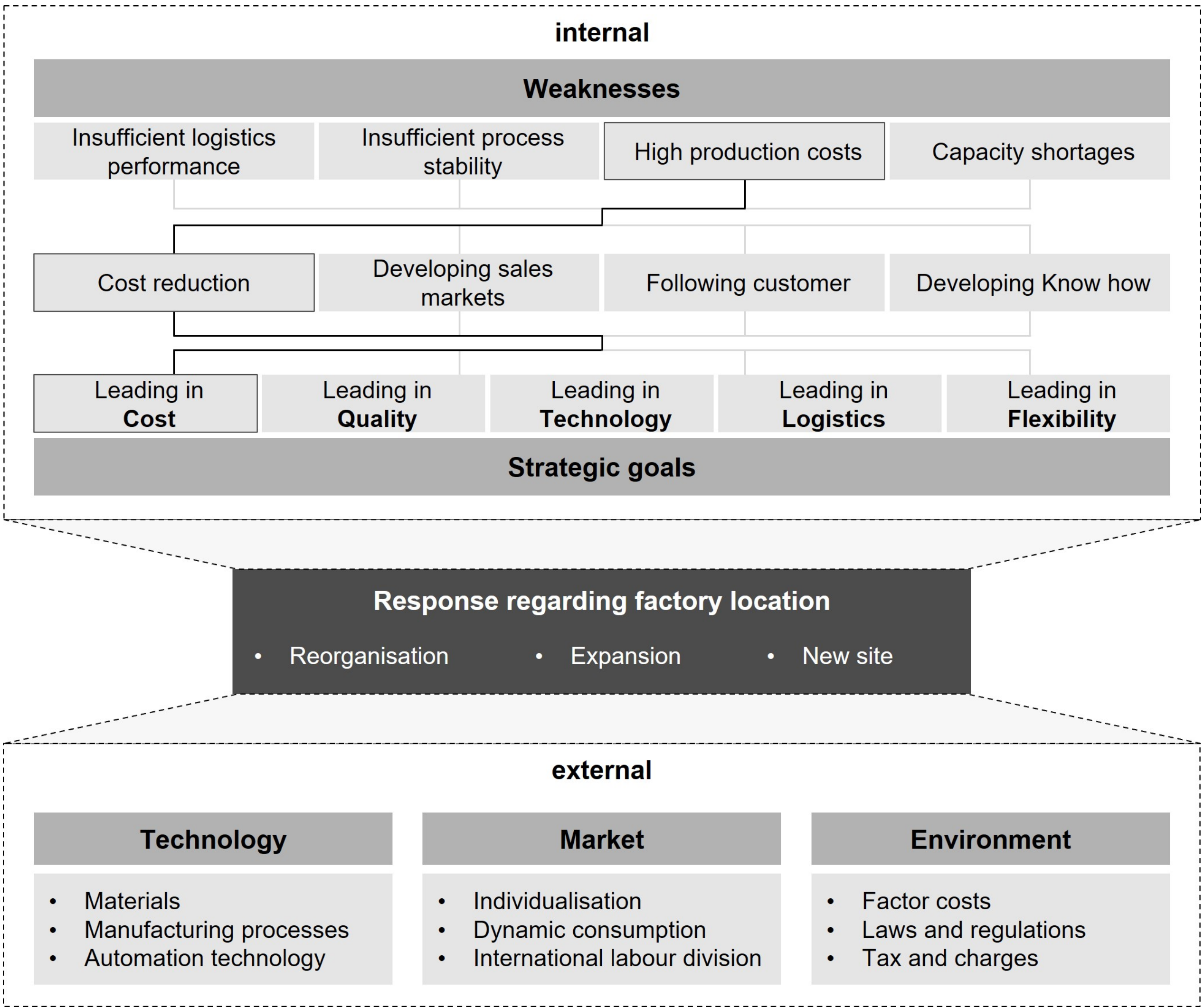

Figure 1: Internal and external influence on location planning

The planning case's complexity depends, particularly on the company environment [4]: A broadly defined product and process scope with comparatively little networking to other locations and suppliers prevails as a framework condition. Such a planning case occurs especially in smaller or medium-sized companies with few locations, customers and suppliers. Location planning can be triggered by an intended cost reduction combined with market development. If companies (often corporate groups) are active in a more significant number of business areas, the complexity of the planning case increases. This is especially true if the target markets and products have little overlap. The most complex initial situation exists for companies with a range of deeply structured series products (e.g. in the automotive industry) that have to take into account a globally distributed production network with different preliminary or intermediate products in their location planning. Of particular importance here are flows of goods that affect not only the company's internal supply chains but also its relationships with suppliers. Due to the diverse interactions, this type of relocation must consider a constant adjustment of the entire production network from the point of view of total costs [1].

The planning initiative for a location usually derives from the company management and can have various causes [8]. The exact procedure for selecting a location is influenced, on the one hand, by the production strategy and, on the other hand, by the cause and the scope of the planned change [1]. A location can have different location qualities depending on the various products, the desired processes and the production requirements of the companies [4]. In all cases, the location selection takes place under consideration of profitable market, production and sales conditions, and optimal location position and conditions in the global economic area [8]. Different location factors taken together define the attractiveness of a location. There are quantitative and qualitative location factors, which should be assessed or forecasted over at least five years, as companies plan to commit to a location in the long term [1]. Analytical decision models can measure quantitative factors, while qualitative ones are estimated subjectively or heuristically [3]. In location planning, a distinction can be made between qualitative and quantitative methods. Quantitative methods are often optimisation models. In continuous models, an infinite number of locations are analysed concerning an optimal objective function value, while discrete models use a finite number. One of the most studied problems in this framework is the minimisation of transport times or costs. A consideration of qualitative location factors characterises the qualitatively based methods.

The increasing complexity of the economy and an increasing focus on the consideration of qualitative "soft" location factors has led to planning approaches using comprehensive location factor catalogues. Soft factors include regional network relationships, cultural proximity or the level of education at a location [3]. In the process, soft factors are transferred into maturity levels to establish comparability. Location factor catalogues, some very long, often mix location factors on a regional and global level, so a clear distinction is often not recognisable. Moreover, the exact contents of the location factors addressed are not specified [9,5,3]. It is important to note that the more complex planning cases occur particularly in large companies, which usually have their own departments or the necessary financial resources to advise on location planning. Smaller companies, on the other hand, often do not have either of these to a sufficient extent but are also less dependent on a complex network structure in their decision-making.

2.2 Current Approaches in Factory Location Planning Using GIS

Various generic process models describe the tasks of corporate location planning. Most of these models focus on global location decisions for implementing internationalisation strategies [10,3,11]. At the Institute for Production Management, Technology and Machine Tools at the Technical University of Darmstadt, a procedure was developed in cooperation with the management consultancy McKinsey & Company. Decisions have to be made on higher decision levels before a location selection can be made on lower decision levels [4]. Using such an approach, location planning can be divided into three decision-making levels [1]. First, a decision for a country is made at the global level. Then, a region within that country is selected at the regional level, and finally, at the local level, an estate decision is made. Before deciding, the company must clearly define the site requirements, as the requirements and the site conditions determine the site's quality [12].

Following the approach of narrowing down a location decision, SCHUH ET AL. have developed a system that accompanies and improves location planning in four steps through the use of GIS. The first step of the approach is analysing the industry with its dynamics and competition. In the second step, regional and location factors are analysed. The consideration of variables at the different geographical hierarchy levels for the analysis is described as case-specific and dependent on data availability. The third step compares potential locations using an objective value function method. The location factors are to be weighted case-specifically, e.g. by pairwise comparison. In the fourth and final step of the method, a sensitivity analysis should ensure robust decision-making. SCHUH ET AL. describe that the weighting of the evaluation dimensions in the described methodology is the only decision to be made subjectively by the management. All other steps in the site selection process are based on quantitative data [2].

2.3 Challenges

The approach of SCHUH ET AL. offers a good starting point for implementing GIS in factory location planning. The assessment dimensions, according to SCHUH ET AL., provide an appropriate framework [2]. However, for targeted application, expert knowledge is necessary both concerning the use of GIS and especially concerning one's own requirements for site planning. For small and medium-sized enterprises, in particular, the dimensions need to be broken down into case-specific criteria to support companies in the decision-making process. Especially small and medium-sized enterprises often lack the technical competence or financial strength to seek third-party support. Past research projects at the Institute of Production Systems and Logistics have shown that small or relatively young companies, in particular, firstly have difficulties translating their corporate goals into location requirements and, secondly, have no experience in translating location requirements into concrete location factors or even indicators. A methodology is therefore needed that considers a "translation" of the company's current requirement profile, its strategic orientation and, to a certain extent, its environment with few input parameters. To be able to carry out a data-based evaluation, however, it is necessary to convert soft factors into measurable criteria especially. An approach to location planning with the help of GIS should, therefore, also support companies in deriving their individual requirements for a location in order to enable a data-based assessment of location in the first place.

3. GIS in Factory Location Planning

This chapter introduces GIS in Factory Planning from a perspective of system theory, described under information processing. After this theoretical introduction, the premises and data requirements are then explained.

3.1 Information Processing

Looking at an application-oriented GIS method for site planning from the perspective of systems theory, an end user should, if possible, only have to come into contact with the functional concept of the system. Figure 2 shows the three concepts of the system theory.

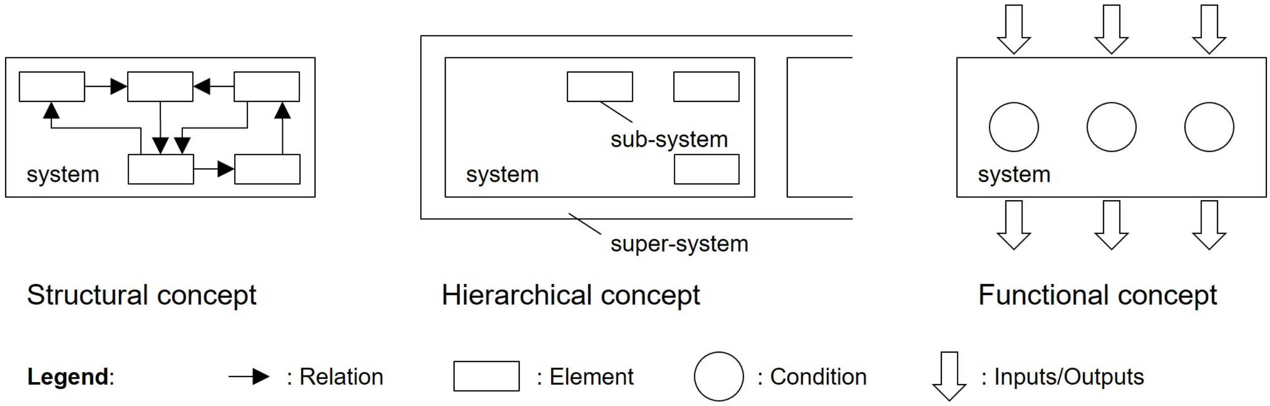

Figure 2: Different concepts of systems theory

According to ROPOHL, a system can be examined from three different perspectives. The functional concept comprises those properties of a system that can be perceived from the outside [13]. The focus of this concept lies on input and output variables (or, in short, inputs and outputs) [14]. Furthermore, states are considered that provide information about the status and situation of the system. This system concept can be explained in the following example. A person without technical expertise expects an output of a technical device (system) when pressing a button (input). The functional concept focuses on the behaviour of the system environment. This concept sets the frame for what the end user should be confronted with if he lacks expert knowledge of the system. The system's interior is not considered in detail [13].

In the structural concept, the system is viewed holistically as a set of elements that are related to each other via relations [13]. A vital point of this approach is not to see a system as the sum of its components but to consider their relationships in equal measure [14]. An element cannot be understood in isolation, but only in the context of the entire system. In addition, the specifics of the elements are taken into account, which determine how well elements can be integrated into a system, determining the 'integral quality' [13].

In the hierarchical concept, the system is divided into smaller systems called subsystems [14]. The totality in the form of the system considered initially is placed into a more comprehensive system which provides a context and constitutes a supersystem. A subsystem provides detailed explanations of the system, while the supersystem shows the meaning of the system [13].

Transferred to an application-oriented methodology for the use of GIS in location planning, this means that a user can generate an output (location recommendations) via the input of clearly defined input parameters (location factors and indicators on the competitive situation and strategic orientation) (functional concept). The locations themselves would be identified based on the different observation levels from global to local (hierarchical concept). A translation of the input factors into a data structure usable by GIS would be generated and analysed by looking at different specifications or levels of maturity (structural concept).

3.2 Premises and data requirements

A manufacturing company's competitiveness and economic success depend significantly on the location decision. Since the location selection is based on the available data when using GIS for location planning, even more attention must be paid to the availability of reliable data when using GIS compared to classic heuristic methods. The information quality of the data used concerning requirements and location profile can thus indirectly influence the success of the company. The quality of data can be ensured by different models, e.g. by considering the 15 dimensions of information quality (IQ) according to WANG ET AL. [15]. These dimensions can help to define requirements for the quality of the data to be used. They are divided into the categories of intrinsic data quality, contextual data quality, representational data quality and accessibility data quality. Some of the dimensions of information quality are interdependent. For example, both the objectivity and credibility (or reputation) of a data set can be violated if it is not fully available. In international location planning, it is crucial to remember that institutions and governments repeatedly withhold or change information [16]. A deeper examination of the data sources is therefore necessary, especially if the user only considers the functional concept of the system.

To make soft location factors measurable, transforming them into data that can be used for GIS is necessary. For this purpose, location factors can be broken down into indicators which, taken together, allow a statement to be made about the characteristics of a location factor, e.g. in the form of a maturity level. To use indicators, a theoretical investigation of the subject area must be carried out, e.g. through literature in the context of the location factors. The interdependencies must then be checked and validated. To be able to guarantee functionality, data sources must be identified, and their contents analysed based on the dimensions of information quality. Data sets that do not meet the 15 IQ criteria are not used for analysis and maturity level determination. In the case of incomplete data sets or a future-oriented assessment of indicators, the approach might be extended by methods such as kriging or the support of artificial intelligence.

The transport infrastructure can be mentioned as an example for translating a location factor into indicators. At the regional level, this factor can be broken down to different modes of transport such as ships, commercial vehicles, aircraft or rail [4]. A consideration of the infrastructure for different means of transport does not appear helpful at the global level. Consequently, the assessment of transport infrastructure should be done on a superordinate level due to the regionally different characteristics. Various indicators can be determined in the evaluation of the transport infrastructure. For example, the "Road Connectivity Index" can describe the road network. This index measures the average speed and straightness of a route, considering the ten or more largest cities, which together contain at least 15% of the country's total population. Greater speed and direct connections between economic centres correspond to a better-developed road network. The existing railway kilometres per 1000 km² can be considered to describe the rail network. A higher value implies a better-developed rail infrastructure. The calculation is made using the existing railway kilometres and the country's total area [17]. Figure 3 shows the visualisation of the road and rail network for India, representing the infrastructure on a course level and information about accidents across the country.

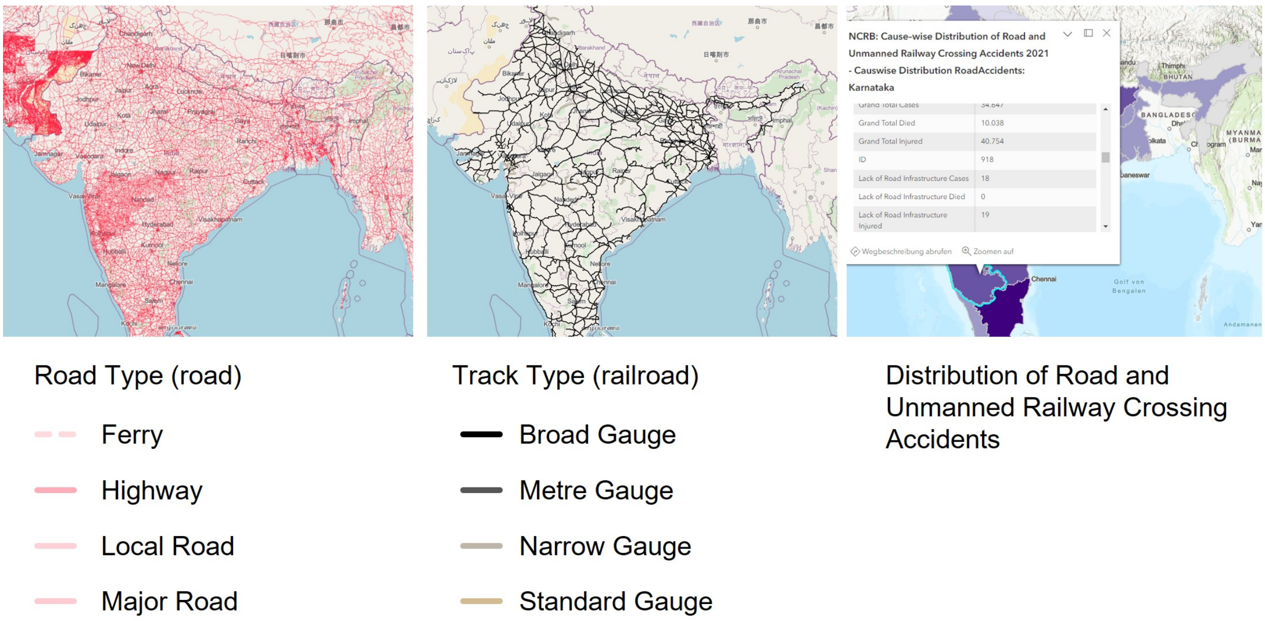

Figure 3: GIS - Visualisation of road and rail network in India

The data about accidents can give a first hint at the reliability of different areas and connecting routes. Countries with sufficient infrastructure in relevant aspects can be further analysed regarding the actual conditions at the regional level. As described above, this analysis should be carried out with only input decisions by the user, making it superfluous for him to understand the hierarchic concept of location planning or the structural concept of influencing indicators on the different levels of observation.

4. Summary and Outlook

This paper showed to what extent GIS can support location planning and why an application-oriented approach is needed, especially for small and medium-sized enterprises. For this purpose, requirements for the structure of such an approach were presented from a system-theoretical point of view, and conditions for transforming input factors into location factors and indicators were discussed. In future studies, it will be necessary to concretise the matters presented and to transfer them into a system for use in an overall design. For the determination of indicators, it can be assumed that there are different demands on the contents of the location factors between the economic sectors. An application-oriented approach to location planning with GIS should therefore enable a sector-specific and company-specific evaluation of the location factors and associated indicators, taking into account appropriate input parameters. These can, in turn, be validated via empirical studies.

References

[1] Wiendahl, H.-P., Reichardt, J., Nyhuis, P., 2014. Handbuch Fabrikplanung: Konzept, Gestaltung und Umsetzung wandlungsfähiger Produktionsstätten, 2., überarb. und erw. Aufl. ed. Carl Hanser Verlag, München Wien, 35469 pp.

[2] Schuh, G., Gützlaff, A., Adlon, T., Schupp, S., Endrikat, M., Schlosser, T.X., 2022. Datenbasierte Standortauswahl. Zeitschrift für wirtschaftlichen Fabrikbetrieb 117 (5), 258–263.

[3] Kinkel, S., 2009. Erfolgsfaktor Standortplanung. Springer Berlin Heidelberg, Berlin, Heidelberg, 437 pp.

[4] Lukas Richter, 2017. Betriebliche Standortplanung auf regionaler Entscheidungsebene. Dissertation, 164 pp.

[5] Hansmann, K.-W., 1994. Industrielles Management, 4., durchges. Aufl. ed. Oldenbourg, München, Wien, 357 pp.

[6] Mevenkamp, N., ´1999. Geographie, Raum und Geographische Informationssysteme: Notwendigkeit und Entwicklung eines verallgemeinerten Algorithmus zur Verschneidung von Flächen. Dissertation, Bremen, 170 pp.

[7] Haghwerdi-Poor, G., 2010. GIS-Konzept und Konturen eines IT-Master-Plans: Planungs- und Systementwicklung für die Informationstechnologie. Vieweg+Teubner, Wiesbaden, 172 pp.

[8] Grundig, C.-G., 2015. Fabrikplanung: Planungssystematik - Methoden - Anwendungen, 5., aktualisierte Aufl. ed. Hanser, München, 377 pp.

[9] Badri, M.A., Davis, D.L., Davis, D., 1995. Decision support models for the location of firms in industrial sites. Int Jrnl of Op & Prod Mnagemnt 15 (1), 50–62.

[10] Emmrich, V., 2002. Globale Produktionsstandortstrategien, in: Krystek, U., Zur, E. (Eds.), Handbuch Internationalisierung. Globalisierung - eine Herausforderung für die Unternehmensführung, Zweite, völlig neu bearbeitete und erweiterte Auflage ed. Springer Berlin Heidelberg, Berlin, Heidelberg, s.l., pp. 331–348.

[11] Perlitz, M., Schrank, R., 2013. Internationales Management, 6. Aufl. = 1. Aufl. bei UTB ed. UTB GmbH; UVK Lucius, Stuttgart, München, 815 pp.

[12] Schoppe, S.G., 1998. Kompendium der Internationalen Betriebswirtschaftslehre, 0004 4., Vollig Uber ed. De Gruyter, s.l., 854 pp.

[13] Ropohl, G., 2009. Allgemeine Technologie : eine Systemtheorie der Technik. KIT Scientific Publishing, s.l., 363 pp.

[14] Claussen, P., 2012. Die Fabrik als soziales System: Wandlungsfähigkeit durch systemische Fabrikplanung und Organisationsentwicklung - ein Beispiel aus der Automobilindustrie. Springer, Wiesbaden, 410 pp.

[15] Wang, R.Y., Strong, D.M., 1996. Beyond Accuracy: What Data Quality Means to Data Consumers. Journal of Management Information Systems 12 (4), 5–33.

[16] Magee, C.S.P., Doces, J.A., 2015. Reconsidering Regime Type and Growth: Lies, Dictatorships, and Statistics. Int Stud Q 59 (2), 223–237.

[17] World Bank, 2020. World Development Indicators: AG.LND.TOTL.K2. https://databank.worldbank.org/source/world-development-indicators. Accessed 13 September 2020.

Biography

Justin Hook (*1994) studied industrial engineering with a focus on production technology at Leibniz University Hannover and the University of Southern Denmark. He has worked as a research associate in factory planning at the Institute of Production Systems and Logistics (IFA) at the Leibniz University Hannover since 2020.

Chris Macdonald (*1995) studies mechanical engineering at Leibniz University Hannover. He has worked as a student assistant at the Institute of Production Systems and Logistics (IFA) at Leibniz University Hannover since 2021.

Prof. Dr.-Ing. habil. Peter Nyhuis (*1957) studied mechanical engineering at Leibniz University Hannover and subsequently worked as a research assistant at IFA. After completing his doctorate in engineering, he received his habilitation before working as a manager in the field of supply chain management in the electronics and mechanical engineering industry. He has been heading the IFA since 2003.

4th Conference on Production Systems and Logistics

Development Of A Digital Planning Tool For Dimensioning And Investment Cost Calculation In An Early Factory Planning Phase

Leonard Rieke[1], Tobias Heinen[2], Cihan Cevirgen[1], Finn Laßmann[1], Peter Nyhuis[1]
[1]*Institute of Production Systems and Logistics / Leibniz University Hannover*
[2]*Grean GmbH, Hannover*

Abstract

As an interdisciplinary task, factory planning represents a key factor for logistics, supply chain and ultimately, the economic success of companies in the manufacturing sector. In factory planning projects, the focus is on the early planning phase, where costs and the associated misinvestments can still be significantly influenced. The challenge lies in the early valid dimensioning of the planned factory despite fuzzy data to provide decision-making support regarding the investment costs. In this context, this article presents the development of a digital service and planning tool based on a scientific procedure model. For this purpose, the research needs are first derived, reference is made to a scientific procedure model and the requirements analysis for the tool is presented. The tool developed on this basis aims to dimension and economically assess planned factories at an early planning stage. In this way, decision-makers in companies will be provided with data-based results to make future-oriented decisions between different project scenarios.

Keywords

Digital planning tool; factory planning; dimensioning; investment cost calculation; feasibility study; early planning phase; uncertainty

1. Introduction and need for research

In the course of increasing customer requirements and the rising number of product variants, the need for planning production systems is constantly growing. Factory planning as a critical factor for the economic success of companies is thus becoming an interdisciplinary and permanent task [1]. The planning object can range from the re-planning of individual operating resources to entirely new plants. The effects of the planning decisions have a significant impact on the future cost structure and, thus, on the economic efficiency of the production systems [2,3]. To systematise the various planning activities and make the complexity of the planning process manageable, multiple approaches have been summarised in VDI Guideline 5200 [4]. The basic understanding of the classic factory planning process provides for sequential planning phases that lead successively from "rough to fine" to a detailed result. The approach of synergetic factory planning significantly contributed to the VDI 5200 procedure, which is widely recognised in practice. Synergetic factory planning combines production planning with a focus on the design of technological and logistical processes from a process perspective and object planning with a focus on interior and exterior design from a spatial perspective [3].

Overall, factory planning projects, especially new and expansion planning, represent a significant challenge due to the long life cycle and high investments [2,5]. Statistical evaluations show that cost targets of factory planning projects are missed in more than 70% of cases [6]. In particular, the early planning phase plays an important role in this context. In the early stage of factory planning projects, on the one hand, the project´s

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scope and, thus also, the associated costs are determined [2,5]. On the other hand, the early planning phase is fraught with uncertainty, and reliable information and data are often not yet available [7]. Figure 1 underlines this conflict. Although it is difficult to estimate costs in the early planning phase due to the lack of information, it is essential to avoid misinvestments. Only in this early planning phase can costs be influenced with sufficient flexibility. Often a project cannot even be started without a budget estimate. Conversely, costs cannot be estimated if the project has not yet started. For this complex problem, a solution needs to be found.

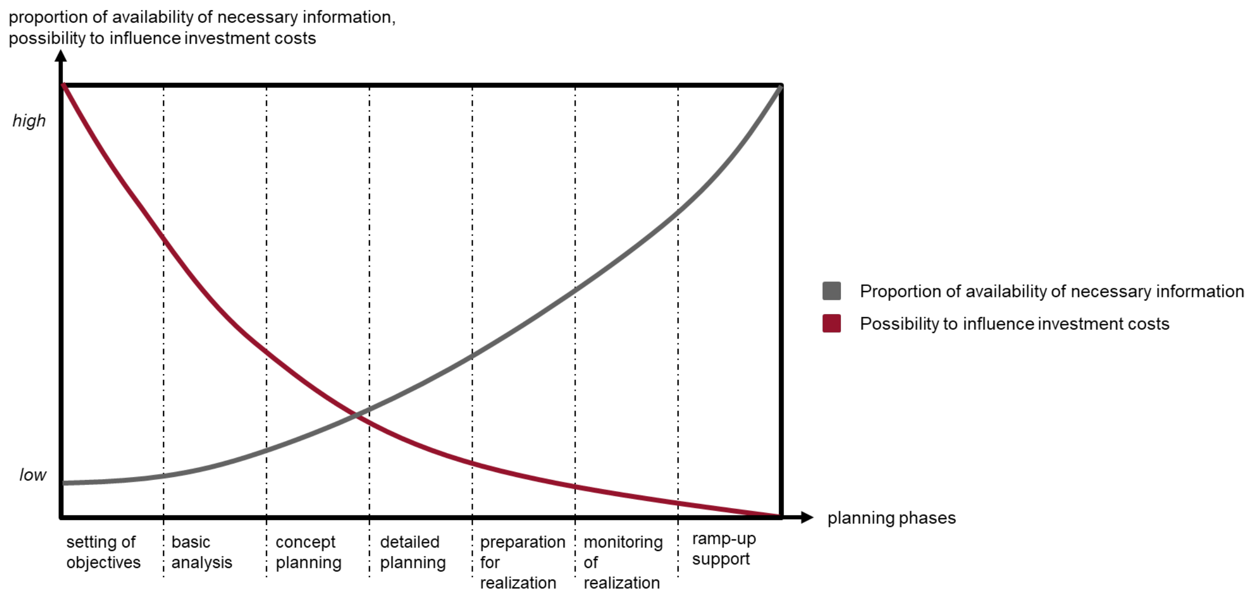

Figure 1: Cost incurrence vs cost influence - own figure based on CHOU and ZEHBOLD [8,9]

Previous work [10–12] has shown that for example feasibility studies in an early planning phase and digital planning tools for dimensioning and investment cost calculation can help address this problem. Furthermore, as previous literature research has shown, some approaches already exist in this area. Still, they do not sufficiently represent the early phase, uncertainties and the calculation of dimensioning variables (personnel, operating resources and area) for estimating investment costs [12]. Therefore, this paper presents a digital planning tool that can serve as decision support for the investment cost estimation of planned factories in an early planning stage.

2. Procedure model

In previous work, a model has already been developed that outlines the scientific and practical procedure for estimating costs in an early planning phase before detailed planning starts (see Figure 2). For this purpose, planning information and planning tasks are first derived in a three-stage model. This is done in the course of a module model, which defines input and output parameters in individual planning modules. In the second step, calculation options are derived for the three main dimensioning variables: operating resources, personnel and area. Since sufficient information is not always available in the early planning phase, relevant surcharge, cost and uncertainty factors are identified in the third step. The procedure should consider both the process perspective from production planning and the spatial perspective from architectural planning and thus underline the importance of synergetic factory planning [12].

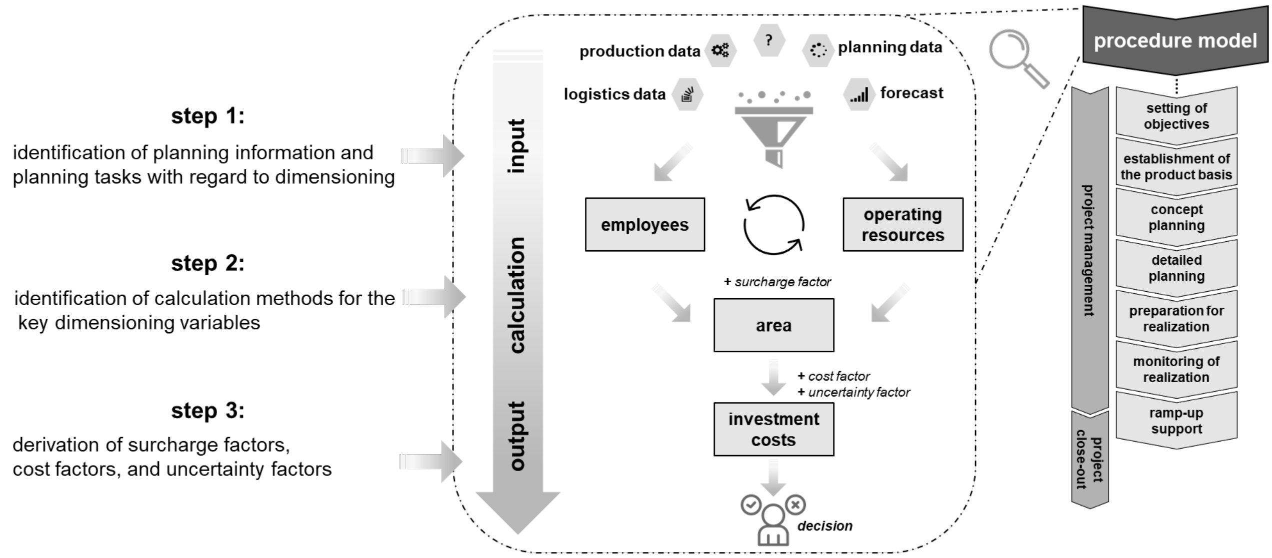

Figure 2: Procedure Model [12]

This procedure model creates the structural framework for standardised dimensioning of the factory to be planned with a small amount of information in an early planning phase and to be able to make monetary estimates on this basis. In order to develop a digital planning tool based on this procedure model various framework requirements were identified. These include the analysis of the early phase of factory planning, the consideration of uncertainties, the calculation of dimensioning variables and the derivation of the final investment costs [12].

3. Requirement analysis for digital planning tool

Digital planning tools in the context of the digital factory can achieve significant quantifiable advantages in planning factories. The main effects are the avoidance of planning errors, the reduction of planning time and the increase in planning quality [13,14]. Building Information Modeling (BIM for short) has also established itself as a cooperative approach to digital building modelling in the interdisciplinary planning environment, especially in the construction sector [15], but also successively in factory planning [16,17]. A few approaches and software solutions for building planning already exist [18,19] but are lacking in considering the process perspective. Final decisions in the context of dimensioning and calculation must still often be estimated by expert opinions [20]. However, this project aims to enable a software-supported decision-making basis for project managers with minimal effort. The overall requirements are, therefore, already derived from the project objective:

1. **Functionality:** The digital planning tool should be able to estimate investment costs despite uncertain data in the early phase.
2. **Usability:** Users should be able to use the tool with as little prior knowledge as possible.
3. **General applicability:** The tool should be applicable across all sectors without significant limitations.

To practically detail these overall requirements, a requirements analysis of the digital planning tool was first carried out according to a standardised procedure [21] to ensure that the system fulfils the intended functionality (see Figure 3). Inadequate requirements significantly influence software development and cannot be compensated for in later planning phases [22]. In general, a distinction is made between two types of requirements, functional and non-functional. Functional requirements define the functions, data and behaviour of the system [21], whereas non-functional requirements refer to the quality requirements such as reliability or availability of the system [23].

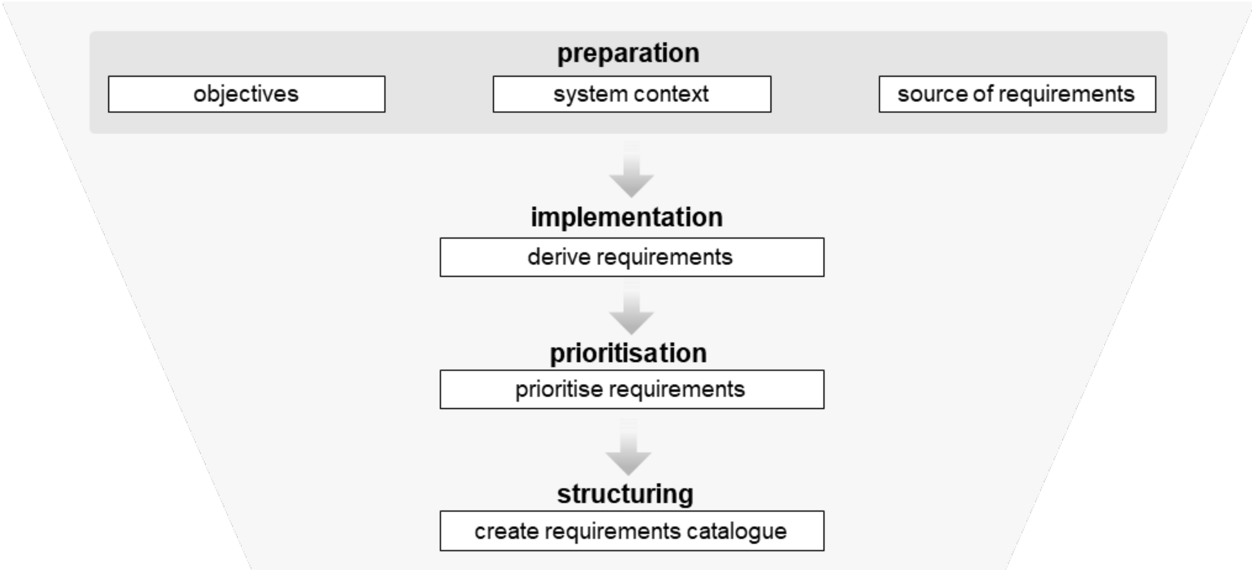

Figure 3: Requirements analysis according to RUPP [21]

By the procedure of a requirements analysis [21], the system context was first defined, the central goals identified, and sources of requirements determined. With this procedure, requirements could be derived and prioritised. Figure 4 shows an exemplary excerpt from the final requirements catalogue with clustered and prioritised requirements in personnel, organisation and operating resources.

requirement type	prioritisation	field	requirements
functional	significant	employees	A.1.8: number of employees A.1.9: working time A.1.10: working days, holidays
		organisation	A.1.12: order strategy A.1.13: manufacturing principles A.1.14: organizational forms of assemblies
		operating resources	A.1.15: machine variants A.1.16: machine area A.1.17: number of machines A.1.18: number of warehouse resources A.1.19: warehouse area A.1.20: warehouse levels

Figure 4: Excerpt from requirements catalogue

A simple data import, a fast calculation and an intuitive user interface were derived as central non-functional requirements. Furthermore, low-effort maintainability and optimisation should be ensured.

4. Development and use of the digital planning tool

The derived requirements (see chapter 3) now provide the basis for the software development and thus the selection of the development framework. The detailed procedure for developing the planning tool has been presented in previous work [10] and is not further discussed in this paper.

The programming language VBA (Visual Basic for Applications) was used for development. A key advantage of this programming language is its widespread use, which facilitates the further advancement and maintenance of the software. With the Windows Presentation Foundation (WPF), a user interface framework and part of the .Net platform from Microsoft was used. WPF uses the XAML markup, which defines application windows displayed to the user across the screen. The main advantage of an easy-to-use desktop application is the local execution of the programme, which is not dependent on web access. The speed of requests and calculation operations is also not limited by the internet connection. Data is stored and processed locally, so there are usually no additional requirements for data encryption [24]. The relational database system SQLite is used as the database, which was specially designed for use in embedded systems and fulfilled the software requirements [25]. The database can be stored as a local file and thus easily backed up or shared [26]. A standardised template in Excel format was developed to import ERP data (Enterprise Resource Planning data) into the database and application. For this purpose, the user has to provide and import the data in a predefined order. For the entire development, the integrated development environment Visual Studio was used, in which coding, debugging, compiling and the final deployment of the application is fully integrated.

In the following, the iteratively developed planning tool is presented, and its functionality is explained. The tool is used in seven simplified steps, as shown in Figure 5. As a **first step**, the data has to be imported. Templates are available to facilitate and standardise data import into the tool. The user downloads these and fills them with his machine data, bill of material, feedback data, etc. The data is then imported into the tool. After checking the correct entry of the data, the filled template can be imported and overwrites the previous data.

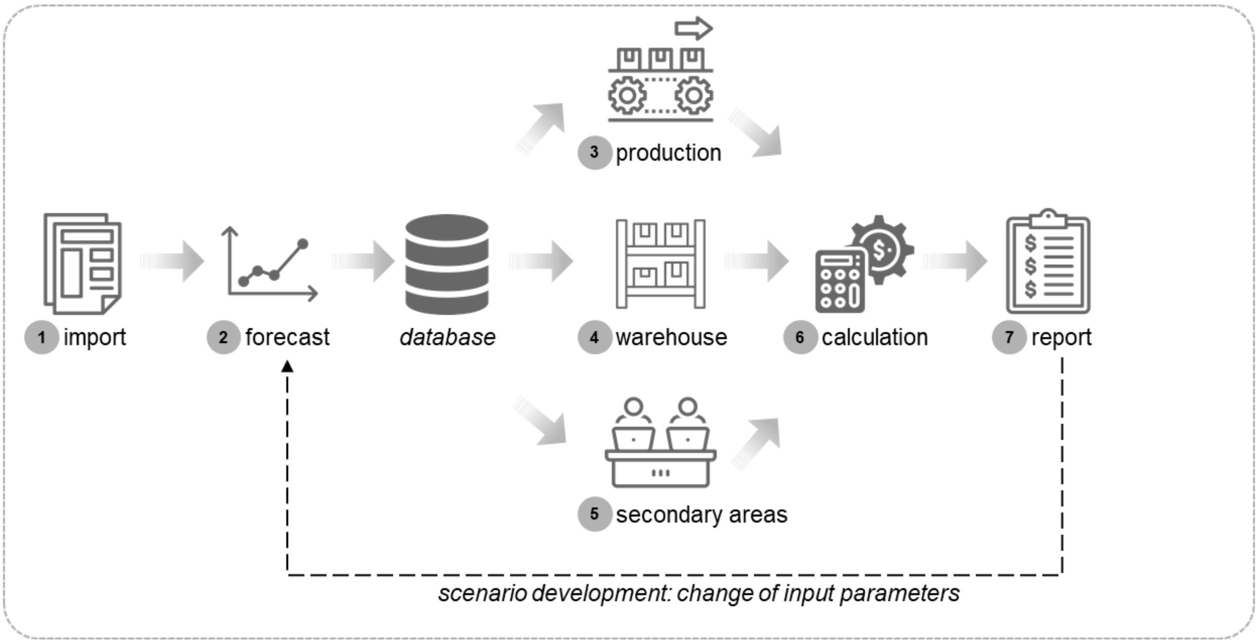

Figure 5: Tool use in seven steps

In a **second step**, forecasts of unit and production growth can be made. The user can decide which year is to be used as the basis for the calculation and define the start and end dates of the forecast period. Furthermore, an indication of the expected growth rates is necessary. In the **third step**, the production areas are dimensioned. In addition to the machine data already available, the user enters working time data. By comparing the capacity provided by the machines with the capacity demanded by the working hours, the software tool can derive the demand for machines and personnel and calculate the corresponding areas. The user can decide whether the substitute area method or the functional area calculation [2] should be used. The individual surcharge factors, e.g. maintenance and operation, are automatically added to the basic machine areas of the workplace directive [27]. Path areas are also considered with the help of a surcharge factor, which was determined as a practical value from numerous past projects. Depending on the favoured means of transportation, 25-30% is added to the production area [3]. At any time, the user has the option to overwrite calculated values with their empirical values and safety margins. In the **fourth step**, the required warehouse areas are dimensioned. The starting point for this is, among other things, the storage carriers, their dimensions and their number. Furthermore, an indication of the temporal range of the warehouse stocks is necessary. The user can make entries in the form of operating hours and days or as a proportion of the annual production. The digital planning tool calculates a warehouse area requirement based on a 6m x 6m warehouse module, to which additional area and safety factors can be applied. In the **fifth step**, the so-called secondary areas are dimensioned. It must be considered that in addition to production and warehouse, areas must also be provided for indirect functions. These are subdivided into the categories of functional areas (e.g. quality assurance, laboratories or shop floor management areas), social and office areas (e.g. break rooms, canteens or customer centres), and sanitary areas (e.g. changing and sanitary rooms or first aid).The main scaling parameter for this is the number of employees per shift. For standard values defined in the workplace guideline, the secondary area is calculated automatically using the determined number of employees ([28]), which can, however, be overwritten by the user with own specifications. In all three categories, additional project-specific areas can also be added. In the **sixth step**, the space requirements for production, warehousing and secondary areas determined in the previous steps are summarised and monetarily assessed. This assessment can be made either based on the areas (€/m²) or the room volumes (€/m³), for which additional height information must be provided. The cost factors that lead from the dimensioned area to the costs are based on comparative projects in the construction fee schedule [29], but the user can also adjust. The possibility of adjustment has proven useful insofar as, depending on the process area (production, warehouse, etc.), different requirements are demanded by the area or space (load-bearing capacity, clean room, etc.). A two-storied hall, for example, also requires higher cost factors per m² due to the necessary massive supporting structure. By adding up the individual items, the costs of the entire planned factory can thus be determined. At this point, safety factors and surcharges for the technical building equipment and construction areas can again be included. In the **seventh step**, the results are summarised and available for download in an Excel report. In this way, all entered parameters and results are documented. This also enables the area and costs of different scenarios to be compared based on other input parameters, such as forecast change.

Figure 6 shows an exemplary section of the tool from the sixth step, in which the individual area requirements are summarised and monetarily evaluated according to different requirements in their functions. According to step 7, a report can be generated now that presents the total area and costs.

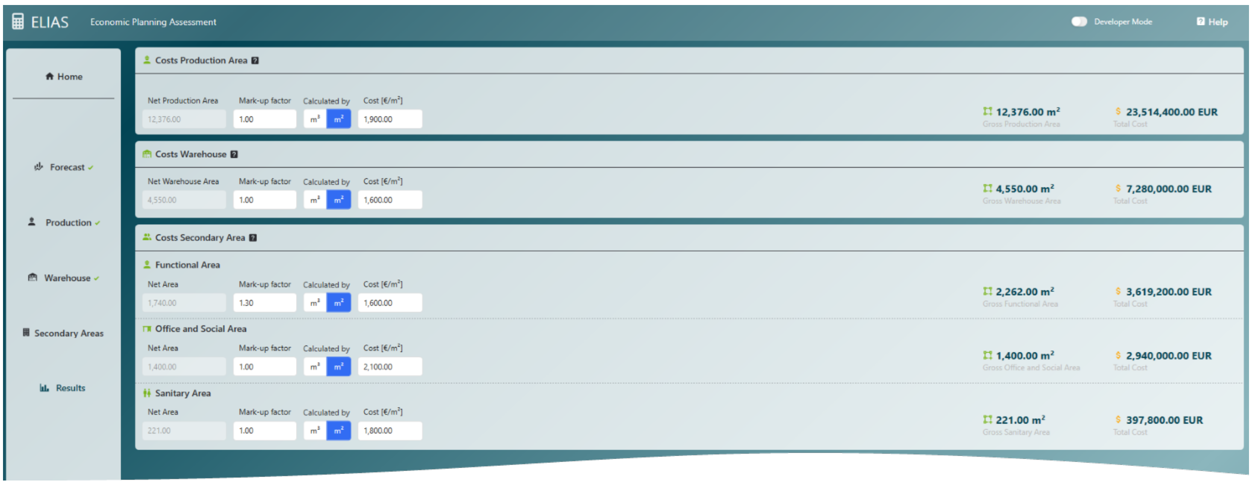

Figure 6: Excerpt from planning tool in step 6

5. Limitations and need for further development

With the result of the planning tool, the user is provided with the investment costs of the planned factory construction based on the process-side input factors with comparatively little effort. In addition to the numerous advantages of the planning tool for decision support in the early planning phase, some limitations must be addressed. Despite the software support, early cost estimation can still be time-consuming in some cases. Data and information must be collected and prepared before they can be processed as templates in the software tool. This data collection effort can be even greater, especially in new planning projects, when specific information and processes are not yet known. In this case, reference processes must be developed first, which can be fraught with uncertainty. The static template affects the flexibility of the implementation. To adapt the template, it is first necessary to analyse different data sets and validate and adjust the tool accordingly. Furthermore, the complex warehouse calculation needs to be revised, and different warehouse types must be integrated as a selection option. In addition, there is a need for further development in the integration of various target fields of factory planning (changeability, sustainability, etc.). The prioritisation of specific target fields could also have area-related or economic effects. For example, growth areas would directly impact area and area-related costs. A process-related enlargement of the column grid would have cost-related influences in the form of a more massive supporting structure. Another general limitation of the tool is the one-sided consideration of investment costs. Particularly with regard to energy consumption and costs, a parallel scenario-based assessment of the associated operating costs can be identified as a central need for further development. Integrating the operating costs could enable holistic decision support in the context of a total cost of ownership assessment. A system administration concept was developed to ensure the tool's ongoing usability regarding technology and content and to identify the need for further development.

6. Conclusion and outlook

New planning and expansion planning, in particular, represent capital-intensive factory planning cases and thus significantly influence companies' profitability. In a turbulent market environment, there is a lack of suitable approaches that can reliably estimate planned projects in monetary terms despite high uncertainty. Costs can only be influenced sufficiently in the early planning phase. The planning tool developed in a cooperative approach between science and industry and presented in this paper is intended to provide a solution to this problem. The tool enables the user to estimate investment costs for planned factories based on process-side input factors with comparatively little effort and thus provides a decision-making aid for project planning. The prototype developed meets the requirements derived, but still needs further development that has identified. In addition to the general validation of the tool, the focus is on the integration of operating costs. The operating costs, along with the investment costs over the entire life cycle, determine the economic efficiency of a factory, particularly from a sustainability perspective. Only a combined consideration of investment and operating costs in the context of a total cost of ownership analysis can also provide holistic decision support. Investments and operating costs have to be considered from both a space and a process perspective. This identified need for research should be addressed in future research projects.

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References

[1] Pawellek, G., 2014. Ganzheitliche Fabrikplanung: Grundlagen, Vorgehensweise, EDV-Unterstützung, 2nd ed. Springer Vieweg, Berlin, Heidelberg.

[2] Grundig, C.-G., 2018. Fabrikplanung: Planungssystematik - Methoden - Anwendungen, 6th ed. Hanser, München.

[3] Wiendahl, H.-P., Reichardt, J., Nyhuis, P., 2014. Handbuch Fabrikplanung: Konzept, Gestaltung und Umsetzung wandlungsfähiger Produktionsstätten, 2., überarb. und erw. Aufl. ed. Hanser, München, Wien.

[4] VDI - Verein Deutscher Ingenieure, 2011. VDI-Richtlinie 5200: Fabrikplanung- Planungsvorgehen / VDI-Guideline 5200: Factory planning - Planning procedures.

[5] Kettner, H., Schmidt, J., Greim, H.-R., 2010. Leitfaden der systematischen Fabrikplanung: Mit zahlreichen Checklisten. Hanser, München.

[6] Reinema, C., Pompe, A., Nyhuis, P., 2013. Agiles Projektmanagement. Zeitschrift für wirtschaftlichen Fabrikbetrieb 108 (3), 113–117.

[7] Unzeitig, W., 2014. Methodik zur frühen Fabrikplanung bei Unsicherheiten. Dissertation, Graz.

[8] Chou, J.-S., 2009. Web-based CBR system applied to early cost budgeting for pavement maintenance project. Expert Systems with Applications 36 (2), 2947–2960.

[9] Zehbold, C., 1996. Lebenszykluskostenrechnung. Gabler, Wiesbaden.

[10] Rieke, L., Cevirgen, C., Nyhuis, P., 2021. Introduction of an Economic Assessment Approach for Factory Planning. In: Journal of Production Systems and Logistics 1 (2021), 9.

[11] Cevirgen, C., Rieke, L., Bischoff, L.-M., Nyhuis, P., 2021. Investment Feasibility Study for Factory Planning Projects. In: Journal of Production Systems and Logistics 1 (2021), 8.

[12] Rieke, L., Cevirgen, C., Gloy, A., Nyhuis, P., 2022. Procedure Model for Dimensioning and Investment Cost Calculation in an Early Factory Planning Phase. In: Herberger, D.; Hübner, M. (Eds.): Proceedings of the Conference on Production Systems and Logistics: CPSL 2022. Hannover : publish-Ing., 2022, S. 308-318.

[13] Bracht, U., Geckler, D., Wenzel, S., 2018. Digitale Fabrik: Methoden und Praxisbeispiele, 2nd ed. Springer Vieweg, Berlin.

[14] Westkämper, E., Spath, D., Constantinescu, C., Lentes, J., 2013. Digitale Produktion. Springer Vieweg, Berlin.

[15] Borrmann, A., König, M., Koch, C., Beetz, J., 2018. Building information modeling: Technology foundations and industry practice. Springer, Cham.

[16] Rieke, L., Schäfer, S.F., Hingst, L., Hook, J., Peter, N., 2021. Einsatz von BIM in der Fabrikplanung/Use of BIM in factory planning. wt Werkstattstechnik online 111 (11-12), 881–886.

[17] Schäfer, S.F., Hingst, L., Hook, J., Rieke, L., Nyhuis, P., 2022. Improving The Planning Quality Through Model-Based Factory Planning In BIM.

[18] Deutsches Institut für Normung e.V., 2018. DIN 276 - Kosten im Bauwesen. Beuth-Verlag, Berlin.

[19] Baukosteninformationszentrum Deutscher Architektenkammern, 2020. BKI-Baukosten 2020 Neubau: Statistische Kostenkennwerte. BKI, Stuttgart.

[20] Weig, S., 2008. Konzept eines integrierten Risikomanagements für die Ablauf- und Strukturgestaltung in Fabrikplanungsprojekten. H. Utz, München.

[21] Rupp, C., 2021. Requirements-Engineering und -Management: Das Handbuch für Anforderungen in jeder Situation, 7., aktualisierte und erweiterte Auflage ed. Hanser; Carl Hanser Verlag GmbH & Co. KG, München.

[22] Kleuker, S., 2018. Grundkurs Software-Engineering mit UML, 4th ed. Springer Fachmedien Wiesbaden, Wiesbaden.

[23] Pohl, K., Rupp, C., 2015. Basiswissen Requirements Engineering: Aus- und Weiterbildung zum "Certified Professional for Requirements Engineering" ; Foundation Level nach IREB-Standard/ Klaus Pohl ; Chris Rupp, 4., überarb. Aufl. ed. dpunkt-Verl., Heidelberg.

[24] Paul Pop, 2002. Comparing Web Applications with Desktop Applications: An Empirical Study. Dept. of Computer and Information Science, Linköping University, Sweden.

[25] Feiler, J., 2015. Introducing SQLite for Mobile Developers. Apress, Berkeley, CA.

[26] Allen, G., Owens, M., 2010. The Definitive Guide to SQLite, 2nd ed. 2010 ed. Apress, Berkeley, CA.

[27] Bundesanstalt für Arbeitsschutz und Arbeitsmedizin - Ausschuss für Arbeitsstätten. ASR A1.2 Raumabmessungen und Bewegungsflächen.

[28] Bundesanstalt für Arbeitsschutz und Arbeitsmedizin - Ausschuss für Arbeitsstätten. Technische Regeln für Arbeitsstätten (ASR): A4.1 Sanitärräume.

[29] BauGo, 2021. Baugebührenordnung; Preisindexzahl (Anlage 2 zur Baugebührenordnung) - Niedersachsen. Accessed 31.01.23.

Biography

Leonard Rieke (*1995) has been a research associate in the specialist factory planning group at the Institute of Production Systems and Logistics (IFA) at Leibniz University Hannover since 2021. He previously studied industrial engineering (B.Sc., M.Sc.) at the Leibniz University Hannover (LUH).

Dr.-Ing. Tobias Heinen (*1981) has been the managing partner of GREAN GmbH, a production consultancy based in Hanover, since 2011. He was previously a research associate in the factory planning group at the Institute of Production Systems and Logistics (IFA) at Leibniz University Hannover between 2006 and 2011. He has a lectureship in "Sustainability in Production" at Leibniz University Hannover.

Cihan Cevirgen (*1990) has been a research associate in the specialist factory planning group at the Institute of Production Systems and Logistics (IFA) at Leibniz University Hannover since 2018. He previously studied industrial engineering (B.Sc., M.Sc.) at the Leibniz University Hannover (LUH).

Finn Laßmann (*1997) studied mechatronics engineering (B.Sc., M.Sc.) at Leibniz University Hannover (LUH) from 2017 to 2022. He has been working in the software development industry since 2020 and contributed his knowledge to the Institute of Production Systems and Logistics (IFA) at Leibniz University Hannover during the work on his thesis.

Prof. Dr.-Ing. habil. Peter Nyhuis (*1957) has been head of the Institute of Production Systems and Logistics (IFA) at Leibniz University Hannover since 2003. Prof. Dr.-Ing. habil. Peter Nyhuis was a member of the German Science Council (2014-2018) and has been Chairman of the Science Council of the AiF (GAG 3) since 2015. He is also a member of the German Academy of Technical Sciences acatech and the Scientific Society for Production Technology (WGP).

4th Conference on Production Systems and Logistics

Training Of PDCA Cycle Using A Catapult In A Virtual Learning Environment

Amelie Karcher[1], Timo Köring[2], Detlef Gerhard[2], Bernd Kuhlenkötter[1]

[1]*Chair of Production Systems, Ruhr-University Bochum, Industriestraße 38C, 44894 Bochum, Germany*

[2]*Digital Engineering Chair, Ruhr-University Bochum, Universitätsstraße 150, 44801 Bochum,, Germany*

Abstract

The sustainable teaching of quality methods in the sense of Lean Management and Six Sigma through assistance systems, such as Virtual Reality (VR) glasses, represents a new and growing aspect of continuing education programs. The development and usage of virtual learning environments offers the chance to deepen the theoretical prior knowledge through interactive learning possibilities. In this way, existing learning concepts are supplemented with virtual teaching content. Complex or difficult to present learning settings can be mapped virtually without high material consumption or costs. This paper presents the state of the art with respect to teaching quality methods with VR. An integration in the Assisted Reality Implementation Model is made. Subsequently, the requirements for a virtual learning environment based on a real business game are determined. The approach and implementation are explained using the example of the PDCA quality method. PDCA is an iterative design and management method used in business for the control and continual improvement of processes and products. First results of the exploration tests from the questionnaires are presented. Based on this, improvements are derived, and next steps are defined.

Keywords

Lean Management; Virtual Reality; Knowledge enhancement; PDCA method; Six Sigma

1. Introduction

Due to the Corona pandemic, face-to-face teaching had to be converted to various online formats in a short period of time. This not only had an impact on (higher) education, but workshops or training offers in learning and research factories also had to find new learning formats [1]. While the impact for theoretical knowledge transfer through video formats has been minor, the impact for practical exercises has been more severe. For the implementation of these practical exercises, different approaches are available as so-called digital laboratories, e. g. remote, digital live or full virtual laboratories [2]. In this context, Virtual Reality (VR) glasses and their versatile applications can provide great advantages for the fully virtual laboratories. Despite a high interest in this technology, also in the engineering field, the implementations in teaching are still under development [3]. At the same time, this technology is suitable for knowledge transfer [4] due to its multiple applications in diverse industries and value streams simultaneously [5, 6], location-independent experiences can be gained in different levels and user-specific difficulty levels. In addition, VR technology, through hands-on applications, supports knowledge transfer supported by the memory of "learning-by-doing" [7]. In general, positive effects can be observed from game-based teaching [8], which also can be used for the realization of the virtual learning environment (VLE) or represent a sub-goal.

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Quality methods are important basic elements in industry and science to achieve progress. The teaching of these methods is based on traditional teaching formats, such as lectures and talks. In addition, practical business games are used to illustrate the relationship between theory and practice. These business games take place in presence, hybrid or digital, rarely in the purely virtual world. For the location-independent training of these methods in interactive, virtual worlds, only a few practical applications, especially with VR glasses, are currently available [9].

2. State of the art of teaching quality methods with VR

Quality methods such as those taught in the fields of Lean Management and Six Sigma represent opportunities for e. g. process optimization. In practice, these methods have been successfully applied for decades and make an enormous contribution to increasing corporate efficiency and effectiveness. To apply such practice-oriented methods requires practice, for which VR applications can provide assistance [10]. The learner within VR can not only practice and try out what he/she has learned, but can also make mistakes that may lead to high costs or additional effort in problem solving in reality [2]. Despite several ongoing and already completed research projects, extensive VR applications for training purposes of quality methods have marginally found their way into practise [9]. Further research has revealed that exemplary applications exist in training first responder unit leaders (fire department), where the application of the PDCA (Plan, Do, Check, Act) method is intended to assist in decision making in complex response scenarios. However, so far only the realization of the Plan and Do phases has been reported [11]. Thus, the application potentials of the technology have not yet been exhausted. For this reason, the possibilities of conceptual application of VR in the context of Lean Management and Six Sigma will be considered in more detail.

Likewise, no standardized approach to the creation of virtual learning environments has been discernible during the extensive research work. This lack of a standardized framework for implementation leads to the fact that current VR learning environments are found in a confusing variety of isolated applications and different implementation premises, such as visual design or even teaching methodology. Systematic concepts for the integration into existing educational processes, system architectures and media concepts are missing here. Furthermore, there are no requirements for the design of VR learning environments and studies to assess its learning effects. Likewise, the organization of these teaching methods into institutional learning concepts is undeveloped [12]. For this reason, the possibilities of conceptual application of VR in the context of Lean Management and Six Sigma are considered in more detail. The development of a holistic approach to the creation and validation of VR learning environments for quality methods is necessary and considered useful. This should provide orientation for the creation of teaching units with virtual learning environments and show answers and possibilities whether and which quality methods from the field of Lean Management and Six Sigma can be implemented in VR in a meaningful way. Out of this necessity, the model of implementation for reality-based assistance systems (=Assisted Reality Implementation Model - ARIM) for the selection of Lean Management and Six Sigma quality methods was developed [9]. This represents a unified approach to create virtual learning environments as standardized and efficient as possible. ARIM is suitable for teaching quality methods interactively using augmented and virtual reality learning environments. Furthermore, ARIM enables meaningful guidance for the implementation of virtual learning environments, as well as subsequent validation. ARIM can be divided into 3 main phases, specifically 1 Potential Analysis, 2 Design and 3 Validation with respective sub-steps. Further information can be found in Figure 1.

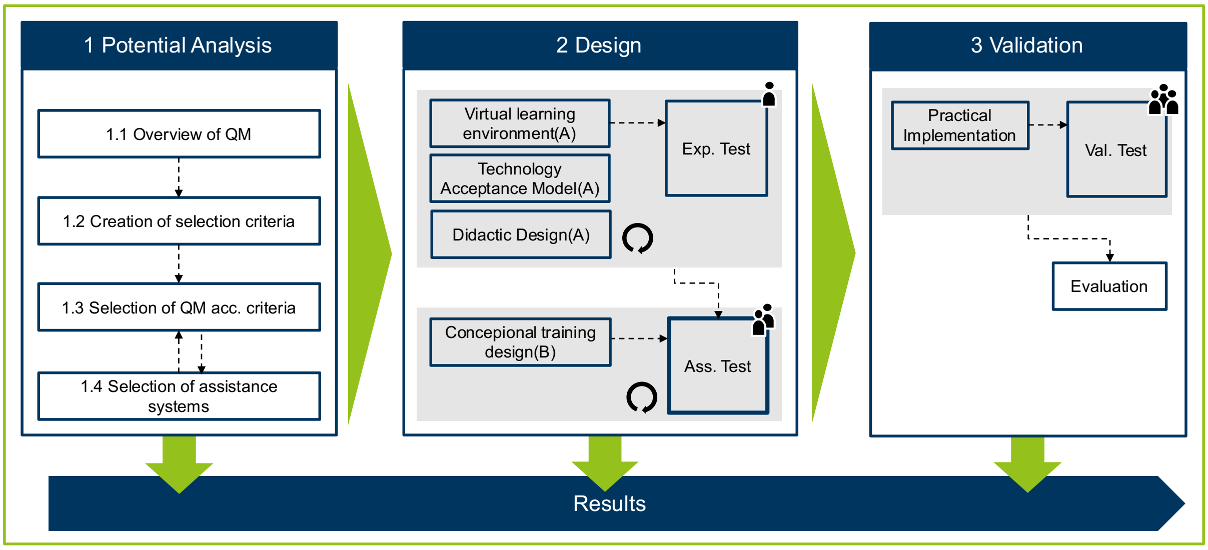

Figure 1: ARIM- Assisted Reality Implementation Model

This paper focuses on phase 2, the ARIM Design phase and the practical realization of the PDCA method. Section (A in 2 Design) includes the aspect of the VLE. For this, it deals with the instructional principles as well as the requirements for hardware, software, context of use, degree of realism, and interaction and navigation modes [13,14]. Another specific feature in content creation is the application of the evolutionary prototyping process [15], which will be validated by the exploration test.

Through these special interaction possibilities, the goal is to create a high recall value, concomitantly to increase the knowledge transfer and to stimulate the knowledge deepening. For this purpose, the development of a holistic VLE for the deepening of knowledge of the PDCA method is considered useful. Thus, this learning environment can be used in the field of further education to train employees of a production company and to provide appropriate qualification measures regarding process improvements.

3. From the real to the virtual PDCA – Catapult

One opportunity for teaching statistical methods but also for training the PDCA method in presence is a wooden catapult simulation [16]. This is also the case in the research project WILLEN (see Acknowledgements), which is the starting point for the virtual realization. The effort to realize a virtual PDCA catapult creates the possibility to offer a flexible use of VLE, so that online and face-to-face teaching can be intelligently combined in the training program. This will be tested in the research project WILLEN for its applicability, completeness, and acceptance. The background to the creation of VR and AR training units is to combine, as far as possible, compressed face-to-face phases in a further education institute with teaching units that can be attended flexibly online from home. This should make it easier to reconcile further training, and thus also the qualification of individuals, with company and, for example, family circumstances. In concrete terms, the first two ARIM Analysis and Design phases are currently being applied. The goal is to test individual methods that support action-oriented learning and, if successful, to embed them in a holistic training program. For a first learning application with VR assistance systems, the research project will implement the PDCA method in conjunction with a virtual catapult, since this method shows an overlap between the areas of Six Sigma and Lean Management [9]. The implementation is aimed with the help of standalone VR glasses, so that a self-sufficient use is guaranteed, which is also a result from phase 1 of the ARIM. This primarily realizes learning at one's own pace as well as learning by doing.

For the concrete realization of the virtual catapult further assumptions were made: For the implementation of the prototype, the necessary theoretical input for the VLE is assumed. This prior theoretical knowledge is made available to the participants through the platform moodle. Moodle is a learning management system that supports both blended learning and 100% online courses [17]. Due to the already existing theoretical input, an intensified examination of the VR technology is possible in the actual application. During the implementation of a virtual learning application, the aim is to design an intuitive interaction, so that it can be used by participants in everyday life without much additional effort. Questionnaires and interviews will then be used to determine whether this aspect is also perceived accordingly by the participants. This type of implementation is referred to as exploration testing. Due to the deliberate lack of theoretical input within the VLE, the element of an initial learning check is integrated, as the scenario cannot be solved without this prior knowledge.

3.1 Virtual PDCA application in design

For the intended implementation of the virtual PDCA method in the use of further education, the analogous business game is analysed in reality, i. e. here a deepening of the ARIM Design phase took place. To this end, the context of use is first understood and defined to determine the usage requirements for the PDCA method in the context of the catapult game. In the subsequent step, the requirements are determined taking into account the context of use. This is done with the help of the classical approach of the product development process [18]. The requirements are numbered with item number (Pos.) and are distinguished between demands (D), which are mandatory criteria, and wishes (W), which are optional criteria. With wishes, the effort to benefit must always be evaluated. As a result, a catalogue of requirements has been created, subdivided according to various aspects. A detailed explanation of the individual criteria is not provided here. An excerpt of the requirements for the implementation of the intended virtual PDCA method can be found in Table 1.

Table 1: Requirement List

Requirement List		
Pos.	**D/W**	**Requirement - Name**
1		**Catapult**
1.1	D	At least: four deflection positions two fixing points two ball cup positions six stop points one rubber band one ball
1.2	D	Clamping angle information
1.3	W	Dismantlability of the catapult
1.4	W	Aging of the rubber belt
1.5	W	Influence of the rubber band tensioning time
1.6	W	Bouncing of the catapult after firing
2		**Lean Management, Six Sigma**
2.1	D	Teaching of the PDCA cycle
2.2	D	Application of the PDCA cycle
3		**Virtual Reality / Programming**
3.1	D	Implementation of the programming
3.2	D	Selection/use of hardware
3.3	D	Analyze and define advantages of VR
3.4	W	Investigate involvement of multiple people
3.5	D	Interactive design
3.6	D	Time limited to 20-25 minutes
Legend: Pos. = Position, D = Demand, W = Wish		

The virtual realization was based on these requirements. For description purposes, the implementation is divided into three parts (A, B, C, see Figure 2). The VLE starts with a welcome message for the user and additional instructions on how to carry out the training on a notice board (A, see Figure 2). At the same time, the goals of the learning environment are defined. Afterwards, the two-part active execution of the PDCA method takes place, which consists of an active experimental design and subsequent execution. The first step is to set up the experimental design on a blackboard according to the PDCA method (B, see Figure 2). For this purpose, signs with different tasks and a PDCA cycle are given on the board. These signs are to be assigned individually to the respective PDCA phase according to the theoretical knowledge of the users (drag-and-drop). After complete assignment, the users receive coloured feedback on their result and the possibility to correct corresponding errors. This preparatory activity supports the targeted implementation of the training and serves as a practical application of the PDCA cycle. This is followed by the practical application of the sequence created on the blackboard by the user (C, see Figure 2). For this purpose, a catapult is to be used to hit a movable container five times in succession. Three balls of different weights as well as different settings on the catapult itself are available as setting options. The last aspect includes the parameters clamping angle, stop rod, rubber band length as well as the position of the ball cup. The execution is supported by an automatic measurement of the target distance as well as a visual display of the flight line to take advantage of the VR. A second display panel shows the settings used with the result achieved.

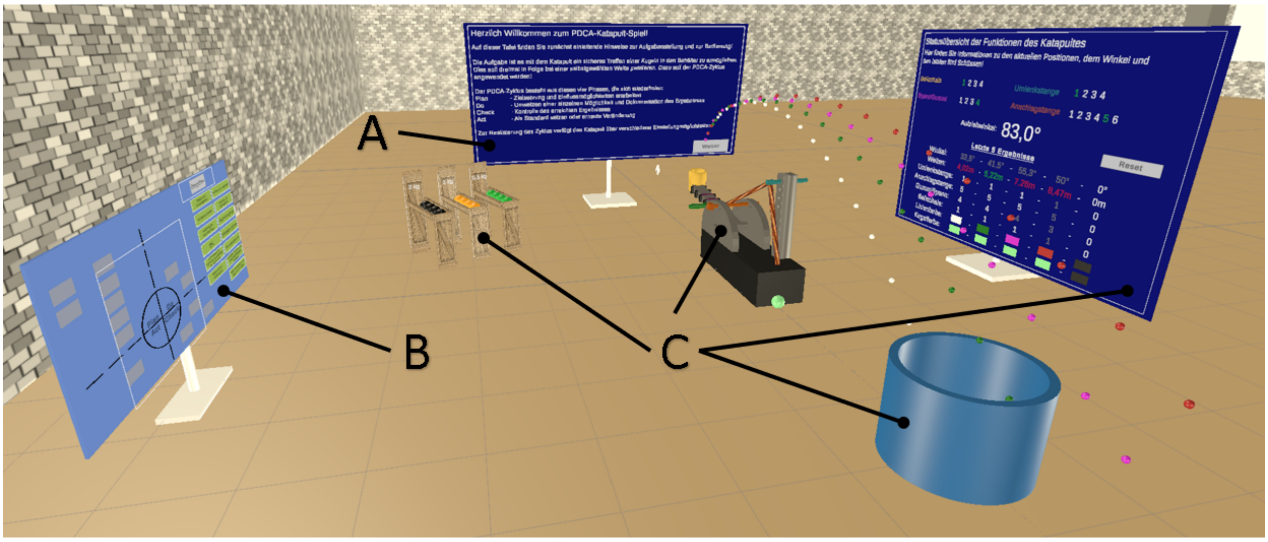

Figure 2: Representation of the virtual catapult and PDCA setting

From the requirements catalogue of Table 1, only the demand requirements were fulfilled in the concept. The requirements for Lean Management, Six Sigma (Pos. 2) were integrated by the blackboard (Pos. 2.1) and the practical implementation at the catapult (Pos. 2.2). The Virtual Reality / Programming (Pos. 3) requirements were also integrated. In this category, the inclusion of several persons was investigated, but not implemented, since this is partly also contrary to the time-individual execution of the test persons. The wishes from the requirement catalogue were not fulfilled, which is justified in the following. The catapult (Pos. 1) contains the necessary components (Pos. 1.1) and the clamping angle information (Pos. 1.2). The dismantlability (Pos. 1.3) as well as the bouncing (Pos. 1.6) of the catapult after a shot have not been implemented, since this catapult, in contrast to a real catapult, does not have to be or is not mobile. Likewise, the aging of the rubber band (Pos. 1. 4) and an influence of the tensioning time of the rubber band (Pos. 1.5) have been neglected, since these do not show any significance in the virtual environment.

For the validation, a two-part questionnaire was created. The first part is given to the users before entering the VLE and provides instructions on how to conduct the experiment. In addition, this collects demographic data, information about prior experience with VR, and knowledge level about the PDCA method. The second part is handed over after the virtual experience and is again separated into two sections. In the first section, the knowledge of the PDCA method and usability is recorded. The created questions are based on ISO 9241/10 questionnaire [19] but are adapted to the task and supplemented by free text expression. The second section covers the user experience. This section is based on the user experience questionnaire [20] but has been reduced by the category originality. In both sections, mainly the format of two bipolar word pairs on a seven-part, endpoint-based scale is applied. In this process, different word pairs are assigned to a category.

3.2 Virtual PDCA application in practice

In the first test run, the training of the PDCA method was now implemented with the help of a virtual catapult game. For the subsequent validation, the methods of thinking aloud and the semi-structured interview were chosen in addition to the previously explained questionnaires. Six persons took part in the validation for the exploration test, consisting of mechanical engineering students who thus overlap with the main target group of the training due to their theoretical prior knowledge in the field of lean management. The implementation took place in the Learning and Research Factory (LFF) of the Chair of Production Systems (LPS) at Ruhr University Bochum. Based on this, the participants were able to carry out the training in a VR replica of the LFF. The recognition value of the learning environment was positively evaluated by the participants. The participants first had the opportunity to familiarize themselves with the virtual mode of operation and then to try out the VLE without time restrictions. Afterwards they were asked to answer the developed questionnaire. For the first prototype, this evaluation was supplemented by a semi-structured interview. In this interview, questions were asked about the perception of the VR experience and conspicuities in the visual design. Likewise, the perception of the functionality of the catapult as well as the connection between the catapult and the PDCA method was queried. In addition, the interview allowed individual suggestions to be recorded and queries from the users to be clarified. The interviews and the thinking aloud also yielded suggestions for further optimizing the prototype used in a later revision. The results of the questionnaire after the test are shown in Figure 3.

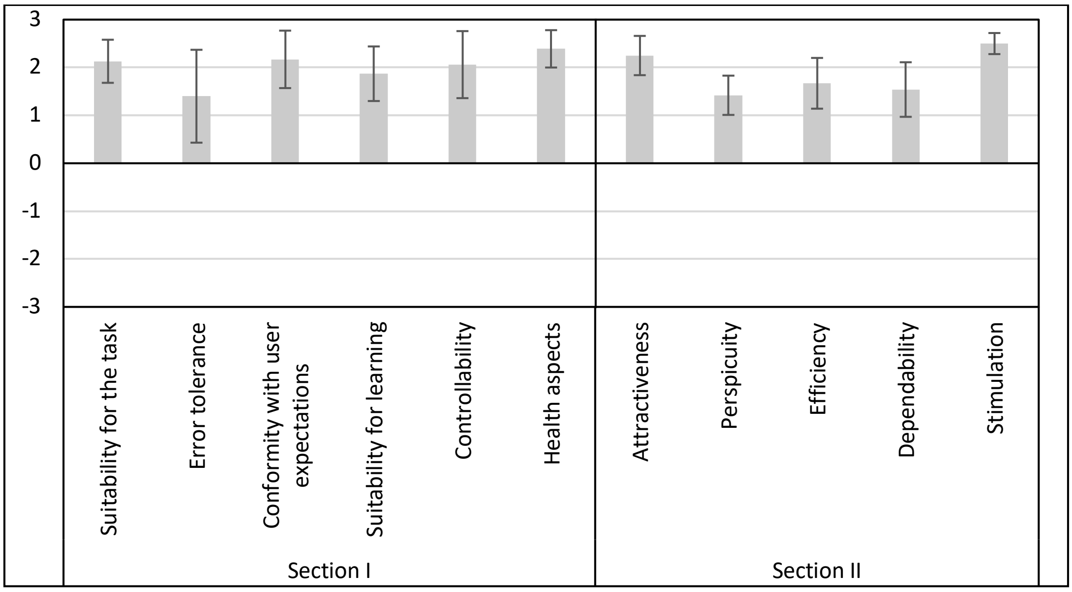

Figure 3: Results of the Questionnaires

Figure 3 shows the results of the individual categories of the word pairs of the questionnaire. The height of the bar represents the mean, and the small lines represent the confidence interval in both directions. The scale values range from -3 to +3. Across all categories, there is a mean of at least 1.4 (error tolerance) to a maximum of 2.5 (stimulation), which can be considered positive. The confidence interval varies between 0.22 (stimulation) and 0.98 (error tolerance). The large deviation of the error tolerance is due to no to few errors in the execution, so that the error tolerance did not appear. The stimulation and the high attractiveness underline the desire to use the VLE more often for other methods.

In summary, all participating subjects successfully completed the VLE and did not have to take an unplanned break or abort. All subjects spent between 10 to 20 minutes in the VR. The application is scheduled for up to 20-25 min, so the duration so far is within reasonable limits. The longer dwell time could be explained in the subsequent evaluation with the help of increased motivation and determination of the participants. In addition, the movement in the VR was evaluated as intuitive by the test persons. Furthermore, the VLE was perceived as motivating, entertaining and innovative, which is cited as the overall result of the exploration test. Based on the above results, minor improvements to the concept could already be implemented.

4. Summary and outlook

The training of quality methods with the help of VR glasses is a promising field of application, which has still received little attention in research, teaching and industry. Digital assistance systems for training purposes offer many advantages compared to classical classroom training, e. g. time independence of the training per participant. To address this emerging need for research, a test run for training the PDCA method was implemented and validated with a first group of test persons. Hereby, first important aspects of the design of virtual learning environments for VR assistance systems could be analysed. Furthermore, it became clear that there is a need for further research in this field, because, for example, the perception of the technology in the training has a significant influence on the experience and thus on the quality of the training. As a further step, the outstanding sub-steps of the ARIM, part A and B of the Design phase, are to be realized and tested. This means above all to work out the immersive technology acceptance model (A) for the evaluation as well as to carry out the assessment test. Subsequently, phase 3 of the validation will start.

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References

[1] Rojas-Sánchez, M.A., Palos-Sánchez, P.R., Folgado-Fernández, J.A., 2022. Systematic literature review and bibliometric analysis on virtual reality and education. Educ Inf Technol, 1–38.

[2] Grodotzki, J., Upadhya, S., Tekkaya, A.E., 2021. Engineering education amid a global pandemic. Advances in Industrial and Manufacturing Engineering 3, 100058.

[3] Radianti, J., Majchrzak, T.A., Fromm, J., Wohlgenannt, I., 2020. A systematic review of immersive virtual reality applications for higher education: Design elements, lessons learned, and research agenda. Computers & Education 147, 103778.

[4] Hönig, J., Schnierle, M., Hüttenberger, M., Polak, C., Röcj, S., 2021. Mixed-Reality-in-the-Loop Simulation für Schulungen im Maschinen- und Anlagenbau, in: DELFI2021 19. Fachtagung Bildungstechnologien der GI. Proceedings of DELFI Workshops 2021. DELFI, Dortmund. 13.08.2021. Hochschule Ruhr West 2021.

[5] Nedjwa, E., Bertrand, R., Sassi Boudemagh, S., 2022. Impacts of Industry 4.0 technologies on Lean management tools: a bibliometric analysis. Int J Interact Des Manuf.

[6] Wang, P., Wu, P., Chi, H.-L., Li, X., 2020. Adopting lean thinking in virtual reality-based personalized operation training using value stream mapping. Automation in Construction 119, 103355.

[7] Stuchlikova, L., Kosa, A., Benko, P., Juhasz, P., 2017. Virtual reality vs. reality in engineering education, in: 2017 15th International Conference on Emerging eLearning Technologies and Applications (ICETA). 2017 15th International Conference on Emerging eLearning Technologies and Applications (ICETA), Stary Smokovec. 26.10.2017 - 27.10.2017. IEEE, pp. 1–6.

[8] Müller, B.C., Reise, C., Seliger, G., 2015. Gamification in Factory Management Education – A Case Study with Lego Mindstorms. Procedia CIRP 26, 121–126.

[9] Karcher, A., Arnold, D., Prinz, C., Kuhlenkötter, B., 2022. Procedure for the implementation of VR/AR learning scenarios for method training - Presentation of the Assisted Reality Implementation Model (ARIM).

[10] Hussein, M., Nätterdal, C., 2015. The Benefits of Virtual Reality in Education- A comparision Study. Chalmers University of Technology and University of Gothenburg, Göteborg.

[11] Mossel, A., Schoenauer, C., Froeschl, M., Peer, A., Goellner, J., Kaufmann, H., 2021. Immersive training of first responder squad leaders in untethered virtual reality 25 (3), 745–759.

[12] Zender, R., Söbke, H., Mulders, M., 2021. 4. Workshop VR/AR-Learning, in: DELFI2021 19. Fachtagung Bildungstechnologien der GI. Proceedings of DELFI Workshops 2021. DELFI, Dortmund. 13.08.2021. Hochschule Ruhr West 2021.

[13] Roussou, M., 2004. Learning by doing and learning through play. Comput. Entertain. 2 (1), 10.

[14] Tönnis, M., 2010. Augmented Reality: Einblicke in die Erweiterte Realität. Springer Berlin Heidelberg, Berlin, Heidelberg.

[15] Naumann, J.D., Jenkins, A.M., 1982. Prototyping: The New Paradigm for Systems Development. MIS Quarterly 6 (3), 29–44.

[16] Air Academy Associates, 2022. Statapult® Catapult: The Official Statapult® Catapult. https://airacad.com/statapult/. Accessed 20 September 2022.

[17] moodle, 2022. About Moodle - MoodleDocs. https://docs.moodle.org/400/en/About_Moodle. Accessed 17 September 2022.

[18] Wallace, K., Pahl, G., Beitz, W., Feldhusen, J., Grote, K.-H., Blessing, L.T.M. (Eds.), 2007. Engineering design: A systematic approach, 3. ed. ed. Springer, London, 617 pp.

[19] Jochen Prümper, 1999. Test IT: ISONORM 9241/10, in: Bullinger, H.-J., Ziegler, J. (Eds.), Human-computer interaction. Proceedings of HCI International '99 (the 8th International Conference on Human-Computer Interaction), Munich, Germany, August 22 - 26, 1999. Erlbaum, Mahwah, NJ, pp. 1028–1032.

[20] Laugwitz, B., Held, T., Schrepp, M., 2008. Construction and Evaluation of a User Experience Questionnaire, in: Holzinger, A. (Ed.), HCI and usability for education and work. 4th Symposium of the Workgroup Human-Computer Interaction and Usability Engineering of the Austrian Computer Society, USAB 2008, Graz, Austria, November 20-21, 2008 ; proceedings, vol. 5298. Springer, Berlin, Heidelberg, pp. 63–76.

Biography

Amelie Karcher, M. Sc. (*1990) studied economics at Bochum University of Applied Sciences and Logistics at the TU Dortmund University, during which time she worked as a student assistant in the Lean Warehousing department of the Frauenhofer Institute for Material Flow and Logistics from 2016. In 2019, she worked as a research assistant at the Department of Product Safety and Quality at Bergische Universität Wuppertal and since 2020 at the Chair of Production Systems in the field of production management at Ruhr University.

Timo Köring, M. Sc. (*1997) studied mechanical engineering at Bochum University of Applied Sciences and at Ruhr University Bochum. Since 2021, he has been working as a research assistant at the Digital Engineering Chair at Ruhr University.

Prof. Dr.-Ing. Detlef Gerhard (*1969), has been head of the Digital Engineering Chair at Ruhr University in Bochum since 2019. Previously, he was Professor at TU Wien and lead the Mechanical Engineering Informatics and Virtual Product Development research group.

Prof. Dr.-Ing. Bernd Kuhlenkötter (*1971) has been head of the Chair of Production Systems at Ruhr University in Bochum since April 2015. Previously, he was head of the Institute for Production Systems at TU Dortmund University.

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Ontology-based Assistance System for Control Process Reconfiguration of Robot-Based Applications

Aleksandra Müller[1], Waldemar Jesse[1], Simon Storms[1], Werner Herfs[1], Christian Brecher[1]
[1]*Laboratory for Machine Tools WZL, RWTH Aachen University*

Abstract

Nowadays, production systems, and subsequently their automation and control procedures, become gradually more complex due to global competition and shortening product life cycles. To simplify the reconfiguration process for the worker, smart assistance systems are needed. The advantages of semantic technologies including ontologies, such as their graph structure and suitability for the use of optimization algorithms, illustrate their potential as the basis for a possible knowledge-based assistance solution. Against this background, the aim of this paper is to develop a concept for an ontology-based assistance system for control process reconfiguration that can consolidate existing product and process information and add expert knowledge to it. The focus is on the design of the ontology and the evaluation of possible SPARQL query-based assistance functions. To evaluate the tool, it is implemented on a use case of robot-based adhesive application and two possible assistance functionalities of the system are presented.

Keywords

Assistance systems; Semantics; OBDA; Optimization; Control process reconfiguration

1. Introduction

Due to increasing global competition, companies are challenged to make their production flexible and adaptable. This leads to a steadily increasing complexity of production systems and thus their automation and control processes [1]. At the same time, control processes must be quickly configurable in order to be able to react to short product life cycles. Downtimes of a plant due to reconfigurations cause high costs: In assembly lines such as automotive assembly, the costs of one minute of line downtime for reactive maintenance can amount to up to 20,000 euros [2]. Shortening the reconfiguration time in complex automation processes thus offers immense cost-saving potential, the actual implementation of which in business reality represents a major challenge.

Robot-based adhesive application in automotive body assembly represents one such control and automation process. In car body assembly, industrial robots are increasingly being used for gluing side panels, enabling flow operation in assembly. In the event of a functional change in the production process, such as the replacement of the adhesive to be used, all the given process interrelationships must be analysed again and reconfigured if necessary in order to ensure the quality of the bonded joint. Comprehensive data management systems that provide an overview of all the system parameters and control levers are often not available in companies, so that reconfiguration is based on experience [3]. Correct adjustment of the process parameters thus requires the user to have precise knowledge of the complex interrelationships between the process and bonding parameters and their effect on upstream and downstream process steps. This makes the search for solutions in the event of a process change more difficult and time-consuming. In order to master the complexity of process planning and configuration, a large number of user-supporting solutions exist in the

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area of product lifecycle management (PLM). However, these neither have the functionality to generate solution and optimization proposals, nor do they map the existing expert knowledge with so-called empirical values about the system behaviour [4]. The advantages of semantic technologies including ontologies, such as their graph structure and suitability for the use of optimization algorithms, illustrate their potential as the basis of a knowledge-based assistance solution [5].

Against this background, the aim of this paper is to develop an ontology-based assistance system that can consolidate existing product and process information and add expert knowledge to it. For this purpose, production-related assistance tools are presented in Section 2, along with common database management systems and ontologies. Based on this, a concept of a semantically based assistance tool is presented in Section 3. Section 4 describes the present robot-based use case on an exemplary implementation is based on, described in Section 5. In Section 5, two exemplary functionalities of the assistance tool are illustrated: a search functionality for necessary process parameter adjustments in dependence of the used adhesive and a selection aid for the adhesive to be used based on existing system boundary conditions. The paper concludes with a summary and outlook on further work in the presented field of research.

2. State of the art

2.1 Production data management systems

Data management systems and information models can be used to secure, manage and model data. In the production environment, database management systems (DBMS) and the Open Platform Communications Unified Architecture (OPC UA) are commonly used for this purpose .

The DBMS represents a software system for creating and maintaining databases. This includes the creation and manipulation of databases, enabling logically structured storage and manipulation of data by users [6]. In the field of production technology, most commonly used database system is the relational DBS (RDBS) [7]. This is represented on the one hand by a database, which from a mathematical point of view is a table-based relational database model and on the other hand by the descriptive query and manipulation language Structured Query Language (SQL) as DBMS [8]. The object-relational database system (ORDBS) is a special form and further development of the RDBS and has gained acceptance in recent years due to its object-oriented approach [9]. The basic idea of the object-relational database system is to link object-oriented programming with the relational database approach. This in turn enables the modeling of complex relationships and the creation of a structure within the ORBDS. Nevertheless, due to insufficient relations, this kind of data modeling is not sufficient to create a higher-level and universal schema for derivable knowledge [10].

An alternative option to data modeling in production systems is information modeling using OPC UA standards. Information modelling with OPC UA offers the possibility to semantically model versatile data relationships in a uniform way, especially with the help of the so-called Companion Specifications. Nevertheless, due to the lack of interfaces for browsing and deriving knowledge from information models, this technology is insufficient for modeling a coherent knowledge base of a consolidating assistance system [3].

2.2 Semantic technologies in production

To model a knowledge base in the production environment, data needs to be extended by means of semantics [11]. Following the Semantic Web rules, the data can be interpreted by a machine [12]. In this context, interpretability for machines means that data is linked to other data by means of relationships, thus generating an explicit knowledge base. This can be processed by machines as well as made accessible to humans. For semantic enrichment of data, the Resource Description Framework (RDF) is used as a standardized syntax and core technology. Since a uniform and declarative structure in RDF was missing, the RDF Schema (RDFS) was introduced. These technologies enable semantic modeling of contexts. When merging many so-called RDF and RDFS statements, the resulting graph has to be made readable to the machine. This happens by means of different serializations, which specify the data format and thus the syntaxes [13]. The respective syntax can be used for the Ontology Web Language (OWL) as data format and represents the essential OWL ontology. OWL enables the complex modeling of relations with additional features like cardinalities or inverse relations [11]. Thus, ontologies using OWL create a suitable data modeling for complex relations and enable the intelligent derivation of knowledge. Furthermore, suitable modeling allows flexible adaptation and transferability to other data models. However, initial modeling is associated with high effort. To address this problem and ensure reusability, modelling should be based on existing approaches. In the following, some chosen upper ontologies are presented, which can be designed as a transferable knowledge base and adapted for diverse production systems, thanks to their basis structure.

The *Suggested Upper Merged Ontology (SUMO)* is an ontology aggregated from a set of Upper Ontologies and serves as a standard document for the further development of specific ontologies [14]. Among other things, SUMO serves as the foundation for the Robotics and Automation Ontology Core Ontology for Robotics and Automation (CORA) as well as the Position Ontology (POS) [15]. The SUMO ontology can also be used as a base to integrate other previously non-standard ontologies.

The usage domain of the *Core Ontology for Robotics and Automation (CORA)* is the integration of robot-specific applications and was created by an aggregation of already standardized and non-licensed ontologies for robotics and automation into one [16]. By incorporating CORA, an ontology for robotics-based and automated production processes can be developed. This Upper Ontology extends SUMO and creates a basic architecture for robot-based systems.

To be able to model information regarding trajectories and coordinate points, SUMO and CORA are extended by *POS (Position) Ontology*. The POS ontology is on the same ontological level as CORA and can represent the position of robots in qualitative or quantitative orientation [15].

Temporal processes are not able to be modeled with the SUMO, CORA, and POS approaches. For this purpose, the *OWL Time Ontology (TIME)* is considered. The TIME ontology represents a recommended W3C candidate for standardization and is used for describing and ordering temporal relations between temporal instances and intervals. Different time formats as well as durations can be implemented with this approach. Moreover, the temporal consideration of resources (URI) can proceed both time-relative and absolutely [17].

In addition, Ontology-Based Data Access (OBDA) approaches are increasingly being used in production engineering. The goal of the OBDA strategy is to give users the ability to directly query data that is dispersed over numerous distributed sources, such relational databases. The mapping layer of an OBDA system converts user questions from a familiar ontology vocabulary into the vocabulary of the underlying data sources, and then transfers responsibility for query evaluation to the data source's appropriate query answering system [18].

2.3 Assistance tools for control process reconfiguration

A current approach to reducing the complexity of reconfiguration processes in production is the use of Decision Support Systems (DSS) for the worker. This is achieved by deriving and displaying information from a knowledge base. In the industrial environment, applications such as Mechatronic Concept Designer and Tecnomatix from Siemens are commonly used. The Mechatronic Concept Designer can accelerate constructive processes by means of simulation as well as by representing information about robot control parameters. However, it is not currently possible to derive a recommendation for action here. The system serves to visualize interrelationships to offer the user the possibility to design processes already during development and thus, for example, to determine process sequences [19]. Tecnomatix offers similar functions and was designed for factory planning applications. Process sequences can be simulated with the tool to see the process result of some pre-set parameters. Through extensions in the application, simulative movements can be implemented and thus a plausibility check can be performed. Also in this case, however, no fully automatic recommended action can be derived for the end user [20].

Recognizing the lack of derivation of a recommended action in the industrial environment, research created a system based on Bayesian networks that can be used to diagnose faults in production equipment. This system calculates the probabilities of triggers of a fault or solutions to it by estimating the probabilities of occurrence, expert knowledge, and available data. Depending on the interaction with the system, the probabilities can be subjected to a learning process so that the system makes better predictions. The drawback to this system is its specific use case. Although the system can derive initial recommendations for action when errors occur, it cannot be extended with further functionalities based on the same knowledge base. Thus, the generated knowledge base is not reusable [21].

To address the problem of reusability, there is some research on ontology based DSS approaches. [22] describes systems for troubleshooting, for energy consumption reduction of oil and gas companies, for network security systems and for medical decision support. In these cases, ontology-based knowledge base is developed, which is extended by means of data and semantic correlations. This knowledge base is searched for explicit knowledge by the systems in order to derive insights. With the help of these insights, decision-supporting actions can finally be extracted. However, none of these application fields are in the production engineering environment, despite promising success.

[23] contains a detailed description of common application areas of semantic technologies in production engineering. It distinguishes between five areas: Data/Service Catalog, Integrating Domains, Database Access, Consistency and Reasoning and Data Aggregation, with Data Service Catalog being the most common application. The examples show the feasibility of complexity modelling of the entire system, which can be used to search for necessary parameter relationships. However, all the systems has a descriptive role and do not have the functionality of intelligent solution proposals for producing optimal production plants.

In summary, it can be stated that semantic approaches to support the user exist in various production sectors, but mostly only serve to consolidate the existing process knowledge. Today, there are hardly any semantic tools on the basis of which intelligent solution proposals can be generated.

3. Concept development

Based on the findings from the previous Sections, there is a need for knowledge-based assistance systems for control process reconfiguration that could reduce the time required for this. Such a system should be able to cope with two relevant challenges: on the one hand, the integration of existing expert knowledge and, on the other hand, the need to generate intelligent solution proposals. Both of these issues might potentially be resolved using semantic technologies: first, by building a comprehensive system knowledge base that includes expert knowledge; second, by providing intelligent support when looking for configuration options.

By establishing new relationships between the data points of remote data resources, an ontology-based configuration tool can integrate currently existing product and process information, enhance it with expert knowledge, and reveal new knowledge linkages. The accumulated knowledge can then serve as the foundation for help programs that optimize process configuration. They can speed up user solution search and reduce planning and configuration time.

The anticipated approach for creating an assistance system for knowledge-based control process reconfiguration is shown in Figure 1. The design of the knowledge management system is a crucial component of the solution hypothesis. The knowledge management system's model specification is carried out using the requirements description (A). This involves analyzing and using as a system base existing methodologies for semantic modelling of robot-based processes, such as CORA, POS and TIME, s. Section 2. The system's potential connections to internal data sources are then investigated (B and C). The evaluation of the created process interface's integration potential with the production process' OPC UA information models is of increased significance (B). Preliminary work for this connection is described in [3]. Additionally, the integration of the current expert knowledge into the system to be constructed in the form of machine-readable, interpretable metadata is the primary factor to be taken into account (D). Finally, it is proposed that the knowledge management system might be integrated into a future, comprehensive semantic network of the Internet of Production (F). This line of research has already been dealt with in detail in [10].

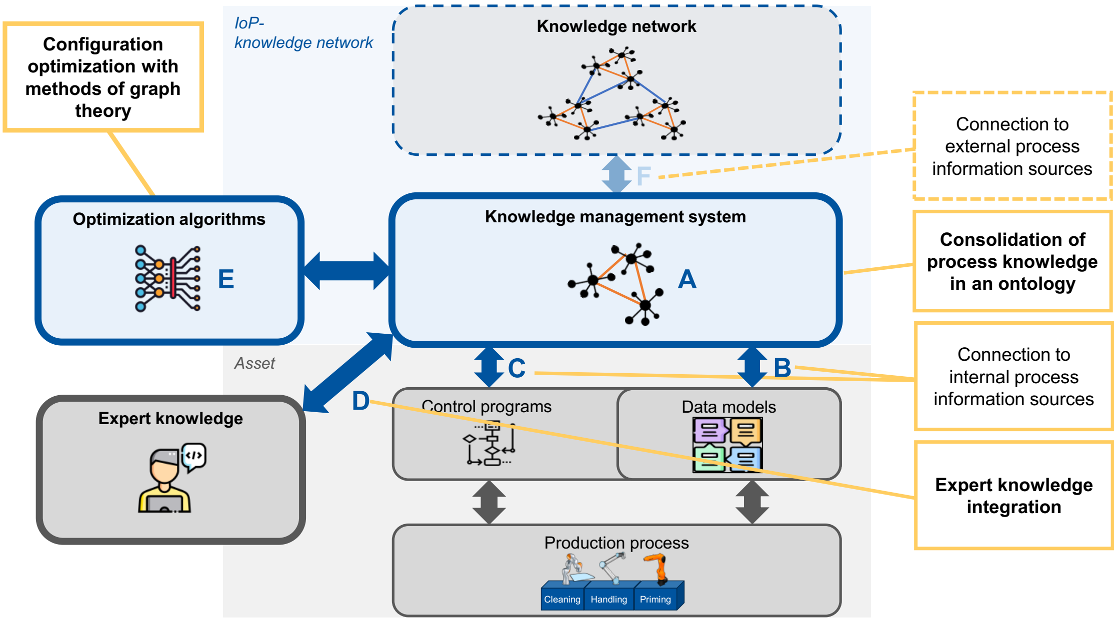

Figure 1: Concept of an assistance system for knowledge-based control process configuration

In the context of this paper, the design of the consolidating knowledge management system (A) and a possible connection of the existing expert knowledge (D) are considered in particular. Based on this, an initial assistance system is to be created that is able to provide the user with solution suggestions for adjusting the parameters. The solution suggestions are to be based on SPARQL queries of the given knowledge graph of the knowledge management system, because the results can be easily processed sequentially.

4. Use Case

Figure 2: Robot-based glass pane completion use case

The idea is put into practice in a robot-based glass pane assembly sub-process, shown in Figure 2. The stations Cleaning, Handling, and Priming make up the sub-process. The first station simulates the procedure of cleaning the working trajectory of a car window. Here, the glass's shape is cleaned with a KUKA iiwa. A KUKA Agilus (KR 6) is utilized in the priming station to apply glue to the glass pane's cleaned shape. The two stations each have a workpiece carrier that the disc is securely mounted to and a proximity sensor that allows the positioning of the disc to be watched. The panes are switched out and passed from station to station by the handling robot (UR 5).

One of the major challenges of the process is the multitude of adhesive and process parameters, such as the flowability, the bead cross-section or the travel and adhesive exit speed, which are interrelated in many complex ways. A correct setting of the process parameters requires the user to have precise knowledge of the interrelationships between the process and bonding parameters and their effect on upstream and downstream process steps. This makes the search for a solution in the event of a process change and more difficult and thus the downtime for reconfiguration time-consuming.

5. Implementation

To implement the concept, a basic architecture of the assistance system was created according to the concept shown in Figure 1.

Process and machine data are extracted and processed. The extraction is done by the combinatorial use of TCP/IP sockets and SFTP, as well as the use of OPC UA communication standard. The extracted data is extended by individual algorithms, classified and secured by means of an ORDBS. Subsequently, the process ontology presented in the following can be modeled based on the ontology standards described in Section 2. Finally, through an Ontology Based Data Access (OBDA) approach, components of the process ontology can be connected to the data in the ORDBS data model. This results in a Knowledge Graph as a knowledge management system, which serves as a decision-making basis. The user can interact with the system via a front-end application. A focused view of the process ontology and the Knowledge Graph are presented in the following.

5.1 Basic ontology for production processes

First, the basic ontology is implemented on the basis of the findings from [15] (s. Section 2) . For this purpose, the SUMO, CORA and POS architectures are adopted and modeled. Consequently, the TIME ontology is integrated into the architecture. It is important to mention that the Upper Ontology logic must not be violated. For this reason, the TIME ontology is placed on the same level as CORA and POS ontologies. Since time has no spatial elements, the ontology must be classified under Abstract. Figure 3 represents the complete basic ontology without associated object and data relations of the TIME ontology. These can be chosen variably depending on the use case.

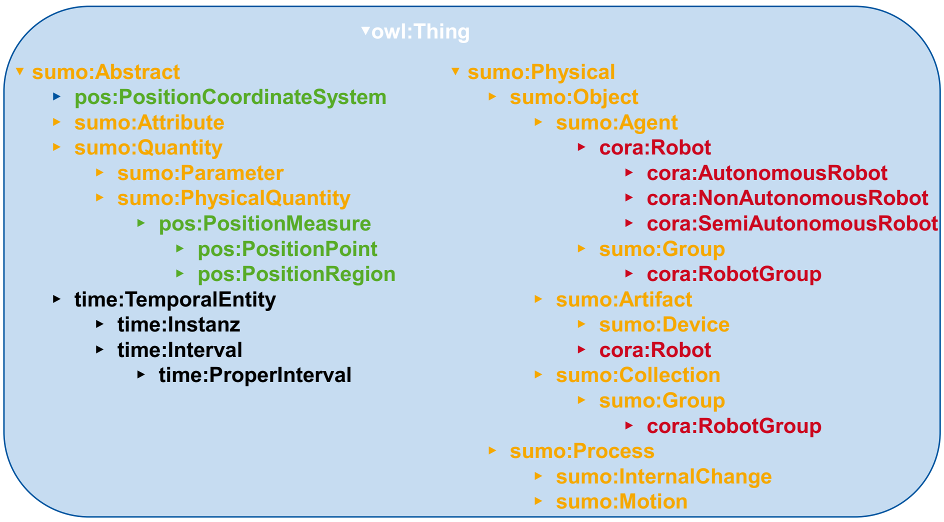

Figure 3: Upper ontology class hierarchy

This ontology can now be used as a basis model of a production process. By choosing this architecture, ontologies representing distributed processes or developed by multiple people can be adapted and combined adaptively and flexibly. For the described use case, the basic ontology is extended by use case specific

Classes, Object relations, Data relations and Instances. Furthermore, an OBDA mapping is applied to assign values to selected Classes and Instances, according to [7]. In the following, two exemplary use cases are considered that demonstrate the smart assistance service with the conceptualized system: first, a parameter adjustment for adhesive change and second, adhesive selection based on system boundary conditions.

5.2 Assistance case 1: Parameter adjustment for adhesive change

The gluing result is largely determined by the interaction of the robot speed and the volume flow, which can be calculated from the pump pressure and drive power, pressure reduction and overflow valve parameters and the density of the adhesive used. There are correlations between the settings of the individual parameters, e.g. between the maximum possible pump pressure, the viscosity and thus the density of the adhesive. Therefore, parameter adjustment after adhesive modification is a major challenge because of this large number of parameter correlations that are not directly apparent and can be influenced by the modification. However, this can be overcome insofar as expert knowledge is mapped in a knowledge graph. For demonstration purposes, two adhesives with associated parameters were linked via a *:hasParameter* object relation , s. Figure 4. The parameters are also associated with a controlling instance indicating the influence on the parameter, and an associated value is assigned using the OBDA approach.

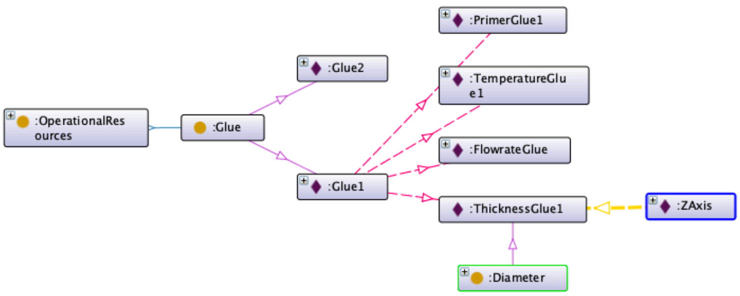

Figure 4: Parameter adjustment for adhesive change: Knowledge Graph extract

The web application of the assistance system can now access the knowledge graph via an endpoint, which is provided by the OBDA approach, and first extract the process components of the "Glue" class using SPARQL. Afterwards, the user is given the possibility to select the desired glue via an interface. Based on the input, the search engine of the tool extracts all parameters found and outputs them with the stored values. If the user requires setting assistance, the controlling parameters can be queried. These represent the software or physical parameters and variables to be set. Figure 5 shows the graphical user interface of the developed tool.

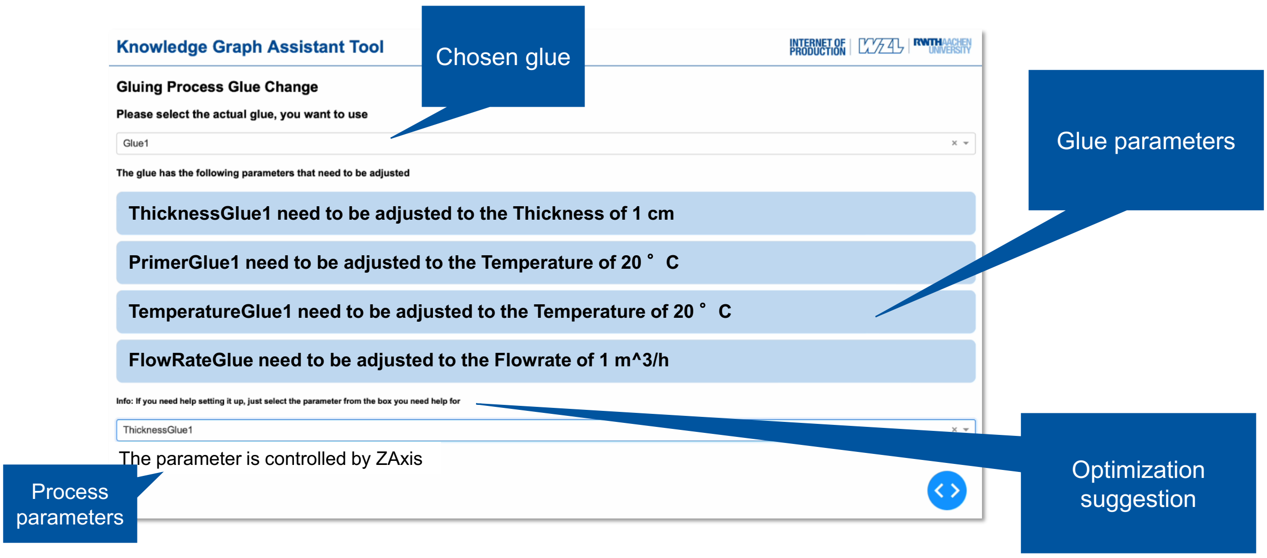

Figure 5: Assistance case 1: Graphical user interface

5.3 Assistance case 2: Adhesive selection based on system boundary conditions

The aim of this assistance case is enabling a user to enter requirements, similar to a technical specification search in a data sheet, and find the appropriate component or adhesive. The search structure in the Knowledge Graph is similar to the structure of assistance case 1, shown in Figure 4. However, the search is done without the controlling instance and the *:hasProperties* relation is used to define the properties. Thus, there is a possibility to define properties such as the maximum or minimum application temperature. An assistance case associated extract of the Knowledge Graph is shown in Figure 6.

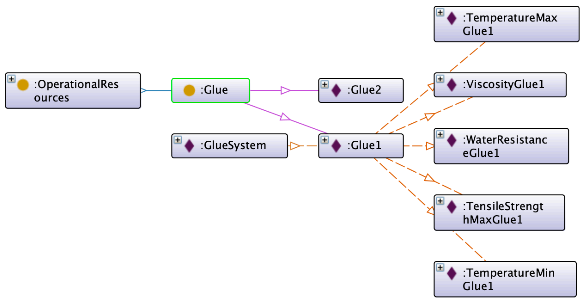

Figure 6: Adhesive selection based on system boundary conditions: Knowledge Graph extract

In this case, the data is stored for all values as well. The decision support starts with an extraction of the different adhesives. Then the *:hasProperties* data relation is used to extract associated properties. Decision support can then use algorithms, the Object relations, Data relations and the specified names to categorize and specify which types of properties are involved and assign them to a data grid. This data grid can output the appropriate component based on an input from the user in the frontend mask. The input mask can either be generated dynamically, based on the values, or defined in advance.

5.4 Further application possibilities

However, the two presented application possibilities do not describe the set of possible applications. In addition to these applications, for example, a temporal modeling of production processes based on the TIME ontology was designed. This can be used to optimize process times. Also a problem finding application, which is a flexible and easy to integrate ontology, was designed. In addition, OBDA mapping architectures for efficient data access have been developed and implemented. It can be seen that ontologies offer a wide range of use cases due to the possibility of complex modeling of semantic relationships and the integration of classical DBS via OBDA.

6. Summary and outlook

In this paper, a system for smart assistance in the reconfiguration of control processes was conceptualized and prototypically implemented on a use case of robot-based glass pane completion. The system is based on a Knowledge Graph built on presented common production ontology standards such as SUMO and CORA. In this graph, process-internal relevant information is consolidated, including the sequence of the process chain, information models and expert knowledge in the form of meta-information. Through targeted queries to the graph, knowledge can be gained about the programming of the process, which helps the end user when changing the process parameters. The system's mode of operation has been prototypically demonstrated in two examples: first, a parameter adjustment for adhesive change and second, adhesive selection based on system boundary conditions.

In further research, the aim is to use a learning or generally more intelligent data extraction algorithm to export knowledge in a more accessible way for the developer. This should be possible without requiring a detailed understanding of the respective Knowledge Graph, as currently necessary for SPARQL queries. In addition, optimization algorithms are to be tested that can make suggestions for process time optimisation from the generated Knowledge Graph. Furthermore, a subsequent study to survey experts from the industry should provide further possibilities to extend the functionality of the developed tool. Finally, the other components of the overall architecture described in Section 3 will be implemented, such as the connection to existing OPC UA models with an OPCUA2OWL algorithm.

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References

[1] Schuh, G., Anderl, R., Gausemeier J., ten Hompel, M., Wahlster, W., Industrie 4.0 Maturity Index. Die digitale Transformation von Unternehmen gestalten (acatech STUDIE). München: Herbert Utz Verlag, 2017.

[2] G. Schuh, J.-P. Prote, M. Molitor, and S. Cremer, "Internet of Production – Steigerung des Wertschöpfungsanteils durch domänenübergreifende Kollaboration," in Springer Reference Technik, Handbuch Industrie 4.0, M. ten Hompel, B. Vogel-Heuser, and T. Bauernhansl, Eds., Berlin, Heidelberg: Springer Berlin Heidelberg, 2020, pp. 1–34.

[3] A. Müller, T. Schnieders, S. Storms, and W. Herfs, "Integration method of custom information models into existing OPC UA Servers," 2022 IEEE ETFA Stuttgart Proceedings, 1-7, 2022, doi: 10.1109/ETFA52439.2022.9921670.

[4] R. Jardim-Gonçalves, Ed., "Engineering, technology & innovation management beyond 2020: new challenges, new approaches": 2017 International Conference on Engineering, Technology and Innovation (ICE/ITMC) : conference proceedings. Piscataway, NJ: IEEE, 2017. [Online]. Available: http://ieeexplore.ieee.org/servlet/opac ?punumber=8269762

[5] Internet of Production: Fundamentals, Applications and Proceedings: Modular Control and Services to Operate Line-less Mobile Assembly Systems, 2022, preprint.

[6] T. Kudraß, Ed., Taschenbuch Datenbanken, 2nd ed. München: Hanser, 2015. [Online]. Available: http:// ebooks.ciando.com/book/index.cfm/bok_id/1877725

[7] C. Brecher, A. Müller, T. Nauck, and S. Storms, "Mapping Application Ontologies as a Gateway into OBDA Systems in the Internet of Production," in 2021 International Conference on Cyber-Physical Systems, preprint.

[8] A. Meier and M. Kaufmann, SQL- & NoSQL-Datenbanken, 8th ed. Berlin, Heidelberg: Springer Berlin Heidelberg, 2016. [Online]. Available: http://nbn-resolving.org/urn:nbn:de:bsz:31-epflicht-1494660

[9] E. Schicker, Datenbanken und SQL: Eine praxisorientierte Einführung mit Anwendungen in Oracle, SQL Server und MySQL, 5th ed. Wiesbaden: Springer Vieweg, 2017.

[10] A. Müller, V. Hütsch, S. Storms, and W. Herfs, "Ontology-based communication service for multi-stage production processes," in 2022 IEEE ICTMOD Proceedings, preprint.

[11] A. Dengel, Semantische Technologien: Grundlagen - Konzepte - Anwendungen. Heidelberg: Spektrum Akademischer Verlag, 2012. [Online]. Available: https://ebookcentral.proquest.com/lib/kxp/detail.action? docID=3067327

[12] M. Merdan, A. Zoitl, G. Koppensteiner, and F. Demmelmayr, "Semantische Technologien – Stand der Technik," pp. 291–299, 2010, doi: 10.1007/s00502-010-0777-3.

[13] A. Heuer, K.-U. Sattler, and G. Saake, Datenbanken - Konzepte und Sprachen, 6th ed. Frechen: mitp, 2018. [Online]. Available: https://ebookcentral.proquest.com/lib/kxp/detail.action?docID=6947688

[14] I. Niles and A. Pease, "Towards a standard upper ontology," in Proceedings of the international conference on Formal Ontology in Information Systems - Volume 2001, Ogunquit, Maine, USA, 2001, pp. 2–9.

[15] IEEE, “IEEE Standard Ontologies for Robotics and Automation,” IEEE Std 1872-2015, 2015, doi: 10.1109/IEEESTD.2015.7084073.

[16] S. R. Fiorini et al., “Extensions to the core ontology for robotics and automation,” Robotics and Computer-Integrated Manufacturing, vol. 33, pp. 1–9, 2015, doi: 10.1016/j.rcim.2014.08.004.

[17] W3C, S. Cox, C. Little, J. R. Hobbs, and F. Pan, Time Ontology in OWL: W3C Candidate Recommendation 26 March 2020. [Online]. Available: https://www.w3.org/TR/owl-time/ (accessed: Aug. 7 2022).

[18] C. Brecher et al., “Gaining IIoT insights by leveraging ontology-based modelling of raw data and Digital Shadows,” in 2021 4th IEEE International Conference on Industrial Cyber-Physical Systems (ICPS), Victoria, BC, Canada, 2021, pp. 231–236.

[19] Siemens Digital Industries Software, Mechatronic Concept Design | Siemens Software. [Online]. Available: https://www.plm.automation.siemens.com/global/de/products/mechanical-design/mechatronic-concept-design.html (accessed: Aug. 7 2022).

[20] Siemens Digital Industries Software, Tecnomatix | Siemens Software. [Online]. Available: https://www.plm.automation.siemens.com/global/de/products/tecnomatix/ (accessed: Aug. 7 2022).

[21] F. Ungermann, A. Kuhnle, N. Stricker, and G. Lanza, “Entscheidungsunterstützungs-systeme in der Produktion,” Zeitschrift für wirtschaftlichen Fabrikbetrieb, vol. 114, 1-2, pp. 34–38, 2019, doi: 10.3139/104.112034.

[22] M. Rospocher and L. Serafini, “An Ontological Framework for Decision Support,” in Lecture Notes in Computer Science, Semantic Technology, D. Hutchison et al., Eds., Berlin, Heidelberg: Springer Berlin Heidelberg, 2013, pp. 239–254.

[23] J. Lipp and K. Schilling, “The Semantic Web in the Internet of Production: A Strategic Approach with Use-Case Examples,” in SEMAPRO 2020 25.10.2020-29.10.2020, 2020, pp. 68–72.

Biography

Aleksandra Müller (*1995) is a research assistant and PhD candidate of the Laboratory for Machine Tools and Production Engineering (WZL) in the department of Automation and Control technology. She is a graduate of RWTH Aachen University with a master degree in business administration and mechanical engineering. She specializes in semantic technologies and robot-based production processes.

Waldemar Jesse (*1997) is a former employee of the Laboratory for Machine Tools and Production Engineering (WZL), an enthusiastic software developer and a graduate of RWTH Aachen University with two master’s degrees in automation engineering and economics.

Simon Storms (*1987) is a chief engineer and head of department at the Laboratory for Machine Tools and Production Engineering (WZL) of RWTH Aachen University, where he is responsible for Automation and Control Technology at the Chair of Machine Tools.

Dr. Werner Herfs (*1975) is an academic director and the managing chief engineer at the Laboratory for Machine Tools and Production Engineering (WZL) of RWTH Aachen University, where he is responsible for the Chair of Machine Tools.

Univ.-Prof. Dr. Christian Brecher (*1969) is a university professor, the holder of the Chair of Machine Tools and a member of the board of directors of the Machine Tool Laboratory WZL at RWTH Aachen University and the Fraunhofer Institute for Production Technology (IPT). Christian Brecher is thus the successor to Manfred Weck.

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Procedure For Hybrid Process Analysis And Design

Günther Schuh[1,2], Seth Schmitz[1], Marco Schopen[1]
[1]*Laboratory for Machine Tools and Production Engineering (WZL)/ RWTH Aachen University, Aachen, Germany*
[2]*Fraunhofer Institute for Production Technology IPT, Aachen, Germany*

Abstract

Performing business processes are a critical asset for manufacturing companies operating on highly competitive markets. Conventional approaches to business process improvement, however, are vulnerable to subjectivity and high manual efforts in their execution. These challenges can be overcome with recent databased approaches that semi-automate process analysis and design. Those approaches formalize methodical knowledge on weakness detection, measure derivation and performance evaluation for business processes into a performance-related decision support. By enabling the databased automation of these tasks this formalization helps to reduce efforts and subjectivity in process analysis and design. However, practice lacks a procedure for applying this decision support in operative business process improvement. Moreover, this decision support only formalises methodological knowledge. Operative business process improvement in practice additionally requires the consideration of experts' contextual knowledge about the company and the business process itself. This paper presents a hybrid approach for the analysis and design of business processes using a databased decision support. First, existing phase models for business process improvement are consolidated into a reference model. Second, an expert-based assessment is conducted on how decision support extends, modifies or eliminates the conventional tasks of process analysis and design. In the third step, a hybrid phase model for process analysis and design is developed that integrates the formalised methodological knowledge of the decision support and contextual knowledge of experts.

Keywords

Business Process; Process Analysis; Process Design; Process Mining; Production

1. Introduction

Performant business processes are a critical necessity for success in a competitive economy [1]. Therefore, the continuous improvement of business processes constitutes an imperative for companies [2]. Business process improvement is defined as the continuous evaluation, analysis and improvement of business processes that are important to an organization's success. [3] Central tasks within business process improvement are process analysis and process design [2]. Within process analysis, process weaknesses are detected and quantified [2]. Process design identifies, evaluates and selects measures to eliminate process weaknesses [2]. Process design measures are semantically and structurally defined modifications to the business process to remedy identified process weaknesses and their related losses in terms of business process performance. Conventional approaches to business process improvement conduct process analysis and design manually in workshops [4]. Therefore, the risk of subjective influences is inherent to conventional approaches [5], as well as high costs and time effort [4].

These challenges can be overcome with recent event log-based approaches that semi-automate process analysis and design [6,7,8]. These approaches formalize methodical knowledge on weakness detection [6],

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measure derivation [7] and performance evaluation for business processes into a performance-related decision support [8]. By enabling the databased automation of these tasks this formalization helps to reduce efforts and subjectivity in process analysis and design. However, practice lacks a procedure for applying this decision support in operative business process improvement [8]. Moreover, this decision support only formalises methodological knowledge. Operative business process improvement in practice additionally requires the consideration of experts' contextual knowledge about the company and the business process itself [8]. Additionally, the consideration of human creativity can lever the effectivity in process design [9].

This paper presents a hybrid approach for the analysis and design of business processes using an event log-based decision support. First, the state of the art is reviewed in chapter 2. In chapter 3 the concept is developed and explained. Finally, the results are summarized and reviewed in chapter 4.

2. State of the art

Business process improvement, including process analysis and design, has been investigated in research and practice for many years. This results in a multitude of procedure models for business process improvement without the use of data. More recent, databased approaches are limited to the use of process mining in process discovery. Only few approaches describe data-based support in particular for process analysis and design.

One of the most cited conventional approaches is the business process management lifecycle of [2], a six-phase-approach for improving business processes. It incorporates the phases of process identification, process discovery, process analysis, process redesign, process implementation and process monitoring, before iterating into the process discovery again. It does not explicitly use databased support, but considers process mining as an event log-based possibility for process discovery. [10] uses a four-phased model for business process improvement. By participative integration of employees in workshops, the contextual validation of analysis results and a creative solution finding is ensured. Databased support is not considered. [11] also present a participative approach to business process modelling and improvement that integrates human creativity and validation in group discussions. As a databased support for business process improvement, [12] combines process analysis on the basis of key performance indicators with process mining approaches. The "KPI4BPI " (key performance indicators for business process improvement) approach enables users to quickly identify negative deviances for process KPIs like quality, costs, time and additionally proposes process improvement heuristics automatically. However, this approach lacks a distinct explanation of a procedure to improve business processes beyond the quantification and delta reporting. The approach of [13] integrates the technology of process mining into the DMAIC *(define, measure, analyse, improve, control)* cycle of Six Sigma. Within the DMAIC-cycle process related data is used to identify processes, determine the process performance, model the process and take further analysis and monitor the process execution. This approach provides an integration of conventional and databased methods, however with a focus on quality management due to the DMAIC method. [14] develops a databased decision support for process improvement, that provides applicable best practices to a process expert. Yet a detailed explanation of its applications is non-existent. The approaches of [7,8,9] develop a decision-support to automate a majority of the tasks in process analysis and design. However, its application in practice is still missing. The evaluation of the state of the art constitutes the need for an approach, that supports process analysis and design by means of event log data like [7,8,9] and at the same time is applicable in practice.

3. Concept

Within preliminary work, the authors developed event log-based support for process weakness detection [7], measure derivation [8] and a performance-based decision support for business process analysis and design [9] in manufacturing companies. This paper's concept describes how this decision support can be integrated hybrid with contextual expert knowledge to a new procedure for business process analysis and design.

Therefore chapter 3.1 consolidates existing phase models for business process analysis and design into a reference phase model considering the most relevant tasks within. Chapter 3.2 presents the functionalities of the performance-based decision support and evaluates to which extent it can automate the tasks in the reference phase model. Within chapter 3.3 a hybrid procedure for business process analysis and design using the performance-based decision-support is introduced.

3.1 Consolidation of a reference phase model for conventional business process analysis and design

Procedures for business process improvement are typically described as a sequence of several phases. A large variety of phase models for business process improvement have evolved over the past decades in literature and practice. The most relevant phase models are summarized in Figure 1.

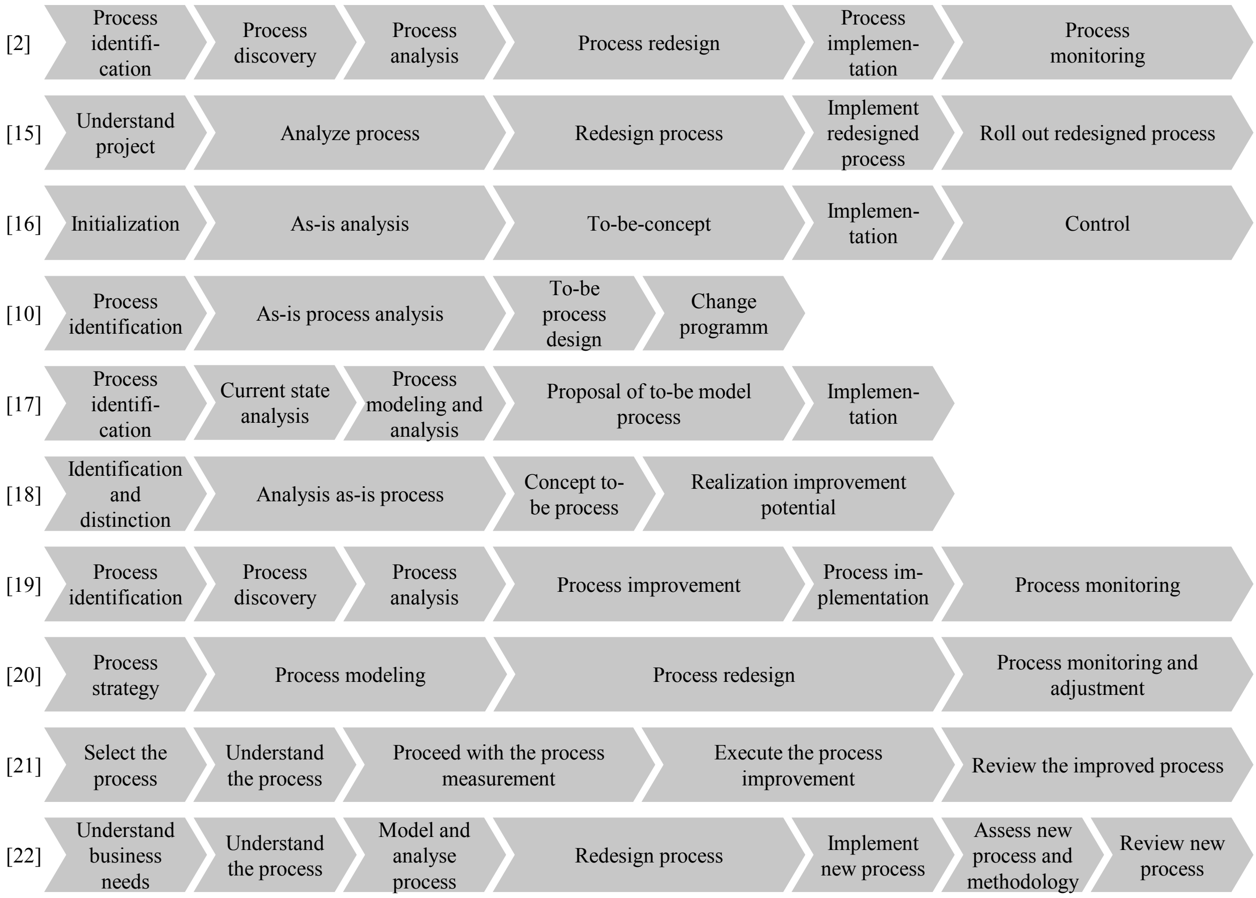

Figure 1: Overview of phase models for business process improvement

The length of the phases graphically illustrates the scope of the tasks contained and thus enables the phase models to be compared regardless of the labelling used. The phase models differ in the scope of the subtasks and the aggregation into main phases. However, their basic logic is similar. Figure 2 consolidates this basic logic of the relevant phase models to a reference phase model.

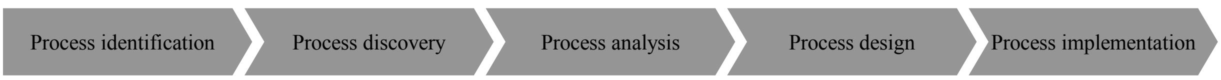

Figure 2: Reference phase model for business process improvement

The reference phase model shall serve as input for the evaluation of adaption needs in chapter 3.2. The consolidation logic and the reference phases are described subsequently. Typically, business process improvement projects are initiated with the **process identification**, e.g. the selection of one business process to be improved in the company. This is followed by the **process discovery**, in which the current as-is process is graphically modelled and documented. In the subsequent **process analysis**, this process model is examined for weaknesses and with regard to its process performance. In some phase models, process modelling and analysis are also combined into one phase and referred to as-is analysis. The process analysis is followed by the **process design**, during which measures to eliminate the process weaknesses and to design an improved to-be process are derived. The final phase following the process design is the **process implementation** of the improved to-be process, in some phase models followed by the monitoring of the implemented process.

For the scope of this paper, the two phases of process analysis and process design are examined more closely and their relevant tasks will be consolidated into a reference process for process analysis and design:

From the examined phase models, four referential tasks emerge for process analysis (cf. Figure 3): qualitative and/or quantitative analysis, validation, prioritisation and documentation. The analysis can be conducted via a variety of qualitative (e.g. value chain analysis, waste analysis) or quantitative (e.g. lead time analysis, queueing theory) methods and is used to identify weaknesses in business processes [2, 23]. Both [2] and [10] include a validation of the manually identified weaknesses. The third referential task within process analysis is the prioritisation of weaknesses according to e.g. their magnitude of impact or effort required to resolve them. Pareto analysis or the decision diagram are possible methods [2]. This requires an assessment of the problems in business processes and serves to concentrate resource allocation on the most severe weaknesses. The last step of the process analysis in the referential phase model is the documentation of the prioritised weaknesses, e.g. in a problem register [2].

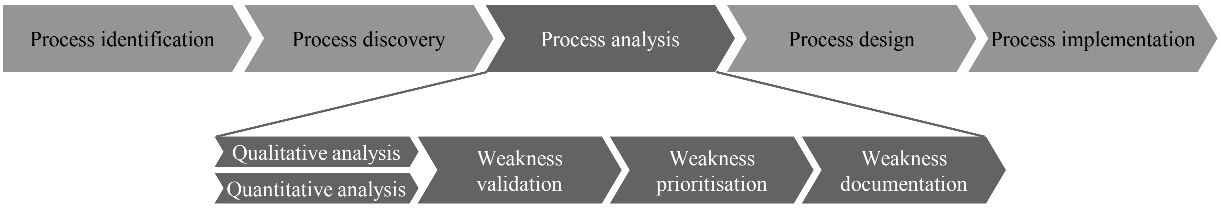

Figure 3: Referential tasks within process analysis

Process design exhibits six referential tasks in the examined phase models (cf. Figure 4): Measure derivation, measure validation, measure quantification, measure prioritization, to-be process design and measure documentation. In the process of measure derivation, creative (e.g. 7FE) or analytical (e.g. improvement heuristics) methods are used to identify measures that solve the identified problems and improve process performance [2]. By conducting workshops, the identified measures can be validated at the same time. In the second step, the identified improvement measures are evaluated (e.g. effectiveness, feasibility, effort) using methods like throughput time analyses, process simulations or cost-benefit matrices [2,4,10]. These and other methods like the Eisenhower matrix or the Pugh matrix enable the subsequent prioritisation of improvement measures [23,24]. The next step is the design of the to-be process. In this process, one or more to-be processes are modelled by application of improvement measures, to cleanse process weaknesses and ideally achieve the process goals. In the case of several to-be process variants, one to-be process model is selected after checking the feasibility, benefit or effort or by assessing through a process simulation. Finally, the last step in process design involves the documentation of the to-be process in a process model.

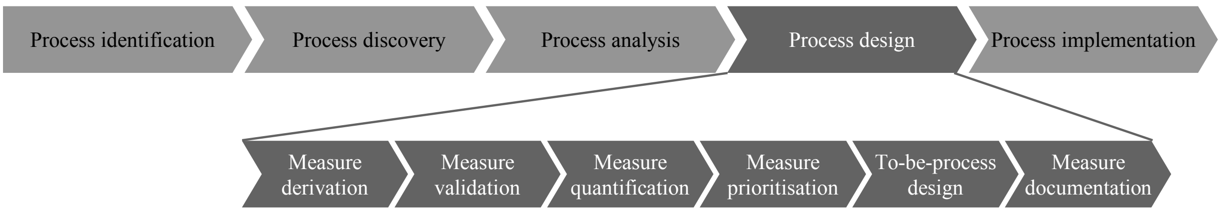

Figure 4: Referential tasks within process design

The reference phase model for process analysis (cf. figure 3) and process design (cf. figure 4) describe their basic tasks in a conventional, for example workshop-based, approach.

3.2 Evaluation on process changes due to decision support

The reference process describes the essential tasks to be executed in the analysis and design of business processes in a conventional, e.g. workshop-based, approach. With the availability of a performance-based decision support that was developed in preliminary work of the authors (cf. [9]) it needs to be examined, how those tasks need to be eliminated, automated, modified or extended. For this purpose, first the functionalities of the decision support developed in [7,8,9] are summarised in Table 1.

Table 1: Functionalities of the databased decision support for process analysis and design

Phase	Functionality
Process analysis	▪ Detection of process weaknesses based on weakness models ▪ Quantification of performance losses (absolute in time, relative in performance) on level of the process instances and the process model for detected weaknesses ▪ Quantification of process performance for process instances and process model ▪ Prioritized documentation of process weaknesses according to performance impact
Process design	▪ Derivation of suitable measures to solve detected process weaknesses ▪ Quantification of measures' performance potentials (absolute in time, relative in performance) on level of the process instances and the process model ▪ Prioritized documentation of measures according to performance potential

These functionalities can be executed for an event log of a business process which serves as input for the databased decision support. Due to their automation in the decision support, the following related tasks from the reference phase model (cf. chapter 3.1) can be automated: process weakness detection in qualitative process analysis, process weakness quantification in quantitative process analysis, process weakness prioritization, process weakness documentation, measure derivation, measure quantification, measure prioritization, measure documentation. The functionality *Quantification of process performance for process instances and process model* extends the tasks of the reference model, since this was typically not possible in non-databased approaches. The remaining delta between the functionalities of the decision support and the reference process for process analysis and design is in the weakness validation and the measure validation. These tasks are not automatable due to the required context knowledge (e.g. about the company and the specific business process) and remain to be conducted manually. Additionally the prioritization of measures can only be semi-automated as the decision support only considers time-based performance. In practice, however, potential measures for process design need to be assessed with regard to additional criteria such as effort, costs, implementation time, etc. Due to the extensive automation of process analysis and design through the decision support, the general structure of existing phase models is no longer appropriate. For this reason, a completely new approach to the analysis and design of business processes is required.

3.3 Hybrid procedure for data-supported business process analysis and design

Following the conclusion of chapter 3.2 a completely new procedure for process analysis and design in manufacturing companies is developed in this chapter. Due to their extensive automation the two phases of process analysis and design are merged into one phase, in which detected weaknesses and suitable measures are examined simultaneously. Within this common phase, the procedure also differs considerably from the reference process. Whereas the reference process was structured sequentially according to the tasks of process analysis and design, the new procedure is structured around the decision support in preparatory, executing and processing-decision phases. This results in a procedure including the four sub-phases

Configuration of the decision support*,* **Execution** of the decision support, the **Process Exploitation** and **Process Exploration** (cf. Figure 5). The **Execution** is fully automated by the decision support, the other phases require preparatory actions or decisions by users. In the following, the tasks within these four sub-phases are detailed.

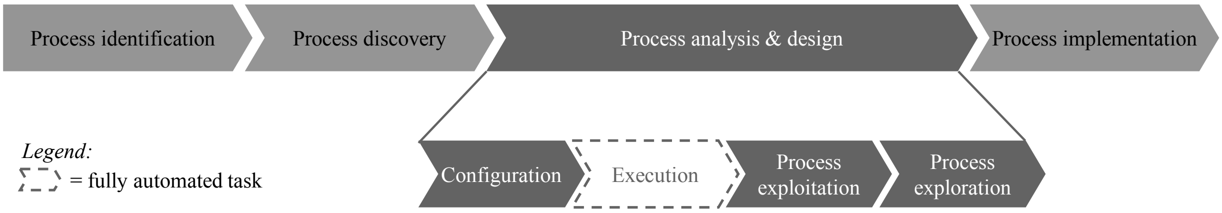

Figure 5: Phase model for hybrid process analysis and design

The sub phase **Configuration** serves to pre-process the data of the event log and to configure the decision support for the application context of the company and the business process to be examined. First, an event log with the attributes process instance, activity, start time and end time is extracted for the business process to be analysed. If in a business process improvement project, the process mapping was conducted with process mining, this event log can be used. Further, the execution time and the upstream transition time are added for each event in order to detect non-realistic outliers (e.g. due to incorrect bookings) via statistical scatter measures. These outliers could influence the detection of the process weakness types *unsuitable scope* and *transition time* (cf. weakness types in [7]) and need to be eliminated from the event log to be examined. In each individual case, a decision must be made whether to eliminate the entire process instance or - if possible - to correct the time. This concludes the data pre-processing as the first task within the configuration phase. Subsequently, the configuration of the data-based decision support for the process analysis and design is conducted for the given context of company and the business process to be analysed. The configuration is ideally carried out in collaboration between an internal process expert and an external method expert. The internal process expert can decide, which of the weakness types shall be applied to the event log. Additionally, he can configure the weakness types developed in [7], e.g. the upper limit of the variation of execution times for the weakness type unsuitable scope or the list of unwanted activities to be detected. If required, the process expert is also able to define new, context dependent weakness types that shall be detected in the event log in accordance to the formalization logic of [7]. Analogously, the measure types are configured. In particular it is defined, to which extent the measures are capable of reducing the performance loss of the related process weakness. This applies to the measure types *reduction of transition time* and *acceleration* (cf. measure types in [8]) that use historic process times to calculate their performance potential. By setting a quantile value, the internal process expert can determine which quantile of historical best times should be considered as realistic and permanently achievable for a to-be process. If required, new, context dependent measure types can be modelled in accordance to the formalization logic of [8]. After this step, the data-based decision support is fully configured for application to the event log of the business process.

The subsequent sub-phase **Execution** begins with the application of the selected, configured and potentially added weakness models to the pre-processed event log to detect process weaknesses. These are added to the event log at the associated event. Transition times are noted to the event following the transition time. The weakness quantification adds the absolute influence of each process weakness on the process time and affected OPE loss type in the process performance key figure OPE[1]to the event log (cf. performance-based decision support in [9]). Single events and their inherent execution and transition times can be affected by several process weaknesses. A multiple consideration of single times would incorrectly reduce the process performance OPE. To avoid this multiple consideration, a weakness hierarchy defines the process performance relevance of detected process weaknesses. Subsequently, the relative OPE performance losses

[1] OPE = Overall Process Efficiency, a holistic key figure for process performance as defined by [9]

at process instance level and process model level are quantified for each process weakness added to the event log. In parallel, a list with all process weaknesses as well as supplementary information (e.g. affected event, loss type, absolute loss, relative loss) is generated. In addition, the total loss time is quantified at the levels of process instance and process model. Furthermore, the absolute and relative values of the loss types (e.g. continuity, linearity and performance loss) are calculated at level of process instance and process model based on the loss type assigned to each process weakness. The performance evaluation of the business process concludes with the calculation of the process performance OPE per process instance and for the entire process model. The functions and calculations presented so far concern the data-based decision support for the process analysis. The data-based decision support for process design starts with the allocation of measures to detected process weaknesses according to process weakness-measures matrix [8]. These measures are added to the extended event log and the process weakness list. After the measure assignment, the measure quantification is done as absolute time values as well as relative OPE potentials on levels of process instance and process model. This information is shown in the extended event log and the process weakness list. The extended event log only serves as a data basis for decision support. The process weakness list serves as a basis for decision-making in the subsequent sub-phase of exploitative process analysis and design. To enable prioritization, the process weakness list is sorted in descending order according to the magnitude of the OPE loss caused by detected process weaknesses at overall process level. This allows limited resources to be focused on particularly serious problems in practice. It is noteworthy that the execution phase fully automates the described tasks so that they are executed almost simultaneously in a very short time. Therefore, despite the numerous tasks, the execution phase substitutes high-efforts for conducting process analysis and design in workshops.

After the automated execution of decision support, all information about process weaknesses, measures and process performance is available for the as-is process. In **Process exploitation**, the decision-relevant information is validated and decisions are made regarding the analysis and design of business processes. Due to its characteristic of incremental process improvements through weakness elimination this phase is called *exploitative* following the logic of [25]. The automated decision support allows an iterative procedure in exploitative process analysis and design, in which single process weaknesses are examined individually. Thereby, the weakness list enables to examine process weaknesses with major impact with priority. This iterative approach allows a flexibly extensive process analysis and design depending on the availability of resources. As a first step in exploitative analysis, the process expert selects any process weakness from the prioritised weakness list (e.g. the process weakness with the highest OPE loss at the overall process level) for detailed analysis. Further, it needs to be validated whether the detected process weakness is actually a process weakness in the context of the investigated business process. Invalid process weaknesses are excluded from the OPE calculation and marked as processed and non-valid in the process vulnerability list. In the case of overlapping process vulnerabilities, the process vulnerability next in the process vulnerability hierarchy becomes OPE relevant. After successful validation of the process vulnerability, potential measures to remedy the process weaknesses are presented to the user including their OPE potential. On this basis, the process expert can assess whether and which measure to select for the process weakness under examination. In addition to the OPE related information in the decision support, the process expert must consider contextual factors for the operationalisation of the measures (e.g. effort, investment, implementation time). The decision on measures in process design therefore involves multiple criteria, of which the data-based decision support automatically quantifies and provides the criterion *benefit for process performance*. When a measure is selected, this measure is transferred into a list of action measures, which serves as the basis for the process implementation. In addition, the event log is manipulated, so that the changes caused by applied measures (e.g. activity elimination) become visible in all process instances. Additionally, the OPE at process instance and overall process level is also increased. This iterative procedure of process weakness examination is repeated at the discretion of the process expert until a satisfactory OPE level is reached, all process weaknesses have been examined or the process analysis and design needs to be terminated due to resource constraints (e.g. time). At the end of this iteration, the process instances of the process model are manipulated by the application of measures and the theoretical OPE of these process instances are known. Among all process instances of the examined business process, the manipulated (historic) process instance with the highest OPE is proposed as the basis for the to-be process. The final selection remains with the process expert, who can display the process model for each process instance.

The last phase of **Process exploration** consists of three tasks. In the first step, a to-be process needs to be generated from the selected manipulated (historic) process instance with the highest OPE. Its process structure is derived from the event IDs or the time sequence of the selected process instance. The to-be execution and transition times can be derived from the manipulated event log. On this basis, a synthetic event log for the target process model can be generated by setting a calculatory start time stamp of the first event to a *zero time*, e.g. 01.01.1900 at 00:00:00 and modelled with process mining discovery algorithms. In the second step, parallelization potentials become visible by discovering the synthetic event log and using the weakness information from the decision support. Contrary to the OPE, the calculation of throughput times in this step enables the quantification of the time potentials through parallelization. In the third step, the actual exploratory improvement of the synthetic process instance to a to-be process model takes place. Here, the process expert can improve the business process beyond the standard improvements of the decision support by applying individual contextual knowledge about the process or creative solution approaches. An example would be the elimination of several activities through a novel technological solution or outsourcing. The implementation in the process model is done by shifting or eliminating activities with adaption of the associated execution and transition times. The implementing software solution should enable intuitive adaptations directly in the process model for both parallelisation and exploratory process analysis and design. These changes in the user interface then need to alter the event log of the underlying synthetic process instance. Thus the effects of the explorative improvements by the process expert on OPE and the throughput time can be calculated and made available to support decision-making.

4. Conclusion

The performance of business processes is a critical success factor for manufacturing companies on competitive markets. Available methods for business process improvement are driven by high efforts and subjective influences, why business process improvement projects regularly fail to fulfil their expectations. In previous research the authors have developed a databased decision support which semi-automates process analysis and design. Together with process mining discover methods for process mapping this decision support is the key lever for reducing efforts and subjectivity in business process improvement. For its application in practice, however, the databased decision support needs a procedure. Conventional phase models for business process improvement are no longer applicable after the significant automation of the included tasks.

This paper provides an approach, how the databased decision support for business process analysis and design can be applied for business process improvement in practice to reduce efforts and subjectivity. For this purpose, existing phase models for business process improvement are consolidated into a reference model in a first step. A second step examines to which extent the functions of the decision support substitute, modify or extend the tasks of business process improvement. On this basis, a hybrid procedure for process analysis and design using the decision support is designed. This paper’s approach makes the preliminary developed decision support applicable for business process improvement in practice. Thereby it levers objectivity and methodological efficiency, while at the same time integrating formalized methodological knowledge, context-specific expert knowledge and creativity to improve business processes.

Future research should address the development of user interfaces to enable technical applicability of the databased decision support in practice. Based on the procedure developed in this paper, requirements for a user interface can be derived, that leads the user through the hybrid process analysis and design. Furthermore, future research can investigate in the integration of process mining discovery and the decision support to offer a holistic event log-based solution for business process improvement. Lastly, it could be examined if modern process mining solutions enable process simulation to further enhance the functionalities of the databased decision support.

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References

[1] Quick, D., Eissen, J., Genge, N., 2019. How Intelligent Processes Differentiate Best-Run Businesses in the Digital Economy. Using Process Mining and Process Monitoring to Create a Foundation for Data-Based Process Excellence, pp. 1-27.

[2] Dumas, M., La Rosa, M., Mendling, J., Reijers, H.A., 2021. Grundlagen des Geschäftsprozessmanagements, Springer, Berlin.

[3] Povey, B., 1998. The development of a best practice business process improvement methodology, in: Benchmarking for Quality Management & Technology, vol. 5, no. 1, pp. 27–44.

[4] Schmelzer, H. J., Sesselmann, W., 2020. Geschäftsprozessmanagement in der Praxis. Kunden zufrieden stellen - Produktivität steigern - Wert erhöhen, vol. 9, Hanser, Munich.

[5] Bergener, P., Delfmann, P., Weiss, B., Winkelmann, A., 2015. Detecting Potential Weaknesses in Business Processes, published in: Business Process Management Journal, vol. 21, no. 1, pp. 25–54.

[6] Schuh, G., Guetzlaff, A., Schmitz, S., Schopen, M., Broehl, F., 2021. Event log-based weakness detection in business processes, published in: 2021 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), pp- 734-738.

[7] Schopen, M., Schmitz, S., Guetzlaff, A., Schuh, G., 2022. Data-based measure derivation for business process design, accepted for publication in: Proceedings of the 12th Congress of the German Academic Association for Production Technology (WGP). Stuttgart.

[8] Schuh, G., Guetzlaff, A., Schmitz, S., Schopen, M., Obladen, A., 2022. Performance-based decision support for business process analysis and design, accepted for publication at 2022 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM).

[9] Falk, T., 2017. Evaluation of a Pattern-Based Approach for Business Process Improvement, in: Leimeister, J. M., Brenner, W., Proceedings der 13. Internationalen Tagung der Wirtschaftsinformatik – Towards thought leadership in digital transformation, pp. 241–255.

[10] Schuh, G., Kampker, A., Stich, V., Kuhlmann, K., 2011. Prozessmamagement, in: Schuh, G., Kampker, A.: Strategie und Management produzierender Unternehmen, 2nd ed., Springer-Verlag Berlin Heidelberg, Berlin.

[11] Front, A., Rieu, D., Santorum, M., Movahedian, F., 2017. A participative end-user method for multi-perspective business process elicitation and improvement, in: Software & Systems Modeling, Springer-Verlag Berlin Heidelberg.

[12] Cherni, J., Martinho, R., Ghannouchi, S. A., 2019. Towards improving business processes based on preconfigured KPI target values, process mining and redesign patterns, in: Procedia Computer Science, vol. 164, pp. 279-284.

[13] Graafmans, T., Turetken, O., Poppelaars, H., Fahland, D., 2021. Process Mining for Six Sigma. A Guideline and Tool Support, in: Business & Information Systems Engineering, vol. 63, 3 ed, pp. 277-300.

[14] Niedermann, F., 2015. Deep Business Optimization. Concepts and Architecture for an Analytical Process Optimization platform.

[15] Harmon, P., Rosemann, M., 2019. Business Process Change: A Business Process Management Guide for Managers and Process Professionals, Morgan Kaufmann San Francisco, California.

[16] Horatzek S., 2019. Toolbox Prozessmanagement: Vorgehensmodell und praktische Methoden für Industrie und Dienstleistung, Carl Hanser Verlag GmbH & Co. KG, München.

[17] Djedović, A., Žunić, E., Karabegović, A., 2017. A combined process mining for improving business process

[18] Wagner K. W., Patzak G., 2020. Performance Excellence – Der Praxisleitfaden zum effektiven Prozessmanagement, Carl Hanser Verlag GmbH & Co. KG, Munich.

[19] Hansen, H. R., Mendling, J., Neumann, G., 2019. Wirtschaftsinformatik, Walter de Gruyter GmbH & Co., Berlin.

[20] Pereira, V. R., Maximiano, A. C. A., de Souza Bido, D., 2018. Resistance to change in BPM implementation.

[21] Lee, K. T., Chua K. B., 2001. A super methodology for business process improvement: An industrial case study in Hong Kong/China, in: International Journal of Operations & Production Management, vol. 21, no. 5/6, pp. 687-706.

[22] Adesola, S., Baines, T., 2005. Developing and evaluating a methodology for business process improvement, in: Business Process Management Journal, vol. 11, no. 1, pp. 37-46.

[23] Tenera, A., Pinto, L. C., 2014. A Lean Six Sigma (LSS) project management improvement model.

[24] Hofmann, M., 2020. Prozessoptimierung als ganzheitlicher Ansatz, Springer-Verlag Berlin Heidelberg New York.

[25] Rosemann, M., 2014. Proposals for Future BPM Research Directions, in: Van der Aalst, W., Mylopoulos, J., et al., Asia Pacific Business Process Management, vol. 181, pp. 1-15.

Biography

Günther Schuh (*1958) holds the Chair of Production Systems at the Laboratory for Machine Tools and Production Engineering WZL at RWTH Aachen University, is a member of the board of directors of the Fraunhofer Institute for Production Technology IPT and director of the Research Institute for Rationalization (FIR) at the RWTH Aachen.

Seth Schmitz (*1991) studied Business Administration and Engineering specializing in Mechanical Engineering at the RWTH Aachen University and Tsinghua University. He is Head of the Production Management Department at the Laboratory for Machine Tools and Production Engineering WZL at RWTH Aachen University.

Marco Schopen (*1993) studied Business Administration and Industrial Engineering at University of applied Sciences Aachen. He is Team Lead Process Management in the Production Management department at the Laboratory for Machine Tools and Production Engineering WZL at RWTH Aachen University.

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Synergy Analysis Methodology For Decreasing Fuel Cell Production Costs

Heiner Hans Heimes[1], Achim Kampker[1], Mario Kehrer[1], Sebastian Hagedorn[1*], Niels Hinrichs[1], Tobias Pfeifer[1]
1 Production Engineering of E-Mobility Components (PEM) of RWTH Aachen University, Bohr 12, 52072 Aachen
* Corresponding author

Abstract

For meeting CO2 emission targets in the mobility sector, decarbonization efforts of referring applications are necessary. Fuel Cell electric vehicles powered by hydrogen demonstrate a viable option to achieve those targets, especially taking the targets of heavy-duty applications into consideration. Higher ranges, short fueling durations and locally emission-free transport represent advantages offered by Fuel Cells in comparison to internal combustion engines or battery-electric powertrains.

However, production costs of Fuel Cells are still a major drawback. Latest analyses show that the utilization of scale effects even in early technology adaption phases can heavily decrease production costs. As the cell structure of Fuel Cells and Electrolyzers show many similarities, the assumption of production synergies is made. Taking advantage of referring synergies, increased production volumes and thus decreased production costs are assumed for both, Fuel Cells and Electrolyzers.

This paper introduces a methodology to identify synergies between Fuel Cell and Electrolyzer production. The methodology is used to evaluate a company's production process portfolio on the example of the three alternative coating processes and a target product, based on an initial evaluation of the processes and the use of the Analytic Network Process. The application of the methodology results in synergy coefficients for production processes, using the exemplary portfolio consisting of slot die, gravure and spray coating. The coefficients are transferred into an overall benefit of a production process portfolio. Finally, the effect of the considered synergies between Fuel Cell and Electrolyzer production on the overall benefit of a company's production process portfolio is visualized. This paper is concluded with a critical review of the methodology and a summary of further research.

Keywords

Fuel Cell; Fuel Cell Production; Electrolyzer; Production Costs; Synergy Analysis; Economies of Scale; Production Process Portfolio; Analytic Network Process; Coating Process

1. Introduction

To address the climate crisis, a large number of comprehensive challenges need to be solved to prevent irreversible damage to the climate system. Consequently, it is essential to reduce CO2 emissions in all sectors as these are directly related to climate change [1]. In order to reduce the emissions in the transport sector, the main aim is to increase the percentage of electric driven vehicles, especially in heavy road and freight transport. To achieve this, various alternative drive systems are currently being researched.[2] Polymer-Electrolyte-Membrane (PEM) Fuel Cell (FC) electric driven vehicles and hydrogen as an alternative fuel promise high potential. Due to short refueling durations, long ranges and locally CO2 neutrality, the PEMFC

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is a potential complement to conventional battery electric driven vehicles, that are indispensable in the passenger car segment and lower loads. This will expand the variety of electric vehicles and take a step towards a CO2 neutral heavy road and freight transport.[3]

For increasing Fuel Cell electric vehicle (FCEV) competitiveness compared to conventional Internal Combustion Engine (ICE) vehicles, investment costs must be reduced. FCEVs are up to 60% more expensive than diesel vehicles, with about 35% of the costs being determined by the Fuel Cell system. Another cost factor is hydrogen as the fuel for the alternative powertrain.[4] Hydrogen fuel is currently up to 90% more expensive than conventional fuels which is partly due to the production costs of the PEM Electrolyzer (EL) components [4]. Due to the largely identical design of PEMFC and PEMEL cells, synergies are assumed to exist in particular in the production processes. This paper is focussing the hypothesis that the exploitation of synergies results in a sustainable reduction of PEMFC and PEMEL production costs especially in early technology adaption phases. Thus, a methodology is developed to identify and examine synergies between the production processes in order to prioritize the utilization of different production processes of PEMFC and PEMEL.

2. Objectives and state of the art

2.1 Introduction in the field of electrochemical energy converters

PEMFC and PEMEL are assigned to the electrochemical energy converters that either use hydrogen and oxygen to produce electricity nor water and electricity to produce hydrogen. Basically, different types of PEMFC and PEMEL exist, whereby the used electrolyte, operation temperature and the conducted ions are the main criteria to divide PEMFC in seven and PEMEL in three categories.[5] Although each type has its advantages, PEM technology is considered to have the highest future potential in terms of variety in applications and robustness in operation for both, PEMFC and PEMEL.[6] The main field of application for PEMFC is the automotive sector due to their potential for dynamic operation strategies as well as their lower operating temperatures compared to other Fuel Cell technologies. Furthermore, PEMFC are able to be used in the field of stationary power generation. PEMEL also show advantages to other Electrolyzer technologies, especially due to its higher efficiency and the ability to take up huge overloads. The latter will become more important, as future energy systems will be operated in a more dynamic manner due to the use of volatile energy sources.[3] Thus, this paper focuses on PEM technologies.

2.2 State of the art of PEMFC and PEMEL cell architecture

In Figure 1, the typical structure of a PEMFC and PEMEL with their main functional layers is shown. A polymeric membrane represents the core of a PEMFC. This membrane is used to transport protons between the anode and the cathode and to separate the reaction chambers of the cell from each other.[6] To accelerate the dissociation process of hydrogen and oxygen, a catalyst layer (CL) is applied to the membrane [7]. The CL usually consists of a platinum-based catalyst, ionomer and a carbon support to further increase the electrochemical surface area and forms the electrode [8]. Both, PEM and CL, yield the Catalyst Coated Membrane (CCM) [9]. The gas diffusion layer (GDL) is attached on both sides to the CCM, contributes to a homogeneous distribution of the reaction gases over the entire cross section of the electrodes active area and conducts the charge carriers [7], [10]. A micro porous layer (MPL) is applied to the GDL and improves water management in the whole system [11]. CCM and GDL represent the Membrane-Electrode-Assembly (MEA). As one single PEMFC produces one voltage, multiple cells need to be stacked and electrically connected in series. Therefore, Bipolar plates (BPP) finalize the package and mainly take responsibility for electrical contacting the various cells, provide mechanical stability and feed the cells with the product gases. [6]

The assembly of an PEMEL cell is comparably similar to PEMFC. Nevertheless, several differences can be observed mainly at anode side of a PEMEL cell as a chemical potential of up to two volts is prevailed. Thus, titanium is used for the BPP, layered expanded metals of titanium form the Porous Transport Layer (PTL), which is the counterpart of the PEMFC GDL and iridium oxide is used as the catalyst. Furthermore, the membrane in PEMELs is thicker than in the PEMFC as operating with differential pressures of up to 50 bar(a) improves hydrogen storage efficiency, but doesn't differ in material or structure.[6], [12]

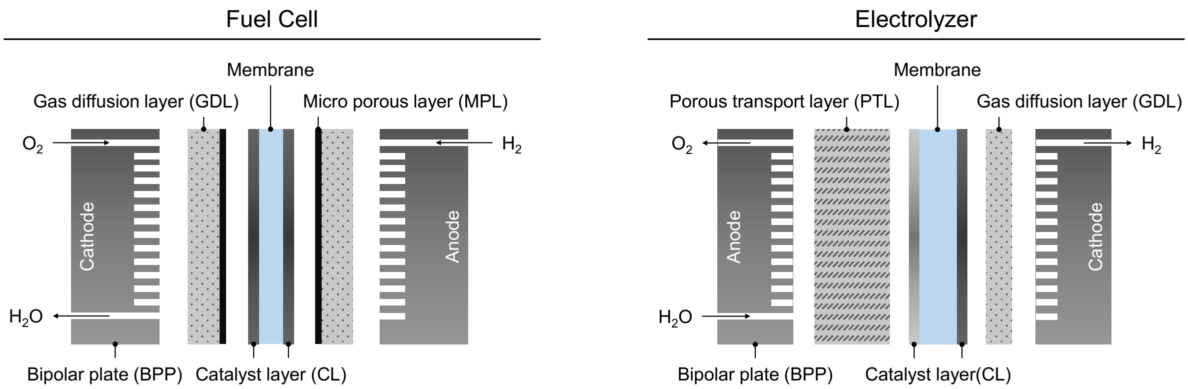

Figure 1: Product architecture of PEMFC and PEMEL [6], [13]

The similarities described between the two cell architectures suggest that there are synergies between the two products that can be exploited. Therefore, the production processes need to be examined in order to confirm this assumption.

2.3 State of the art of PEMFC and PEMEL catalyst coating

Catalyst coating processes for PEMFC and PEMEL do not greatly differ between the two technologies and are still accompanied by several challenges against the background of a high-volume production (Figure 2). In order to demonstrate the method presented later, three processes that are usually used in small- to large-scale production environments will be described more in detail: Spray, slot die and gravure coating.

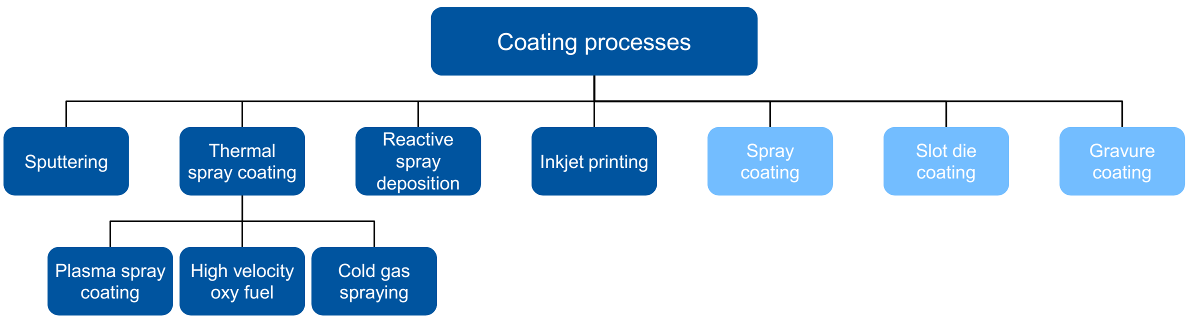

Figure 2: Overview coating processes for electrochemical energy converters [14], [15], [16], [17], [18], [19], [20], [21], [22]

In the three processes, the CL can either be applied in a direct manner to the membrane or GDL, or in an indirect manner to a transfer Decal foil. A Decal foil is a PTFE-based foil, that is used in combination with an additional hot press process to transfer the CL to the membrane or GDL. In case, the CL is applied to the membrane, the final product type is the CCM; at the GDL, the product is called GDE.[23]

In spray coating, the CL is built up layer by layer by multiple pre-defined spraying paths, that allows high homogeneity and precise adjustment of the catalyst loading [24]. Due to the layered structure, the process is usually used for small series production and is characterized by a higher production duration [24,25]

In slot die coating, the catalyst is applied through a slot die in a continuous roll-to-roll process. The layer thickness of the CL is adjusted by the gap between the slot die and the substrate.[15] By aligning the substrate vertically, its both sides can be coated simultaneously. This saves installation space in the coating machine but is only conceivable when direct coating the membrane.[26]

In (roto-)gravure coating, the catalyst ink is applied to the substrate by a roller with incorporated structures in a continuously manner. Due to its viscosity, the ink adheres to the structures and is then applied to the substrate. The thickness of the CL is adjusted by the relative speed difference between the roller and the substrate, by varying the incorporated structures of the roller, and by the properties of the catalyst ink (Figure 3).[16]

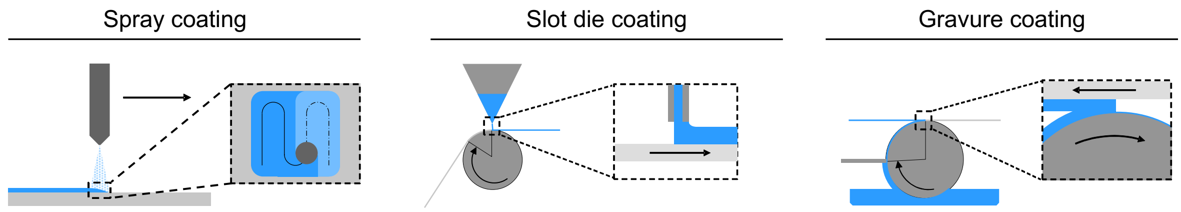

Figure 3: Process details spray coating, slot die coating and gravure coating [14], [27], [28]

2.1 Methodological approaches already existing

The Analytic Network Process (ANP) approach according to SAATY is considered for a multi-criteria evaluation of quantitative and qualitative characteristics through an individual assessment of objectives, target criteria and components. The approach according to LI ET AL. is considered for synergy identification according to the ANP procedure. The general definition of synergies according to WÖGINGER is described as well and its proposed positive and negative synergy categories. In general, synergies can be defined as the effect of increasing the benefit of a totality of sub-elements compared to the sum of the benefits of the individual sub-elements on its own. In this paper, in comparison to positive synergies, negative synergies can occur when the sum of the individual benefits exceeds the total benefit. Positive synergies usually have to be actively pursued in order to occur. Negative synergies, on the other hand, occur undesirably and unplanned.[29]

2.1.1 Analytic Network Process according to SAATY

In the ANP according to SAATY, the objectives, target criteria and components are compared in pairs to form a control component. From the pairwise comparisons, prioritization vectors are generated. Individual prioritization vectors are collected in a supermatrix. Apart from the direct influences of the components to each other, also indirect influences between components exist. Such indirect influences are developed by the direct influence on a third component, which itself interacts again with one of other components. These indirect chained influences are then combined with the supermatrix to form the boundary matrix. Prioritization factors of the considered components are calculated taking the indirect influences of the components to each other into account. This consideration is likewise applicable under the target criteria and objectives, if dependencies exist. SAATY additionally introduces an inconsistency ratio in order to detect inconsistencies in the individual pairwise comparisons. [30]

2.1.2 Synergy Identification approach according to LI ET AL.

An approach for synergy investigation based on the ANP is presented by LI ET AL. The methodology is used to identify the best combination of individual processes considering the synergies among them. For this purpose, the processes are first evaluated in the categories of cost, quality, time, service, resource consumption and environmental impact. Following, the processes are referred to as components. The categories are weighted relative to each other and for a quantitative evaluation, subcategories are assigned to each of these categories. The subcategories within a category are weighted likewise relative to one another. Subsequently, a value from zero as "very poor" to ten as "very good" is assigned to the considered component. The evaluation results in the direct benefit of the respective components.[31]

The components are following compared with each other using the ANP according to SAATY. For this, the components are compared with each other to maximize the total benefit as the overall target. Further, the individual components are compared to the control component pairwise with one another to form the supermatrix and further computing the boundary matrix. The values of the boundary matrix are defined as synergy coefficients, which need to be offset with the ratios for the direct benefit of a component portfolio to calculate its total benefit. [31]

2.1.3 Synergy Definition according to WÖGINGER

According to WÖGINGER, positive and negative synergies exist, which will be further considered in the Synergy Analysis methodology. Positive synergies are represented by knowledge transfer between two production processes. This effect occurs, when a company has different product programs that have similarities in process parameters, resources and capabilities. Furthermore, economies of scale occur with an increased output quantity of a product, which is accompanied by cost reduction per unit. WÖGINGER additionally classifies synergies that increase the company's sales and market power through the development of new markets or the expansion of the product range as growth synergies. Diseconomies of scales represent negative synergies and occur, when the output quantity is increased above a company-specific optimum and thus results in cost increase per unit. After describing different types of synergies, WÖGINGER introduces the realization probability as an additional factor. The probabilities range from 100% for "expected" to 10% for "hypothetical" realization probability.[29]

2.1.4 Comparison of the presented approaches existing in the literature

In order to evaluate the presented approaches, a set of requirements has to be defined. First of all, the coverage of a given data basis is needed in a detailed and structured manner by the approaches. Another requirement is the general applicability of an approach on a predefined scope. Additionally, the utilization of an approach to analyze quantitative as well as qualitative criteria has to be ensured. As a final requirement, the approach should provide a guideline for classifying and identifying positive and negative synergies. The evaluation of the previously introduced approaches is illustrated in Figure 4.

Evaluation criteria	Approach according to LI ET AL.	Approach according to WÖGINGER
Coverage of a given data basis	✓	O
General applicability	✓	—
Qualitative and quantitative analysis	O	O
Classifying and identifying synergies	—	O

✓ Fulfilled   O Partially fulfilled   — Not fulfilled

Figure 4: Comparison and evaluation of existing literature approaches for synergy analysis [31], [29]

The method according to LI ET AL. combines a comprehensive qualitative evaluation of different components. As a result, a value for the total benefit of the component portfolio is given, which enables the comparability of different portfolios. In addition, the approach provides a detailed and structured coverage of a given data base. Likewise, the method allows a general applicability, which makes a reformulation to application-specific considerations possible. However, only the qualitative evaluation of the methods is presented and the implementation of quantitative features is not further discussed. Furthermore, no guideline for synergetic classification and synergy identification is described. [29]

The method according to WÖGINGER offers a detailed elaboration of the synergy definitions and considerations. Thus, it provides a mature definition framework that can be used to guide the formulation of application-specific synergies. However, the method requires detailed quantified data and only cost factors are included in the evaluation. Thus, a methodology for quantifying qualitative characteristics has to be developed beforehand.[31]

Taking these results into account, a methodology to systematically consider and evaluate synergies in production processes and referring company process portfolios has to be conceptualised. Furthermore, the influence of individual synergies on the total benefit of company's production process portfolio has to be analysed.

3. Methodological concept

3.1 General structure of the methodology

The objective of the methodology is to maximize the benefit of a portfolio of components. Following, the methodology will be enhanced by a dedicated synergy analysis. To evaluate the portfolios, the benefits of the individual components are first assessed. Subsequently, synergies are identified and coefficients of the components are determined. The synergy coefficients and the direct benefit of the components are used to calculate the total benefit of a portfolio of components (Figure 5).

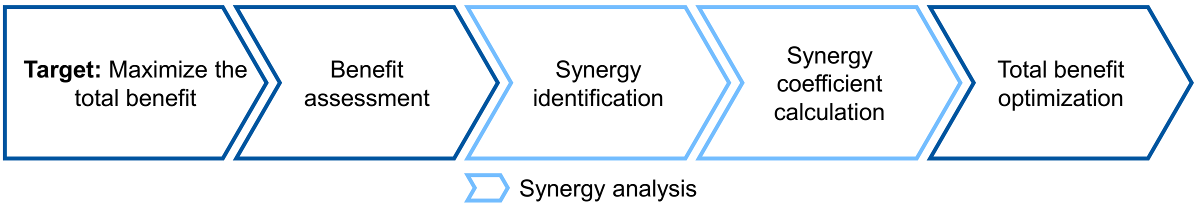

Figure 5: General structure of the methodology for benefit optimization enhanced by synergy analysis steps

3.2 Objective

The objective of the methodology is to maximize the total benefit of a portfolio of components. This objective assumes, that not every component is selected for the portfolio from an existing number of components. Accordingly, the best combination of components has to be identified so that the overall benefit of the portfolio is maximized.

3.3 Benefit assessment

In the benefit assessment, the categories and subcategories are defined and weighted. An ANP approach is used in order to compare more than two categories to each other and minimize inconsistencies. A "zero" to "nine" scale is used to evaluate the components following a standardization towards the best value within the scale. The direct benefit of a component is calculated according to LI ET AL (see Formula 1) [31].

$$u_n = \sum_{p=1}^{P} d_p \sum_{m=1}^{M_p} c_{pm} u_{npm} \tag{1}$$

In Formula 1, u_n defines the direct benefit, P defines the number of categories, d_p defines the weighting of the category p, M_p defines the number of subcategories of the category p, c_{pm} defines the weighting of the subcategory m of the category p and u_{npm} defines the evaluation of the component n in the subcategory m of the category p.

3.4 Synergy identification

In order to identify synergies between individual components, an identification process is performed for each component (see Figure 6). Therefore, each component is considered once as an identification component to determine the synergies of the other components to that identification component. Subsequently, the synergies are quantified by taking referring realization probabilities into account. The result are synergy values of the individual components to an identification component which is represented in Figure 6.

3.5 Synergy coefficient calculation

To calculate synergy coefficients, the approach of LI ET AL. is conducted based on an ANP approach. For this purpose, the synergy values and the direct benefit values are used. In an initial comparison matrix, the components are compared to the control component of the direct benefit. Subsequently, the components to be considered are listed once each as control components. The remaining components are then compared in their synergy count values to the control component in pairs. The prioritization vectors of the different comparison matrices are collected in a supermatrix and the boundary matrix is calculated. The row entries of the boundary matrix form the synergy coefficients of the components of the respective row. The synergy coefficients describe in their height the number of synergies to the other components (Figure 6). Within the example illustrated in Figure 6, the Decal Fuel Cell approach shows the highest synergy coefficient and thus the highest synergy in total compared to the other two production approaches itself.

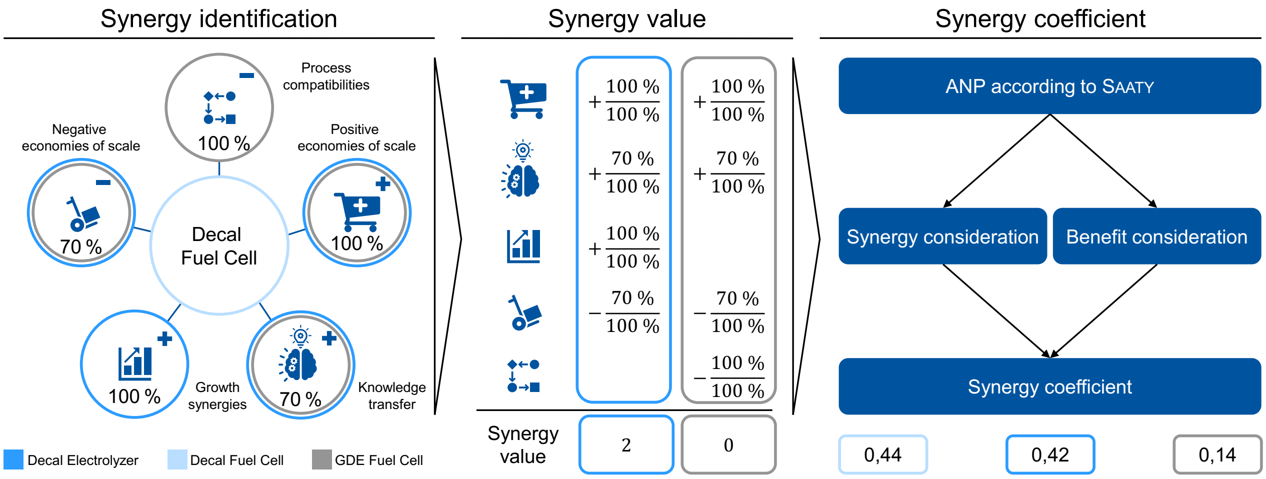

Figure 6: Synergy Analysis steps of the methodology

3.6 Total benefit optimization

The total benefit of a component portfolio is calculated according to LI ET AL. and is illustrated in Formula (2) [31]. For this purpose, the direct benefits of the individual components are set against the referring synergy coefficient.

$$U = \sum_{n=1}^{N} u_n(1 + s_n) \tag{2}$$

In Formula (2), U defines the total benefit of a portfolio, N defines the number of components in a portfolio, u_n defines the direct benefit of component n and s_n defines the synergy coefficient of component n.

4. Model application

4.1 Use case definition

The methodology is applied to a use case in which production process portfolios of spray, slot die and gravure coating are investigated. Therefore, the coating processes in the three possible coating concepts CCM, GDE and Decal transfer are being investigated. In this use case, the Decal transfer considers only the application to the membrane (Decal (CCM)). In addition, the expansion of the product portfolio to the production of PEMEL applications is also being considered.

Based on the state of the art of coating processes, for spray coating 75 nozzles are connected in series and 160 layers are assumed for the CL. For slot die coating, double-sided coating across the full width of the substrate is assumed. For gravure coating, only a single-sided coating process is possible in this case.

The identified synergies are based on the approach by WÖGINGER and extended by the synergy of the process compatibilities. The synergy of process capability illustrates, whether the integration of a further coating concept to a machine requires major or minor equipment changes.

4.2 Results and discussion

4.2.1 Results

In Table 1 the results of the total benefit calculation for exemplary portfolios are illustrated. It can be seen that the three coating processes achieve their highest values in the overall benefit in different portfolios of coating concepts. While slot die coating has its highest total benefit in the first portfolio, spray and gravure coating achieve this in portfolio two. This is due to the implementation of two-sided coating in slot die coating for the CCM concepts. Spray coating can be identified as the coating process with the lowest priority. This is mainly due to the long process time, which is still disadvantageously compared to roll-to-roll processes. Thus, slot die coating was identified as the best coating process for the use case. The concept combination of CCM PEMFC, CCM PEMEL and Decal PEMFC was identified as the best process portfolio.

Table 1: Overview results of the total Benefit

Portfolio	Spray coating	Slot die coating	Gravure coating
CCM PEMFC CCM PEMEL Decal PEMFC	18,75	27,21	23,90
Decal PEMFC Decal PEMEL CCM PEMFC	19,43	26,51	25,14

4.2.2 Critical reflection and visualization of synergies on product portfolios

A benefit coefficient that does not consider synergies is introduced to visualize the impact of synergies on the overall result. It is calculated by solely taking the amount of direct benefit values into account. The benefit coefficient and the synergy coefficient are shown in the following table for selected portfolios (see Table 2).

Table 2: Overview synergy and benefit coefficient

	Portfolio 1			Portfolio 2		
Coefficient	CCM PEMFC	Decal PEMEL	PTE PEMEL	Decal PEMFC	Decal PEMEL	PTE PEMEL

Synergy coefficient	0,43	0,22	0,35	0,42	0,44	0,14
Benefit coefficient	0,37	0,32	0,31	0,36	0,33	0,31

It is noticeable that the rankings of the components change in their prioritizations. While in the second portfolio, taking synergies into account, the Decal PEMEL components are to be prioritized. This balance shifts towards Decal PEMFC without taking synergies into account. In addition, while synergies are considered, a clearer distribution of priorities can be seen compared to the direct benefit without considering synergies.

In Table 3 the total benefits of the two portfolios with and without taking the synergies into account are illustrated. For the later, s_n equals zero in Formula (2). It can be seen that the ranking of the two portfolios changes in their overall benefits. While portfolio 2 is just preferred to portfolio 1 when synergies are considered, this ranking shifts without the consideration of synergies.

Table 3: Total benefit with and without taking Synergies into account

	Portfolio 1	Portfolio 2
Taking Synergies into account	23,60	23,62
Without taking Synergies into account	23,62	23,31

5. Conclusion

For PEMFC and PEMEL production competitiveness, a reduction of production costs is necessary. One cost potential can be exploited by combining and utilizing potential synergies between PEMFC and PEMEL production. As a result, a methodology was developed to evaluate different combinations of coating processes, taking the synergies into account. The result of the methodology is the overall benefit of the considered production process portfolio, which allows a ranking of different portfolios in relation to each other.

The evaluation of the processes is followed by the identification of synergies between the components. In this paper, synergy categories were defined and realization probabilities related to the occurrence of the synergy effects were introduced. However, the weighting of the synergies was not considered in order to be able to simplify the comparison of synergies with each other. Thus, further research is needed to develop a methodology for weighting the synergies independence of a dedicated use-case. However, it is important to ensure that the weights are determined and calculated systematically in order to avoid inconsistencies in the methodology.

The calculation of the synergy coefficients is based on the synergy identification. Synergy coefficients are calculated using the ANP approach by comparing the components of a portfolio in pairs. Thus, coefficients result that prioritize the components in the associated component portfolio. By normalizing the coefficients to one, the value is solely related to the synergy consideration of the respective portfolio. Values of the quantified synergies between components of other portfolios is not considered in the calculation of the synergy coefficients. Thus, a systematic approach is further needed that enables the comparison of synergy coefficients of different portfolios.

Furthermore, although the influence of the synergistic effect on the prioritization and selection of the portfolios was illustrated, the utilization of this effect was not validated. Thus, further research effort has to be conducted in the validation of the synergetic effects. The methodology is based on an initial evaluation of the processes to be compared. However, the framework of the evaluation is based on subjective assumptions and the required data sets for the production processes as well as the evaluation of synergies.

Thus, as a further research activity, the quality of the methodology has to be validated with real and uniform data.

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7. References

[1] Len Barrie and Geir Braathen, 2022. The State of Greenhouse Gases in the Atmosphere Based on Global Observations through 2021. WMO Greenhouse Gas Bulletin 18, 1–10.

[2] Europäische Kommission, 2019. Mitteilung der Kommission an das europäische Paralament, den europäischen Rat, den europäischen Wirtschafts- und Sozialausschuss und den Ausschuss der Regionen. Europäische Kommission, Brüssel, 29 pp.

[3] Fragiacomo, P., Piraino, F., Genovese, M., Corigliano, O., Lorenzo, G. de, 2022. Strategic Overview on Fuel Cell-Based Systems for Mobility and Electrolytic Cells for Hydrogen Production. Procedia Computer Science (200), 1254–1263.

[4] Olabi, A.G., Wilberforce, T., Abdelkareem, M.A., 2021. Fuel cell application in the automotive industry and future perspective. Energy 214, 1–47.

[5] Mekhilef, S., Saidur, R., Safari, A., 2012. Comparative study of different fuel cell technologies. Renewable and Sustainable Energy Reviews 16 (1), 981–989.

[6] Bessarabov, D.G., Wang, H., Li, H., Zhao, N., 2016. PEM electrolysis for hydrogen production: Principles and applications. CRC Press, Boca Raton Florida, xii, 389 pages.

[7] Barbir, F., 2013. PEM fuel cells: Theory and practice, 2nd ed. ed. Elsevier/Academic Press, Amsterdam, Boston, xvii, 518.

[8] Shiva Kumar, S., Himabindu, V., 2019. Hydrogen production by PEM water electrolysis – A review. Materials Science for Energy Technologies 2 (3), 442–454.

[9] Shen, P.K., 2008. PEM Fuel Cell Catalyst Layers and MEAs, in: Zhang, J. (Ed.), PEM Fuel Cell Electrocatalysts and Catalyst Layers. Springer London, London, pp. 355–380.

[10] Teuku, H., Alshami, I., Goh, J., Masdar, M.S., Loh, K.S., 2021. Review on bipolar plates for low-temperature polymer electrolyte membrane water electrolyzer. International Journal of Energy Research 45 (15), 20583–20600.

[11] Sharma, J., Lyu, X., Reshetenko, T., Polizos, G., Livingston, K., Li, J., Wood III, D., Servo, A., 2022. Catalyst Layer Formulations for Slot-Die Coating of Pem Fuel Cell Electrodes, 1–29.

[12] Babic, U., Suermann, M., Büchi, F.N., Gubler, L., Schmidt, T.J., 2017. Critical Review-Identifying Critical Gaps for Polymer Electrolyte Water Electrolysis Development. Journal of The Electrochemical Society 164 (4), 387-399.

[13] Wang, Y., Ruiz Diaz, D.F., Chen, K.S., Wang, Z., Adroher, X.C., 2020. Materials, technological status, and fundamentals of PEM fuel cells – A review. Materials Today 32, 1–26.

[14] Deschamps, F.L., Mahy, J.G., Léonard, A.F., Lambert, S.D., Dewandre, A., Scheid, B., Job, N., 2020. A practical method to characterize proton exchange membrane fuel cell catalyst layer topography: Application to two coating techniques and two carbon supports. Thin Solid Films 695, 1–14.

[15] Mauger, S.A., Wang, M., Cetinbas, F.C., Dzara, M.J., Park, J., Myers, D.J., Ahluwalia, R.K., Pylypenko, S., Hu, L., Litster, S., Neyerlin, K.C., Ulsh, M., 2021. Development of high-performance roll-to-roll-coated gas-diffusion-electrode-based fuel cells. Journal of Power Sources 506, 1–12.

[16] Mauger, S.A., Neyerlin, K.C., Yang-Neyerlin, A.C., More, K.L., Ulsh, M., 2018. Gravure Coating for Roll-to-Roll Manufacturing of Proton-Exchange-Membrane Fuel Cell Catalyst Layers. Journal of The Electrochemical Society 165 (11), 1012-1018.

[17] Bezerra, C.A.G., Deiner, L.J., Tremiliosi-Filho, G., 2020. Inkjet Printed Double-Layered Cathodes for PEM Fuel Cells. Journal of The Electrochemical Society 167 (12), 1–7.

[18] Mehta, V., Cooper, J.S., 2003. Review and analysis of PEM fuel cell design and manufacturing. Journal of Power Sources 114 (1), 32–53.

[19] Talib, R.J., Saad, S., Toff, M., Hashim, H., 2003. Thermal Spray Coating Technology - A Review. Solid State Science and Technology 11 (1), 109–117.

[20] Mohd Rabani, N.A., Kamdi, Z., 2016. Corrosion Behaviour of High Verlocity Oxygen Fuel Spray Process and Electrodeposited Coating in Aqueous Environment. ARP Journal of Engineering and Applied Sciences 11 (12), 7638–7644.

[21] Fauchais, P., Heberlein, J.V.R., Boulos, M.I., 2014. Overview of Thermal Spray, in: Fauchais, P., Heberlein, J.V.R., Boulos, M.I. (Eds.), Thermal Spray Fundamentals. Springer US, Boston, MA, pp. 17–72.

[22] Ouimet, R.J., Gado, A.M., Bliznakov, S., Bonville, L.J., Maric, R., 2021. Advanced electrodes for electrochemical energy storage and conversion devices fabricated by reactive spray deposition technology. Electrochemistry Communications 133, 1–9.

[23] Lim, B.H., Majlan, E.H., Tajuddin, A., Husaini, T., Wan Daud, W.R., Mohd Radzuan, N.A., Haque, M.A., 2021. Comparison of catalyst-coated membranes and catalyst-coated substrate for PEMFC membrane electrode assembly: A review. Chinese Journal of Chemical Engineering 33, 1–48.

[24] Liu, H., Ney, L., Zamel, N., Li, X., 2022. Effect of Catalyst Ink and Formation Process on the Multiscale Structure of Catalyst Layers in PEM Fuel Cells. Applied Sciences 12 (8), 1–41.

[25] Mayyas, A.T., Ruth, M.F., Pivovar, B.S., Bender, G., Wipke, K.B., 2019. Manufacturing Cost Analysis for Proton Exchange Membrane Water Electrolyzers. National Renewable Energy Laboratory, 65 pp.

[26] Kampker, A., Krieger, G., Ayvaz, P., Schön, C., Reims, P., 2020. Produktion von Brennstoffzellenkomponenten. PEM der RWTH Aachen; VDMA, Aachen, 24 pp.

[27] Mauger, S., 2017. Material-Process-Performance Relationships for Roll-to-Roll Coated PEM Electrodes, NREL (National Renewable Energy Laboratory). NREL, Washington, 26 pp.

[28] Burdzik, A., Stähler, M., Friedrich, I., Carmo, M., Stolten, D., 2018. Homogeneity analysis of square meter-sized electrodes for PEM electrolysis and PEM fuel cells. Journal of Coatings Technology and Research 15 (6), 1423–1432.

[29] Wöginger, H., 2003. Das Synergy-Value-Konzept: Synergien bei Mergers und Aquisitions. Dissertation, Wien, 301 pp.

[30] Saaty, T., 2004. Decision Making: The Analytic Hierarchy and Network Processes (AHP/ANP). Journal of Systems Science and Systems Engineering 13 (1), 1–35.

[31] Li, C., Liu, F., Tan, X., Du, Y., 2010. A methodology for selecting a green technology portfolio based on synergy. International Journal of Production Research 48 (24), 7289–7302.

8. Biography

Heiner Hans Heimes studied mechanical engineering with a focus on production engineering at RWTH Aachen University. From 2015 to 2019, he was head of the Electromobility Laboratory (eLab) of RWTH Aachen University and chief engineer of the newly established chair “Production Engineering of E-Mobility Components” (PEM). Since 2019, Dr.-Ing. Heimes has held the role of executive engineer of the PEM facility.

Achim Kampker is head of the chair “Production Engineering of E-Mobility Components” (PEM) of RWTH Aachen University and known for his co-development of the “StreetScooter” electric vehicle. Kampker also devotes himself to numerous projects. These include his commitment to the “Expert Group Transformation of the Automotive Industry” (ETA) of the Federal Ministry for Economic Affairs and Climate Action (BMWK) and in the “Expert Council on Electric Mobility” of the state government of North Rhine-Westphalia.

Mario Kehrer studied electrical engineering and information technology at Karlsruhe Institute of Technology (KIT). In 2017 he joined the chair “Production Engineering of E-Mobility Components” (PEM) of RWTH Aachen University. There, Kehrer initially acted as a research assistant and later as a group leader in the Battery Engineering and Safety group. Since 2021, he is chief engineer of the Fuel Cell and Electrification Engineering division.

Sebastian Hagedorn studied mechanical engineering with a focus on production engineering at RWTH Aachen University. After joining the chair “Production Engineering of E-Mobility Components” (PEM) of RWTH Aachen University in 2019, Hagedorn became the leader of the Fuel Cell group in 2021. He is focusing his research on the adaption of process innovations in the process chain for Fuel Cell stack and system production.

Niels Hinrichs studied mechanical engineering with a focus on energy and process engineering at Ruhr-University Bochum. After working for an energy supplier in the field of gas grid technology for five years, Hinrichs joined the chair “Production Engineering of E-Mobility Components” (PEM) of RWTH Aachen University in 2021. He is researching Fuel Cell technology from a production engineering perspective against the background of automotive applications.

Tobias Pfeifer is pursuing his Master of Science in energy engineering at RWTH Aachen University and successfully completed his Bachelor of Science in Mechanical Engineering in 2022. Since 2022 he has been working as a research assistant at the institute "Production Engineering of E-Mobility Components" (PEM).

4th Conference on Production Systems and Logistics

Toward Responsible Use Of Digital Technologies In Manufacturing Companies Through Regulation

Günther Schuh[1], Max-Ferdinand Stroh[1], Lara Johanning[1]

[1]FIR, Institute for Industrial Management at RWTH Aachen University, Aachen, Germany

Abstract

Digital technologies have gained significant importance in the course of the 4th Industrial Revolution and these technologies are widely implemented, nowadays. However, it is necessary to bear in mind that an ill-considered use can quickly have a negative impact on the environment in which the technology is used. For more responsible and sustainable use, the regulation of digital technologies is therefore necessary today. Since the government is taking a very slow response, as the example of the AI Act shows, companies need to take action themselves today. In this context, one of the central questions for companies is: "Which digital technologies are relevant for manufacturing companies in terms of regulation?" This paper conducted a quantitative Delphi study to answer this question. The results of the Delphi study are presented and evaluated within the framework of a data analysis. In addition, it will be discussed how to proceed with the results so that manufacturing companies can benefit from them. Furthermore, the paper contributes to the development of an AI platform in the German research project PAIRS by investigating the compliance relevance of artificial intelligence applications.

Keywords

digital technologies; compliance; regulation; manufacturing companies; Delphi study; Artificial Intelligence; 5G, Conversational Interfaces

1. Introduction

In today's world, there is a noticeable trend towards mandatory and comprehensive transparency and trust in corporate compliance and governance due to requirements imposed by legislators and regulators [1]. Nowadays, information and information technology (IT) must be considered as part of these compliance efforts in the company [2]. This takes into account the increasing relevance of the operational resource information as a production and competitive factor [3]. In addition, it is to be expected that the legal and regulatory requirements relating to IT will increase for companies in the future [4]. Beyond this assumption, new digital technologies, such as artificial intelligence or edge computing, are among the central building blocks of the digital transformation, in addition to traditional information technology [5]. These must also be taken into account in the future compliance efforts of companies, as they are a central component on the path of digital transformation. In the case of artificial intelligence, for example, the EU Commission has published a regulation on artificial intelligence (AI) with the aim of using the technology in accordance with the values, fundamental rights and principles of the Union. [6]

These developments in the field of artificial intelligence in recent years and months exemplify the need for compliance in the use of digital technologies in companies. Thus, there is a need for support for companies

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to systematically create compliance guidelines for a variety of digital technologies that are used in manufacturing companies.

This paper presents the first model in a series of four models to address the problem of compliance for digital technologies in manufacturing companies. Therefore, the compliance-relevant digital technologies must be identified and structured, as well as a blueprint and guideline for creating regulations must be developed. This paper provides the basic foundation for the project and describes the identification of the compliance relevance of digital technologies by a Delphi study. The overall research goal is to enable companies to formulate compliance regulations for digital technologies in systematic ways. The interim results of the first model, discussed in this paper, highlight the relevance of the topic and provide an assessment of various digital technologies in terms of compliance relevance.

The remainder of this paper is organized as follows. Section 2 reviews the literature regarding compliance of digital technologies and Delphi studies. Section 3 presents the Delphi study design and the study conduction. Then, in section 4 the collected data is described. This is followed in section 5 by an analysis of the data and a presentation of the key findings. Finally, section 6 contains a discussion and section 7 presents a conclusion and an outlook.

2. State of the art

This section summarises the previous activities in the field of compliance of digital technologies. It also briefly introduces the scientific basis of the Delphi study.

2.1 Compliance of digital technologies

In the literature, there is a two-sided view of compliance of digital technologies. On the one hand, there is the understanding that digital technologies can support the detection of compliance violations in order to counter compliance risks. This understanding is often also found under the keyword digital compliance. On the other hand, there is the understanding that the use of digital technologies must take place under defined rules. [7] The understanding of compliance of digital technologies on which this paper is based corresponds to the second view. A prominent example of this understanding is the AI Act of the EU Commission, which aims to make AI safe, transparent, ethical, impartial and under human control. [6] The EU's proposal establishes a grading of AI application based on risk. In addition to the assessment of risk, corresponding rules are also defined for use depending on the risk. For example, social scoring is to be banned due to the high risk, and chatbots with a low risk will be subject to transparency obligations in order to enable users to decide if they want to take advantage of them. [6] So far, there are no holistic approaches to describe compliance of digital technologies. Only AI as a lighthouse project is being examined with regard to these aspects.

2.2 Delphi Study

The Delphi study has been used since the 1950s and has existed in various forms. Available publications offer a broad spectrum of different definitions and interpretations of the Delphi study. [8] Delphi studies aim to solve complex problems and questions with the help of the knowledge of many individual experts [9]. For this purpose, selected experts from different domains are consulted [8]. According to HÜTTNER, the Delphi study can be classified as a more formalised expert survey [10]. Especially in comparison to the method of an open group discussion, the Delphi study, due to its anonymity, does not allow a change of the individual judgement by orientation on the answers of others [8]. However, since several rounds of questioning are carried out, it is possible to communicate the evaluated results of a wave as feedback to the participants, so that they reflect on their answers in a targeted manner [10]. This results in a prognosis or solution for the addressed problem that is superior to an individual performance and brings the advantages of a group performance [9]. HÄDER divides Delphi studies into four different types, each with its own profile.

Type 1: Delphi studies for the aggregation of ideas.

Type 2: Delphi studies for the most accurate possible prediction of an uncertain issue or for its precise(r) determination.

Type 3: Delphi studies to identify and qualify the views of a group of experts on a diffuse issue.

Type 4: Delphi studies to build consensus among the participants. [8]

3. Methods

For this paper, a Delphi study was conducted to identify the compliance relevance of digital technologies. In the previous section, the method of the Delphi study was briefly introduced, and in this section the method is explained in more detail, as well as the design and execution of the study.

3.1 Delphi study design

The Delphi study was designed as a HÄDER type three study, as the focus is on collecting, determining and qualifying expert opinions on the diffuse topic of compliance for digital technologies. The type three study has specific characteristics. A decisive feature is the quantitative procedure, which was implemented by integrating 22 expert opinions. Furthermore, the experts are selected on the basis of their expertise in the areas of compliance and digital technologies. Moreover, the interdisciplinarity of the experts was taken into account. This means that scientific experts as well as practitioners were interviewed. The expert group is described in detail under Section 5. [8]

In the first step, the question was operationalised by using the facet theory in order to achieve a comprehensible reduction of the complexity of realistic questions [11,8]. In addition, the scope of digital technologies was narrowed down. For this purpose, various technology radars and trend radars were examined. The technology radar and trend radar of the German Federal Ministry for Economic Affairs and Climate is particularly comprehensive and was therefore selected for the study [12]. Based on this, a longlist of 18 technologies was generated, which results in the first facet. Furthermore, in the second facet, different points of view on digital technology were determined. These are data, technology and organization. They were taken from the Aachen Digital Architecture Management and are particularly suitable as they describe the perspectives on digital infrastructure [13]. Moreover, a rating scale for compliance relevance was defined. The exact levels for the evaluation of the relevance can be found in the following mapping sentence (see Formula 1).

$$\text{The respondent } (p_i) \text{ evaluates the digital technology } \overbrace{\begin{Bmatrix} 5G \\ \text{edge computing} \\ \dots \\ AI \end{Bmatrix}}^{F_1} \text{ regarding to}$$

$$\text{the viewpoint } \overbrace{\begin{Bmatrix} \text{data} \\ \text{technology} \\ \text{organisation} \end{Bmatrix}}^{F_2} \text{ as } \overbrace{\begin{Bmatrix} \text{not relevant at all} \\ \text{less relevant} \\ \text{moderately relevant} \\ \text{sufficiently relevant} \\ \text{highly relevant} \\ \text{I don't know} \end{Bmatrix}}^{F_3} \text{ for compliance.} \qquad (1)$$

A decomposition into further facets would be possible, but the pre-test and the study itself showed that the reduction of complexity through three facets was sufficient. The questionnaire was designed with the help of the formulated mapping sentence. This means that for each digital technology (facet one), the points of consideration data, technology and organization (facet two) were queried via the relevance scale (facet three). The questionnaire also contains questions to indicate how confident the respondent is in his/her answer.

3.2 Conducting the Delphi study

To finalise the survey document, a pre-test was conducted with a selected expert to check the questionnaire for comprehensibility and to determine the approximate processing time. Subsequently, the actual study was conducted according to the typical procedure as shown in Figure 1.

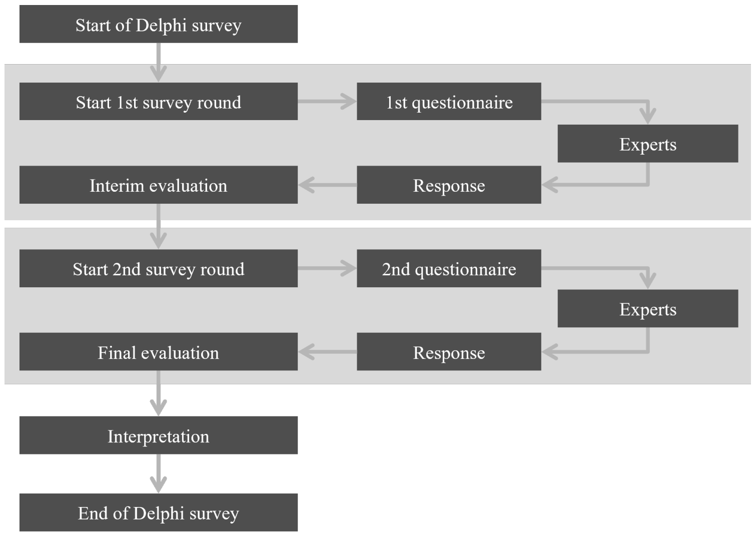

Figure 1: Procedure of the Delphi study

The questionnaire was initially sent to 34 experts as an online survey. 22 of the experts contacted responded within the processing period of four weeks. Subsequently, an interim evaluation of the data was carried out in order to generate feedback for the following round. For this purpose, the number of mentions for each answer option was prepared in the form of a bar chart. An exemplary evaluation for technology 5G can be seen in Figure 2.

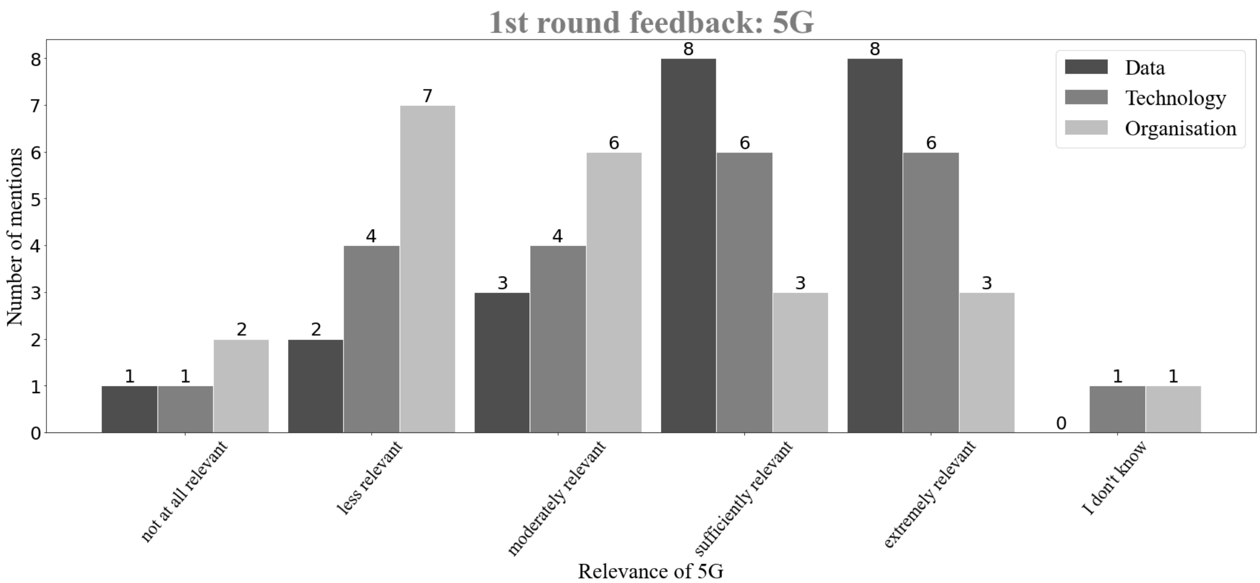

Figure 2: Evaluation example 5G

This feedback was integrated into the second survey and the survey was sent to the 22 participants fromm the first round. The processing period of the second round was four weeks and 16 of the participants sent a response. The number of participants can also be seen in Table 1. This concluded the conduct of the study.

Table 1: Number and participation of the requested experts of the Delphi study

Field of activity of experts	Quantity of requests	Quantity of Experts	
		First round	Second round
Science	7	5	4
Practice	27	17	12
Total	34	22	16

4. Data description

The data is divided into the collected head data and the collected core data. The head data of the questionnaire contains general questions. The self-assessment of the expert regarding his expertise should be emphasized here. The self-assessment takes place on an ordinal scale with five response options. These are "don't know" {NaN}, "none" {0}, "low" {1}, "medium" {2} and "high" {3}. The Expertise is assessed for digital technologies in general, as well as for compliance. In addition, at the end of the questionnaire, respondents could once again highlight the digital technology for which the corresponding expertise is particularly high. This results in a list of all 18 digital technologies for each expert, which is binary coded for the evaluation ("no particular expertise" {0}, "particular expertise" {1}). These Boolean truth values can be viewed as weights for individual responses in the later analysis. The core data includes 54 characteristics generated by three observation points for 18 technologies and are each ordinally scaled. Experts could choose between "not at all relevant" {0} and "extremely relevant" {4} on a five-point scale. In addition, the questionnaire contains the option "I don't know" {NaN}. The entire scale can be found in Table 2.

Table 2: Overview of the scale for assessing the relevance of technologies

Statement	Scale value
Highly relevant	4
Sufficiently relevant	3
Moderately relevant	2
Less relevant	1
Not relevant at all	0
I don’t know	NaN (Not a Number)

5. Data analysis and finding relevant technologies for compliance

Using the data collected in the Delphi study, the relevance of the individual digital technologies for a compliance guideline will be derived. For this purpose, a data-driven analysis of the head data and a simplified form of hypothesis-driven analysis of the core data will be performed.

First, the head data is analyzed because it provides the basis for the following analysis of the core data and ensures the transparency and validation of the expert group. The spider diagram in Figure 3 shows how the 22 participants assess their own expertise on the two topics of concern, compliance and digital technologies.

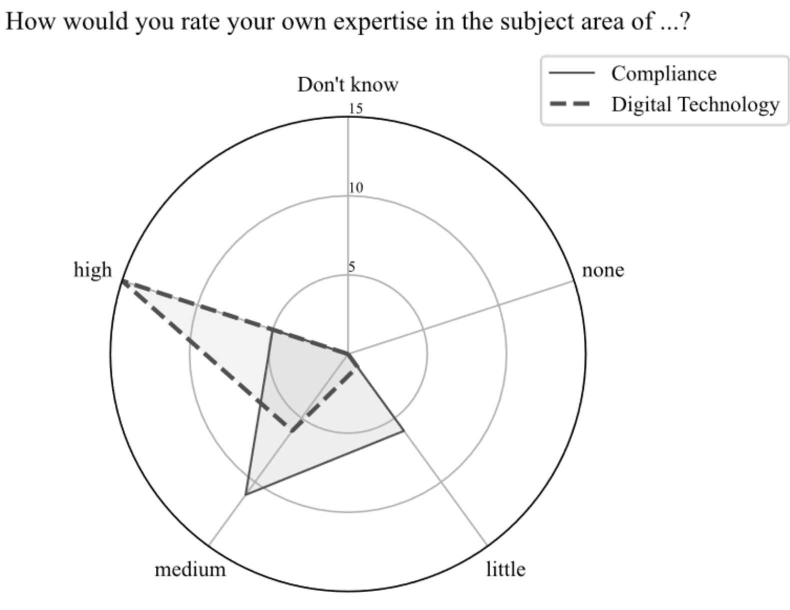

Figure 3: Expertise of the respondents

It shows that both areas are represented in the expert group by correspondingly high or medium levels of knowledge. It can be concluded that the expert group formed for the Delphi study is suitable for the research due to its mixed expertise and mixed backgrounds from business and research (see Table 1).

Before the hypothesis-driven analysis of the core data is presented in the following, a preselection of digital technologies based on particular characteristics is necessary. During the initial examination of the core data, one particular feature of the digital technology thread stood out. Here the participants answered particularly frequently "I don't know" {NaN}. This can be seen in the first as well as in the second survey round. Due to the lack of meaningfulness, this technology is therefore excluded from the evaluation. Furthermore, the core data for the digital technology Brain Computer Interface showed a particularly high demand for compliance. It should be noted, however, that this technology has a very low degree of maturity and has not yet found regular application in manufacturing companies. This can also be borrowed from the technology and trend radar [12]. Consequently, this technology is excluded for the further procedure.

The hypothesis-driven analysis of the core data is presented below. For this purpose, three hypotheses are stated and proven or disproven.

H1 Based on the compliance relevance determined in the Delphi study, a clear ranking of the digital technologies can be generated.

The statistical measures median, mode and interquartile range (IQR) are used to determine a ranking in descending order of the compliance relevance of the digital technologies. Only ordinally scaled data is available in the Delphi study, so both the median and the mode are suitable. Since the median reflects the distribution of responses and the mode only shows the most frequent response, it is the more decisive measure. In addition, the IQR is only a measure of dispersion and not a measure of location like the median and mode. Consequently, the median is used as the first criterion. If a respondent indicated that he or she was particularly confident about a digital technology, the median would be weighted twice. Furthermore, the average is taken to combine the dimensions of data, technology and organization. The ranking by using the weighted median leads to the result that there are still a large number of split ranks. Therefore, the mode is additionally introduced as a second criterion. The same principle of weighting and averaging is applied here. After using the mode as the second criterion, the number of split ranks was reduced, but there are still many split ranks. Therefore, IQR is used as the third criterion. Continuing with the application of the explained weighting and averaging. The result can be seen in Table 3.

Table 3: Result ranking by median, mode and IQR

Rank	Digital technology	Median	Mode	IQR
1	Deep Learning	3,3333	3,6667	1,25
	Machine Learning	3,3333	3,6667	1,25
2	Natural Language Processing	3,3333	3,3333	1,0
3	Computer Vision	3,1667	3,0	1,1667
4	Conversational Interfaces	3,0	3,0	0,6667
5	5G	3,0	3,0	1,0
6	RFID	2,8333	3,3333	1,3333
7	WiFi-6	2,6667	3,0	1,3333
8	System virtualization	2,6667	2,6667	1,0
9	ZigBee	2,6667	2,6667	1,4167
10	Virtual Reality (VR)	2,6667	2,6667	1,6667
11	Distributed Ledger Technologien	2,6667	2,3333	1,0
12	Edge Computing	2,3333	2,3333	1,5
13	Augmented Reality	2,3333	2,0	1,0
	Bluetooth 5	2,3333	2,0	1,0
14	Quantum Computing	2,0	2,6667	2,0

Using the measures median, mode and IQR, the hypothesis could still not be proven because the ranking of the digital technologies is not clear. The ranks one and 13 are still divided. Nevertheless, it can be stated that it was possible to make the relevance of the digital technologies comparable with one another.

H2 The generated ranking list enables a systematic identification of compliance-relevant digital technologies.

To test the hypothesis two, the previously generated ranking list is considered. With a relevance score of at least three, which corresponds to "sufficiently relevant", it is assumed in the following that the compliance relevance is sufficient for consideration in the subsequent models. Moreover, the use of the word "sufficient" in everyday language already indicates the adequacy and appropriateness of the relevance. The scale value below three corresponds to "moderately relevant", which in turn is understood in everyday language as " slightly" relevant and is therefore not sufficient for the further considerations. The minimum relevance of three or "sufficiently relevant" defined in this way is applied to the leading statistical measure, the median. This results in a list of compliance-relevant digital technologies shown in Table 4.

Table 4: Identified compliance relevant digital technologies

Rank	Digital technology	Median	Mode	IQR
1	Deep Learning	3,3333	3,6667	1,25
	Machine Learning	3,3333	3,6667	1,25
2	Natural Language Processing	3,3333	3,3333	1,0
3	Computer Vision	3,1667	3,0	1,1667

4	Conversational Interfaces	3,0	3,0	0,6667
5	5G	3,0	3,0	1,0

The six digital technologies identified are all at least sufficiently relevant at the median. This statement is strengthened by the fact that the mode is also three or greater for all six digital technologies. In summary, a system of two position measures was used to identify the top six compliance-relevant digital technologies. Systematic identification has thus been successful and the hypothesis put forward is substantiated.

H3 There are thematic clusters within the compliance-relevant digital technologies.

The list of compliance-relevant digital technologies which has already been compiled is used to investigate the third hypothesis. This means a search is made for thematic clusters in the six most compliance relevant digital technologies that are at least sufficiently relevant. First of all, it is noticeable that the ranks one to three are all occupied by digital technologies that are related to artificial intelligence. However, the digital technologies: machine learning, deep learning, natural language processing and computer vision, are also related to each other [14]. In the field of computer science, machine learning focuses on developing efficient algorithms to solve problems using computational power [15]. While machine learning uses approaches from statistics, it also includes methods that are not solely based on previous work by statisticians, leading to new and widely cited contributions in the field [16]. In particular, deep learning is used in these contributions. Deep learning models consist of multiple processing layers capable of learning representations of data with multiple levels of abstraction. Deep learning has dramatically improved machine learning capabilities, e.g., in speech or image recognition [17]. Sub-applications of deep learning such as computer vision and natural language processing exist for this purpose [18]. In the context of artificial intelligence, the described techniques such as machine learning and thus deep learning and computer vision or natural language processing are now applied to mimic human intelligence in machines. [14]. The described connections can also be taken from Figure 4.

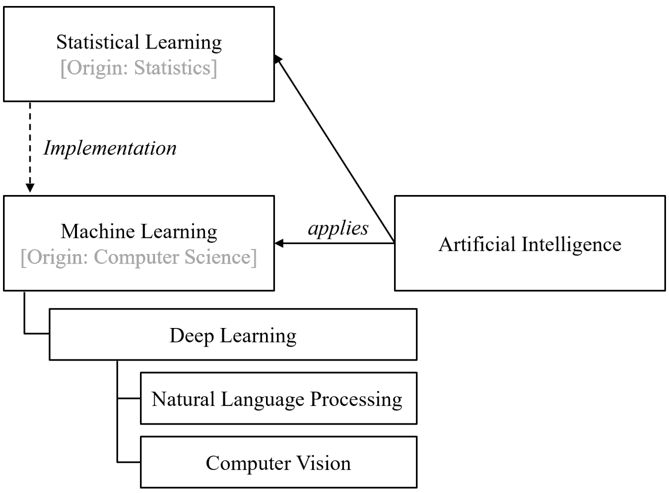

Figure 4: Applications of Artificial Intelligence based on KÜHL [14]

Thus, the identified cluster is named with the overarching term "Applications of Artificial Intelligence" and includes the digital technologies machine learning, deep learning, natural language processing and computer vision. After explaining the proximity in terms of content, it should be further emphasized that the median of all digital technologies in this cluster only varies between 3.3333 and 3.1667. This supports the clustering that was carried out.

The digital technology conversational interfaces is ranked fourth and 5G is ranked fifth. Conversational interfaces is a human-machine interface topic and 5G is a communication technology. No other meaningful content cluster can be formed for 5G. In the case of conversational interfaces, it should be considered whether it would make sense to join the cluster Applications of Artificial Intelligence. However, the authors decided against this because conversational interfaces are based on the technological development of artificial intelligence applications and speech recognition in particular, but interaction with humans has a special role and trust is an important component when using them in manufacturing companies [19]. In summary, the hypothesis set up can be confirmed, as the content cluster Applications of Artificial Intelligence was found.

6. Discussion

Digital technologies continue to evolve over time, so the results developed in the paper may change over time. Therefore, the described results of the Delphi study represent a current snapshot that is valid for a limited period of time. When selecting the digital technologies, care was taken to use those that are state-of-the-art today. In addition, the study was structured in a way that is clearly comprehensible. This would allow to reproduce the work at a later time and to update the results. In case of changes, this means that the model has to be adapted or extended.

7. Conclusion and Outlook

The aim of the work was to identify the compliance-relevant digital technologies for manufacturing companies. To this purpose, a Delphi study was conducted to integrate the expertise of many individual experts. In analyzing the data obtained, a hypothesis-driven approach was followed and statistical measures were used to derive a ranking of digital technologies in descending order of their current compliance relevance for manufacturing companies. The study showed that the experts were able to narrow down the relevant digital technologies. In order to achieve the overarching research goal of enabling manufacturing companies to write their own compliance for the digital technologies they use, further work is needed, in particular to enable the systematic derivation of compliance rules. For this purpose, a framework has to be developed in the following models to ensure a holistic derivation of compliance rules. In addition, the challenge is to enable companies to do the individual actions themselves and a meta-model has to be developed for this purpose in further work.

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References

[1] Dietzfelbinger, D., 2008. Praxisleitfaden Unternehmensethik: Kennzahlen, Instrumente, Handlungsempfehlungen. Gabler, Wiesbaden.

[2] Bertele, M., Lehner, F., 2008. IT-Compliance: rechtliche Aspekte des IT-Managements: Darstellung rechtlicher Aspekte - organisatorische, technische und personelle Maßnahmen - Rahmenkonzepte zur Umsetzung. VDM-Verl., Saarbrücken, 126 pp.

[3] Krcmar, H., 2015. Informationsmanagement, 6., überarb. Auflage ed. Springer, Berlin [u. a.], Online-Ressource.

[4] Falk, M., 2012. IT-Compliance in der Corporate Governance. Gabler Verlag, Wiesbaden.

[5] Stich, V., Hicking, J., Stroh, M.-F., Abbas, M., Kremer, S., Henke, L., 2021. Digitalisierung der Wirtschaft in Deutschland: Technologie- und Trendradar 2021.

[6] Europäische Kommission, 2021. Verordnung des europäischen Parlaments und des Rates zur Festlegung harmonisierter Vorschiften für künstliche Intelligenz (Gesetz über künstliche Intelligenz) und zur Änderung bestimmter Rechtsakte der Union.

[7] Bräutigam, P., Habbe, S., Gergen, P., Daum, A., Heckmann, D., Marx, L., Auer, J., Brand Thimo, 2021. Digitalisierung & Compliance: Compliance-Studie 2021.

[8] Häder, M., 2002. Delphi-Befragungen. Springer Fachmedien Wiesbaden, Wiesbaden.

[9] Döring, N., Bortz, J., 2016. Forschungsmethoden und Evaluation in den Sozial- und Humanwissenschaften, 5. vollständig überarbeitete, aktualisierte und erweiterte Auflage 2016 ed. Springer, Berlin, Heidelberg, 1051 pp.

[10] Hüttner, M., 1982. Markt- und Absatzprognosen. Kohlhammer, Stuttgart, Berlin, Köln, Mainz, 196 pp.

[11] Borg, I., 1986. Facettentheorie: Prinzipien und Beispiele. Psychologische Rundschau 37.

[12] Stich, V., Hicking, J., Stroh, M.-F., Abbas, M., Kremer, S., Henke, L., 2021. Digitalisierung der Wirtschaft in Deutschland: Technologie- und Trendradar 2021.

[13] Hicking, J., Wenger, L., Abbas, M., Benning, J., Clemens, F., Bremer, M., Engländer, J., Heimes, P., Henke, L., Kaminski, L., Kremer, S., Niederau, M., Seelmann, V., Stroh, M.-F., Walter, T., 2020. Aachener Digital-Architecture-Management: Wegweiser zum digital vernetzten Unternehmen.

[14] Kühl, N., Goutier, M., Hirt, R., Satzger, G., 2020. Machine Learning in Artificial Intelligence: Towards a Common Understanding. Karlsruhe Institute of Technology.

[15] Mohri, M., Rostamizadeh, A., Talwalkar, A., 2018. Foundations of machine learning, Second edition ed. The MIT Press, Cambridge, Massachusetts, 486 pp.

[16] Sebastiani, F., 2002. Machine learning in automated text categorization. ACM Comput. Surv. 34 (1), 1–47.

[17] He, K., Zhang, X., Ren, S., Sun, J., 2016. Deep Residual Learning for Image Recognition, in: 2016 IEEE Conference on Computer Vision and Pattern Recognition (CVPR 2016). Las Vegas, Nevada, USA, 27-30 June 2016. 2016 IEEE Conference on Computer Vision and Pattern Recognition (CVPR), Las Vegas, NV, USA. 6/27/2016 - 6/30/2016. IEEE, Piscataway, NJ, pp. 770–778.

[18] Russell, S., Norvig, P., 2022. Artificial intelligence: A modern approach, Fourth edition ed. Pearson, Hoboken, N.J., 1115 pp.

[19] Gupta, A., Basu, D., Ghantasala, R., Qiu, S., Gadiraju, U., 04252022. To Trust or Not To Trust: How a Conversational Interface Affects Trust in a Decision Support System, in: Proceedings of the ACM Web Conference 2022. WWW '22: The ACM Web Conference 2022, Virtual Event, Lyon France. 25 04 2022 29 04 2022. ACM, New York, NY, USA, pp. 3531–3540.

Biography

Günther Schuh (*1958) is head of the chair of Production Systems (WZL-PS) at RWTH Aachen University and member of the directorates of the Machine Tool Laboratory (WZL) at the RWTH, Fraunhofer Institute for Production Technology (IPT) and Director of the FIR at RWTH Aachen University.

Max-Ferdinand Stroh (*1991) is a researcher at FIR at RWTH Aachen University since 2017 in the department Information Management. He is head of the department Information Management. His scientific work is focused on the practical application of AI, smart products, and IT-OT-Integration.

Lara Johanning (*1995) is a researcher at FIR at RWTH Aachen University in the department of Information Management since 2021. While her degrees in mechanical engineering and business administration at University of Hannover and Karlsruhe Institute of Technology, she focused on the business applications and Technologies in producing companies.

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Method For Identifying And Evaluating The Fields Of Application Of A Digital Twin

Fabio Oettl[1], Sebastian Dietl[1], Christian Göltl[2], Daniel Müssig[2], Johannes Schilp[1, 3]
[1]Chair of Digital Manufacturing, Faculty of Applied Computer Science, Augsburg University, Augsburg, Germany
[2]WEISS GmbH, Buchen, Germany
[3]Fraunhofer Research Institution for Casting, Composite and Processing Technology – IGCV, Augsburg, Germany

Abstract

In the context of Industry 4.0, digital technologies and concepts are becoming more and more important in companies, as they can provide solutions to current challenges. The digital twin in particular can be used in various fields of application and thus create added value. However, the variety of different application possibilities as well as the difficult evaluation of the added value of the digital twin poses great challenges for companies. This publication therefore presents a method that offers companies a structured approach to identifying and subsequently evaluating possible uses of the digital twin based on their digital maturity. First, the digital maturity of a company is determined by means of a point-based questionnaire and a suitable identification method is proposed based on the result of the digital maturity. If a field of application could be identified with the proposed method, it is evaluated by a self-developed "Digital Twin Canvas" and, depending on the field of application, by a suitable simulation. By applying the method in various companies from different sectors, the method's functionality has been validated.

Keywords

Digital Twin; Digital Shadow; Digital Readiness; Digital Maturity; Evaluation; Identification; Simulation

1. Introduction

Competitive pressure on companies is increasing due to globalisation, as well as the rising demand for individual products with simultaneously shorter product life cycles [1]. In this environment, companies are confronted with strong price and efficiency pressures [2]. At the same time, technological progress in recent years and the accompanying digitalisation give companies the opportunity to make their processes more efficient through the automation and networking of their production and thus maintaining their competitiveness [3]. One technology that has great potential for connecting the real world with the virtual world is the digital twin (DT) [4]. This technology has a variety of application fields in the life cycle of a product.

For example, the DT can already be used in the design phase of a product to identify and reduce potential problems with products before they are produced [5]. It also enables a virtual commissioning of machinery, which speeds up the real commissioning and enables the detection of potential defects [6]. In addition, with the help of a DT, the training of employees can be carried out on a digital image, thus avoiding a stop in production or the generation of rejects [7]. If a product has sensors and the operating data generated by them are transferred to a DT, the condition of the product can be recorded and, if necessary, condition-based maintenance can be performed [8]. If this collected data is stored over a longer period, anomalies can be detected using various methods of data analysis, such as algorithms from machine learning [9]. Furthermore,

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the use of these methods in combination with a DT can determine the probability of failure of components if the database is adequate, thereby enabling predictive maintenance [10]. The collected data in the DT of a product provides information about the stresses during its life cycle and allows optimisation of the individual components of the product in order to extend its lifespan [11]. The use of a DT can also offer benefits for companies in the application areas of reuse, remanufacturing, and recycling of the product [12].

The fields of application of the DT listed here represent only a small part of the variety of different fields of application. Since it is often difficult for companies to identify the most suitable fields of application, this paper presents an approach that supports companies in identifying and evaluating the fields of application of a DT. This method is discussed in this paper after the introduction and the state of the art. The approach presented here is divided into 3 parts. First, the digital maturity level of the company is determined. Based on this result, suitable methods for identifying application fields are presented. After the successful identification, the selected application fields are evaluated to check whether the use of a DT is profitable in this application field. Subsequently, the method presented here is validated on an application example. Afterwards, the advantages and limitations of the method are shown in the discussion and, finally, the conclusion summarises the most important findings and gives an outlook on the need for further research.

2. State of the Art

This section presents various works in the areas of "Digital Maturity Level in Companies", "Identification of Application Fields of a Digital Twin" as well as "Evaluation of Application Fields of a Digital Twin".

To determine the digital maturity level of companies, Bastos et al (2021) developed a questionnaire. After evaluating this questionnaire, an index is calculated based on the points awarded and, with the help of this index, companies are classified in terms of their digital maturity [13]. Next, depending on the classification, measures are identified to increase digital maturity [13–15]. Gill et al. (2016) and Lödding et al. (2017) have also developed a questionnaire to determine the digital maturity of companies. In addition to these quantitative approaches, there are also qualitative approaches to determine the digital maturity of companies [16]. In many works, the term digital readiness is used instead of digital maturity. This will also be the case in this paper. Overall, there are some papers that determine the digital readiness of companies, but most approaches are very general and do not focus on the assessment of digital readiness for a DT. In 2020, the MSG Group published a study in cooperation with Fraunhofer IPK called "Digital Twin Readiness Assessment" [17]. In this study, the authors investigated how far the companies are regarding the use of a DT and which use cases are being pursued. However, an identification and evaluation of use cases did not take place but will be done in this paper alongside the determination of Digital Twin Readiness (DTR).

The life cycle of a product is often considered for the classification and identification of application fields of a DT [6,18]. Through the enrichment of data and models during the product life cycle, the DT of the real image is expanded and can thus be used for several application fields [19]. The classification of the different application fields can be based on the criteria of hierarchy, data flow type and functional benefit [20]. Other works refer to Industry 4.0 concepts to find application fields for the DT [21]. These concepts are sometimes extended to include the interdependence between the real and virtual image, in order to better classify the fields of application [22]. These works classify existing application fields and do not consider the identification of new application fields in their work. In contrast to these works, this paper provides an approach that presents different methods for identification and classification.

There are various possibilities for evaluating the fields of application of a DT. One possibility is the evaluation based on the aspects of business models, which can be done, for example, using the Business Model Canvas according to Osterwalder [23]. This model was used to evaluate a DT, but the model was not adapted to the application fields of the DT [24]. In addition to the aspects of a business model, the evaluation of the DT in the Data Science Canvas also involves the data situation in the company [25]. Simulations can be used to evaluate the possible effects of a DT when it is introduced and, in addition, interactions can be recognised [26,27]. The application field of a DT can also be evaluated via quality criteria such as extensibility, interoperability, transferability, and reusability [28]. The approach presented here represents a mixture of the evaluation opportunities presented here to be able to provide the appropriate evaluation depending on the field of application of the DT.

3. Method

For a generic identification and evaluation of application fields of a DT a modular system was developed. The aim of this system is to be able to respond to the digital readiness for a DT of different companies. The user is guided through steps A, B and C (see Figure 1). Each module contains sub-modules. The initial situation in the company is evaluated by determining the degree of digital readiness in all sub-modules of A. Based on the score of the assessment, a sub-module of module B is chosen by using a decision tree. These sub-modules aim to suit the needs of the company and provide a method to identify an application field of a DT. After an application has been identified using module B, the application is evaluated in module C.

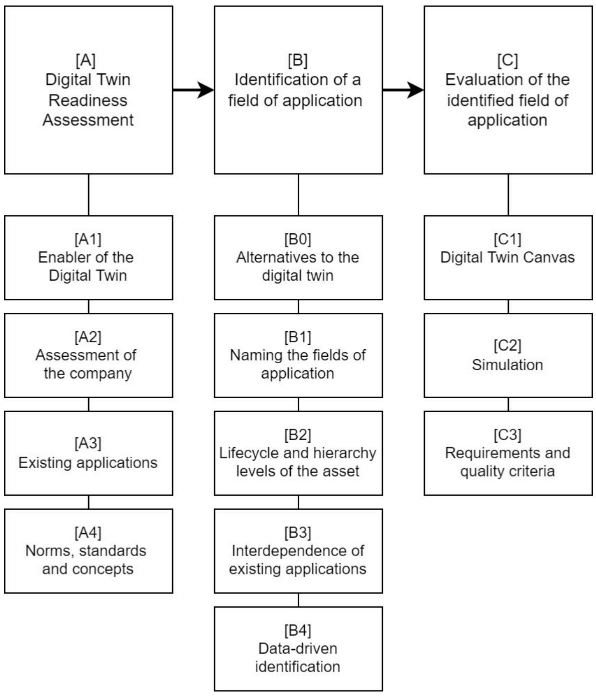

Figure 1: A modular system to identify and evaluate the application fields of a DT

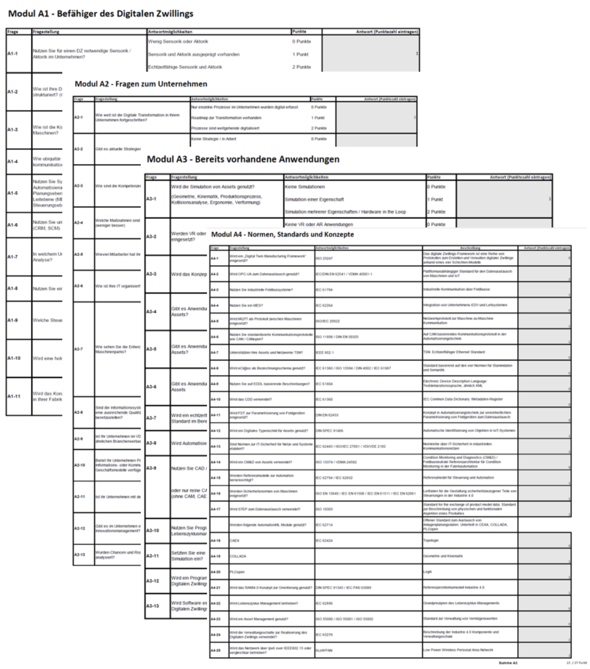

Figure 2: DT readiness assessment with point-based questionnaires

The module system ensures that:

- The method can easily be adopted by companies.
- The modular system allows to present different approaches to identify applications based on the digital readiness of various companies.
- Different perspectives can be taken.
- Companies can process the system in a short amount of time or in more detail.
- A further development of the modules and sub-modules can easily be adopted by adding modules.

Module A: Digital Twin Readiness Assessment:

The realisation of a DT can only be successful if the company has reached a high level of digital readiness in all areas - this requires increased agility and holistic thinking [17]. To determine the DTR, four point-based questionnaires are provided (see Figure 2):

A1 - Enabler of the DT: The enablers of Industry 4.0 were evaluated for the properties of a DT (the questionaries are inspired by [29,17,30]). Further questions regarding the enablers of a DT were explored.

A2 - Assessment of the company: The Digital Twin Readiness Assessment study [17] deals with questions in three "maturity areas" (understanding and commitment, targeting and concept, implementation of a DT). These questions are adapted to the assessed company and its structure. The questions were evaluated, and further questions were added.

A3 - Existing applications: Simulations, visualizations, digital models, and shadows can be completed to a DT by increasing the interdependence of the physical and the digital object. This block of questions also considers the whole spectrum of automation technologies and software like Profinet, Automation Studio, Siemens TIA, Ansys Twin Builder, AWS IoT TwinMaker, MS Azure DT, ISG-viruos, Mnestix and many more. The naming of technologies helps companies to get an overview of the market.

A4 - Norms, standards and concepts: Norms and standards that already have been introduced in companies provide information about the digital readiness of the company for a DT. The questions in this module are based on a list of norms of the DIN [31] , Platform Industrie 4.0 [32] and IEEE [13]. Only norms and standards that are relevant to the introduction of a DT were considered, like OPC-UA (IEC/DIN 62541), MQTT (IEC 20922), TSN (IEEE 802.1), eCl@ss (IEC 61360), AutomationML (IEC 62714), AAS (IEC 63278) and more.

Module B: Identification of a field of application:

The aim of module B is to identify one or more fields of application for the DT that does already exist in the company. Based on the result of the DTR a corresponding sub-module of B is chosen by a decision tree (B0 - B4). In these sub-modules, a perspective on the fields of application of the DT that corresponds to the degree of DTR is taken. Each sub-module thus represents one of several different perspectives on the fields of application of the DT.

B0 - Alternatives to the digital twin, initial situation: low DTR. Regarding the degree of the DTR, this module focuses on alternatives to the DT. The requirements for a company to introduce a digital shadow or model are lower than the requirements for introducing a DT. The perspective of this module is based on the decreasing interdependence (see Figure 5). These alternatives are a more sensible decision for companies with a low DTR. The aim should be to expand the application field in future by adding interdependence.
B1 - Naming the fields of application, initial situation: few DTR. It can be assumed that the company has little knowledge of the application fields of a DT. It is therefore useful to name and describe application fields to familiarize the companies with the spectrum of applications of a DT. Therefore, a table describing the application fields of a DT is provided. This method is often to be found if companies are looking for an identification in literature and web [33]. In addition to naming application fields, reflective questions are used to help the companies to understand and identify the applications of a DT.
B2 - Lifecycle and hierarchy levels of the asset, initial situation: average DTR. The decision tree also a check about the result in module A3 (existing applications of the DT). An average DTR means that a company usually has knowledge of application fields of the DT but has few or no applications of a digital model, shadow or twin. With the architecture model RAMI4.0 / DT a perspective on the life cycle and hierarchy axis can help companies to identify new applications with a provided template (see Figure 3). This represents a horizontal layer of the RAMI4.0 / DT model.

B3 - Interdependence of existing applications, initial situation: above average DTR. Applications and knowledge of a digital model or shadow are available. The perspective of this module is based on the increasing interdependence of existing applications (see Figure 5). The goal is to expand the dependencies between the physical and the digital object. An existing application of a digital model or shadow needs to be checked for the expandability of the interdependences successively to generate new applications. Maintenance of a machine prior based on condition monitoring can then be transformed into predictive maintenance by realising the bidirectional automated dataflow (and the corresponding algorithms for prediction).

B4 - Data driven identification, initial situation: high DTR. Applications of a digital model, shadow or twin are available. In this module the perspective of the company focuses on the dataflow. Companies with a high DTR are facing and solving the issues of big data. Therefore, a data-, a simulation- and a control-twin are considered in data mining, process mining and machine learning applications. For example, a data-twin can be used in machine learning applications for predictive maintenance. Another example could be a simulation-twin in data mining application for virtual commissioning.

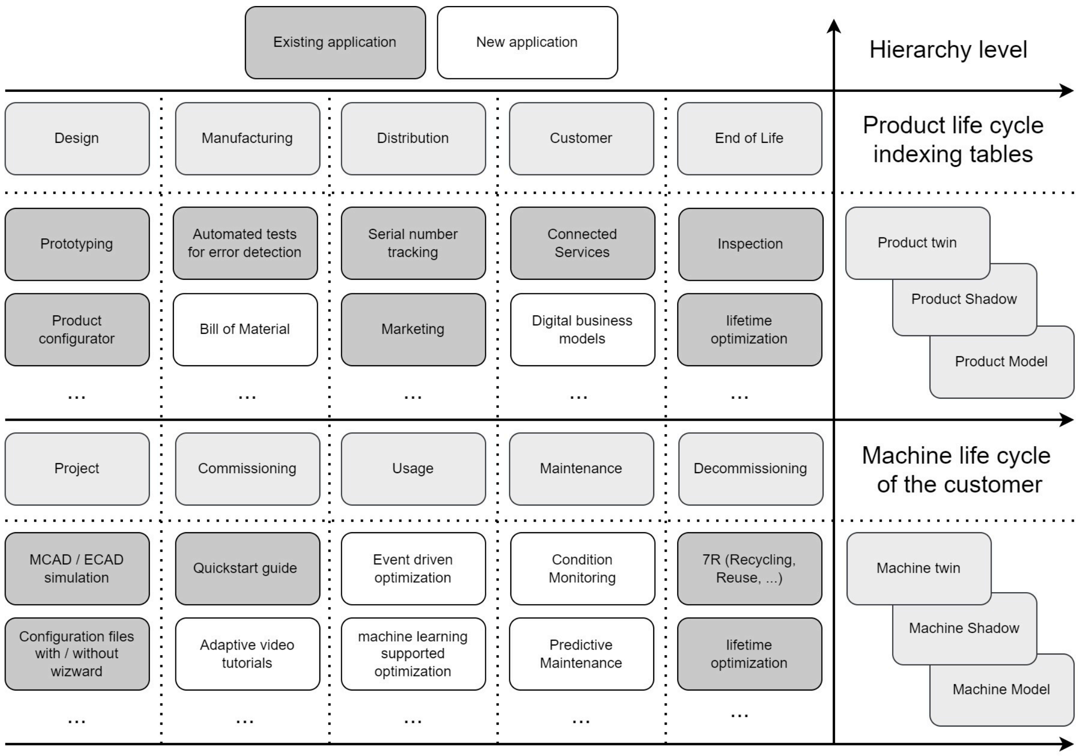

Figure 3: Module B2 - Lifecycle and hierarchy levels of the asset

Module C: Evaluation of the identified field of application

After one or more applications of a DT were identified, the aim of this module is to evaluate the application. An evaluation can be done under serval aspects: business model, investment, trend, functionality, requirements, and implementation.

C1 - Digital Twin Canvas: A canvas is an intuitive model for evaluating different aspects. The Digital Twin canvas addresses the aspects of business model, investment, and trend of an application. Different already existing canvases were evaluated regarding their applicability to the subject of a DT:

- Business Modell Canvas [23]
- Data Science Canvas [34]
- Trendmicrocosmos [35]

To meet the requirements of evaluating a DT, individual elements were taken and supplemented. The Digital Twin Canvas covers the following aspects seen in Figure 6:

Driver, Disruptors, Digital Readiness, Key Resources, Value Propositions, Implementation, Customer, Data, Key Resources, Synergies, Channels, Cost Structure, Revenue Streams.

C2 - Simulation: A simulation can validate the functionality of an application field. A simulation can also be used to evaluate the effects of realizing an application. The concepts developed during a simulation can be used in the implementation of the DT.

C3 - Requirements and quality criteria: This module is considering all aspects regarding the requirements [28] and quality criteria (ISO/IEC 25000) of an application if implemented.

4. Use Case

To evaluate the applicability of the method a study was carried out with eight different companies between May and September 2022. The company WEISS GmbH processed all modules of the method.

About the WEISS Group:

With its automation solutions, WEISS GmbH is one of the world's leading system suppliers in the automotive industry, machine and plant manufacturing, life science, and electronics. The reliable and durable rotary indexing tables (see Figure 4), handling units, delta robots, and linear transfer systems are making the industrial production of tomorrow a reality. By applying their engineering expertise, knowledge of industries and processes, and high affinity for serving customers, the experts assist system integrators and producers in designing and operating innovative and sustainable production plants. Founded in 1967, WEISS now has a staff of around 700 employees in its sales, service, and manufacturing locations in 49 countries.

Module A:

The DTR of the company was determined in cooperation with a product manager for controls and digitalization and also the development engineer for advanced development. The DTR result was above average and knowledge about the application fields of the DT was available. Therefore, the decision tree directed the company to proceed with module B3, the increasing of the interdependency of existing applications.

Module B:

The Weiss GmbH already has existing applications in the preliminary stages of a DT. By extending bidirectional data exchange, these offer potential for new applications of a DT. Thus, the sub-module B3 is ideally suited to the company´s initial situation. Here, new applications for the DT can be identified (see Figure 5): Condition-based Maintenance with the possibility of further development to predictive maintenance with anomaly detection, an event-controlled optimization with the possibility of further development for artificial intelligence and a hardware agnostic commissioning.

Module C:

Digital Twin Canvas: Condition-based maintenance was selected for the evaluation from several identified applications, since WEISS GmbH aims to introduce condition-based maintenance for different components in a timely manner. With the Digital Twin Canvas, the application was evaluated according to various aspects. In 45 minutes, the drivers, disruptors, the digital readiness, the key resources, the value proposition, the implementation, potential customers, the data situation, the key activities, synergies, channels, the costs and the revenues of condition-based maintenance in the company could be evaluated (see Figure 6). This increased the understanding of the different aspects of the new application.

Figure 4: WEISS indexing table

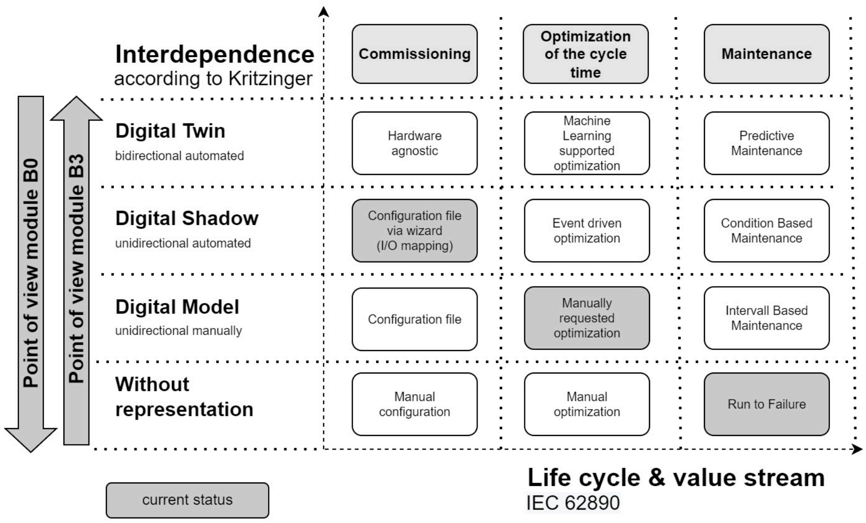

Figure 5: Improving the interdependence of an asset

Digital Twin Canvas: Application Condition Monitoring - Weiss GmbH

Driver
Fewer and fewer people are working in production facilities and robots are replacing staff. The human senses (seeing, hearing, etc.) need to be digitized. Data-driven business models enable a secure future. Differentiation from the competition is necessary. Customer expect Condition Monitoring in future products.

Disruptor
Incorrect interpretations / messages lead to increased downtimes and thus to higher costs and a loss of image. Customer acceptance is lower than expected. Customers may not want Condition Monitoring. A crowding out from the market by "big players" in the field of Condition Monitoring is possible.

DT Readiness
New development in the company - but skills have been improved through education and training. The domain knowledge was strengthened. The infrastructure was created. The company's mindset regarding CM was strengthened.

Key Resources
- sensors
- infrastructure
- data preparation and analysis
- human skills

Value Proposition
- a data collection that describes the state of the component
- domain knowledge for customers
- increase the availability of the system
- production peaks analyses are better assessable
- increased transparency in the production
- data for future projects
- deeper insights into the production process

Implementation
- hardware development (measuring technologies)
- software development (data acquisition, preprocessing)
- product development (link mechanics and measurement technology)
- integration into the service landscape
- and business model

Potential Customers
- external customers (machine builders / integrators / operators)
- internal customers (service, development, quality assurance)

Data
- Machines are already operating in a test field
- data is used to develop artificial intelligence applications
- validation for algorithm

Key Activities
- data driven developed business models
- training of the sales staff
- service development

Synergies
- process optimizations
- ERP notifications at events
- improved ability to communicate for the components
- know-how generation
- more insights into the use of the components

Channels
- new deliveries
- retrofit existing products
- retrofit for repairs as a service
- magazines
- lectures
- trade fairs
- automation platforms
- associations

Cost Structure
- hardware / software development costs
- manufacturing costs
- infrastructure costs
- operating costs
- employee training
- IT security costs

Revenue Streams
- hardware (measurement technology, sales indexing tables)
- training for customers
- data-driven business models
- service contracts

Figure 6: Digital Twin Canvas for evaluating different aspects of the application

Simulation: An important step in evaluating an identified application is a comparison of possible improvements with the current state. The simulation offers an opportunity to illustrate complex relationships and interactions. Furthermore, customers can also benefit from the evaluation of the application through a simulation. The WEISS GmbH agreed to carry out a simulation of Run to Failure, Condition-based and predictive maintenance based on data from their service work.

5. Discussion

To validate the developed method structured expert interviews were designed and conducted to examine whether the modular system can help companies to identify as well as evaluate the application of a DT and is therefore useful in practice. These are the results:

- Module A is seen as a good introduction to the topic for companies. Some have already been able to identify first applications based on the questions and the gaps that have been identified. Clarity about the status quo is created.
- Companies that have already identified applications of a DT before, see their decision confirmed. The method can therefore be used to validate existing applications.
- Repeated processing of the modular system by using different personas can provide new insights.
- For all participating companies the development of norms and standards is essential in the future.
- The Simulation showed that Condition-based and predictive maintenance have a positive effect on the detection time of a defect, the number of fatal defectives, the total disruption time and enables remote maintenance.

Limitations:

- The method is limited to applications for manufacturing companies. Considering the twin of a person, the weather or the environment would meet the generic claim of the method but reduce the quality of the work. Many companies gave feedback that an industry-specific approach to identifying and assessing DT application can provide better solutions than a generic approach. For this reason, an even more detailed method is more sensible than a general one.
- The implementation of an identified and evaluated application was not considered in this work. However, there is sufficient literature in the form of frameworks or standard software for e.g., virtual commissioning, condition monitoring, predictive maintenance or asset administration shell. However, a method that takes all steps into account would be of great value in practice.

The modular system can be used in practice for a management consultancy. However, companies are also able to use this work as a guide to familiarize themselves independently with the topic of identification and evaluation, to determine their degree of maturity, and to identify and evaluate new applications of a DT. Individual concepts of this work can be useful for further research and in practice. The determination of the DTR for the DT, the RAMI4.0/DT model and the Digital Twin Canvas offer many possible applications due to their generic approach. The modular principle of the method also allows modules or sub-modules to be exchanged or supplemented.

6. Conclusion

In this paper, a method has been introduced with which application fields of a DT for a company can be identified and evaluated. The method is divided into 3 modules, which were presented after the introduction and the state of the art. In Module A, the DTR of a company is derived with the help of a questionnaire and the score calculated from it. In Module B, various approaches are used to identify areas of application for a DT based on the company's DTR. Finally, Module C evaluates the identified fields of application. Subsequently, the results of the application of the developed method in cooperation with WEISS GmbH are described. Finally, the advantages and limitations of the method were shown in the discussion.

There is a need for further research, especially in the adaptation and evaluation of the sub-modules of the method, as the research field of DT's is continuously developing. In addition, standards and norms are constantly being revised or further ones published. Due to the expandability and adaptability of the method, these changes can be considered, and the modules can be adapted accordingly. The evaluation of the application fields of the DT should also be expanded to include ecological criteria, as the evaluation is mainly based on economic and qualitative criteria. Due to the increasing consequences of climate change, an evaluation from an ecological point of view will become essential for companies in the future, as the various possible uses of the DT can save resources and energy and enable an efficient recycling.

References

[1] Pistorius, J., 2020. Industrie 4.0 – Schlüsseltechnologien für die Produktion: Grundlagen • Potenziale • Anwendungen. Springer Vieweg, Berlin, Heidelberg, 2 pp.

[2] Ciupek, M., 2022. Diese sechs Megatrends entscheiden über die Wettbewerbsfähigkeit der Industrie. https://www.vdi-nachrichten.com/technik/produktion/diese-sechs-megatrends-entscheiden-ueber-die-wettbewerbsfaehigkeit-der-industrie/. Accessed 22 April 2022.

[3] Schebek, L., Kannengießer, J., Campitelli, A., Fischer, J., Abele, E., Bauerdick, C., Anderl, R., Haag, S., Sauer, A., Mandel, J., Lucke, D., Bogdanov, I., Nuffer, A.-K., Steinhilper, R., Böhner, J., Lothes, G., Schock, C., Zühlke, D., Plociennik, C., Bergweiler, S., 2017. Ressourceneffizienz durch Industrie 4.0: Potenziale für KMU des verarbeitenden Gewerbes. https://www.ressource-deutschland.de/fileadmin/Redaktion/Bilder/Newsroom/Studie_Ressourceneffizienz_durch_Industrie_4.0.pdf. Accessed 22 April 2022.

[4] Barwasser, A., 2021. Resiliente Wertschöpfung: mit Digitalem Zwilling zu Transparenz und Krisenfestigkeit. Fraunhofer IAO. https://blog.iao.fraunhofer.de/resiliente-wertschoepfung-mit-digitalem-zwilling-zu-transparenz-und-krisenfestigkeit/. Accessed 24 April 2022.

[5] Kennel, M., Juhasz, T., 2017. Engineering mit VINCENT – Der digitale Zwilling für die Entwicklungsphase. https://publica-rest.fraunhofer.de/server/api/core/bitstreams/9605af7f-a040-4181-bbb9-4ee789c8b5e0/content. Accessed 21 October 2022.

[6] Güntner, G., Hoher, S., 2020. Digital Twins im Anlagen-Lebenszyklus.

[7] Back, M., 2020. So funktioniert der digitale Zwilling: Voraussetzungen, Möglichkeiten und ein 5-Schritte-Programm. https://www.technik-und-wissen.ch/digitaler-zwilling-voraussetzung-und-moeglichkeiten.html. Accessed 21 October 2022.

[8] Aivaliotis, P., Georgoulias, K., Arkouli, Z., Makris, S., 2019. Methodology for enabling Digital Twin using advanced physics-based modelling in predictive maintenance. Procedia CIRP 81, 417–422.

[9] Thiele, C.-D., Brötzmann, J., Huyeng, T.-J., Rüppel, U., Lorenzen, S.R., Berthold, H., Schneider, J., 2021. A Digital Twin as a framework for a machine learning based predictive maintenance system, in: Semenov, V., Scherer, R.J. (Eds.), ECPPM 2021 – eWork and eBusiness in Architecture, Engineering and Construction. CRC Press, London, pp. 313–319.

[10] Classens, K., Heemels, W.M., Oomen, T., 2021. Digital Twins in Mechatronics: From Model-based Control to Predictive Maintenance, in: Proceedings, 2021 IEEE 1st International Conference on Digital Twins and Parallel Intelligence (DTPI 2021). Jul. 15-Aug. 15, 2021, Beijing, China. 2021 IEEE 1st International Conference on Digital Twins and Parallel Intelligence (DTPI), Beijing, China. 7/15/2021 - 8/15/2021. IEEE, Piscataway, NJ, pp. 336–339.

[11] Schmitt, J., Richter, R., Deuse, J., Zarges, J.-C., Heim, H.-P., 2021. Digitaler Zwilling in der Kunststofftechnik: Lebensdaueroptimierte Herstellung technischer Bauteile durch Einsatz datengetriebener Methoden.

[12] Wang, X.V., Wang, L., 2019. Digital twin-based WEEE recycling, recovery and remanufacturing in the background of Industry 4.0. International Journal of Production Research 57 (12), 3892–3902.

[13] Bastos, A., Sguario Coelho De Andrade, M.L., Yoshino, R.T., Santos, M.M.D., 2021. Industry 4.0 Readiness Assessment Method Based on RAMI 4.0 Standards. IEEE Access 9, 119778–119799.

[14] Gill, M., VanBoskirk, S., 2016. The Digital Maturity Model 4.0: Benchmarks: Digital Business Transformation Playbook.

[15] Lödding, H., Riedel, R., Thoben, K.-D., Cieminski, G. von, Kiritsis, D., 2017. Advances in Production Management Systems. The Path to Intelligent, Collaborative and Sustainable Manufacturing. Springer International Publishing, Cham.

[16] Schuh, G., Anderl, R., Dumitrescu, R., Krüger, A., ten Hompel, M., 2020. Der Industrie 4.0 Maturity Index in der betrieblichen Anwendung: Aktuelle Herausforderungen, Fallbeispiele und Entwicklungstrends. acatech KOOPERATION.

[17] Samarajiwa, M., Kai Lindow, David Salamon, Rainer Stark, 2020. Digital Twin Readiness Assessment: Eine Studie zum Digitalen Zwilling in der fertigenden Industrie, 1st ed. Fraunhofer Verlag, 2 pp.

[18] Massonet, A., Kiesel, R., Schmitt, R.H., 2020. Der Digitale Zwilling über den Produktlebenszyklus. Zeitschrift für wirtschaftlichen Fabrikbetrieb 115 (s1), 97–100.

[19] Mandolla, C., Petruzzelli, A.M., Percoco, G., Urbinati, A., 2019. Building a digital twin for additive manufacturing through the exploitation of blockchain: A case analysis of the aircraft industry. Computers in Industry 109, 134–152.

[20] Newrzella, S.R., Franklin, D.W., Haider, S., 2021. 5-Dimension Cross-Industry Digital Twin Applications Model and Analysis of Digital Twin Classification Terms and Models. IEEE Access 9, 131306–131321.

[21] Deuter, A., Pethig, F., 2019. The Digital Twin Theory. I40M 2019 (1), 27–30.

[22] Kerber Florian, Eichinger Peter, Förster, F., Händel, G., 2022. Der Digitale Zwilling im industriellen Kontext - Eine regionale Perspektive. TTZ Flexible Automation.

[23] Osterwalder, A., 2013. Business model generation: A handbook for visionaries, game changers, and challengers, 1st ed. Wiley & Sons, New York, 278 pp.

[24] Klostermeier, R., Haag, S., Benlian, A., 2020. Geschäftsmodelle digitaler Zwillinge. Springer Fachmedien Wiesbaden, Wiesbaden.

[25] Stevens, G., Bossauer, P., Esau, M., Neifer, T., 2020. Data Science Canvas: Ein Instrument zur Operationalisierung von Daten. https://www.kompetenzzentrum-usability.digital/kos/WNetz?art=News.show&id=985. Accessed 21 October 2022.

[26] Oppermann, I., 2021. Von der Simulation bis zur virtuellen Inbetriebnahme. CITplus 24 (7), 38–39.

[27] Schluse, M., Roßmann, H.-J., 2021. Von der Simulation zum Experimentierbaren Digitalen Zwilling und zurück, in: Franke, J., Schuderer, P. (Eds.), Simulation in Produktion und Logistik 2021. Erlangen, 15.-17. September 2021, 1. Auflage ed. Cuvillier Verlag, Göttingen.

[28] Moyne, J., Qamsane, Y., Balta, E.C., Kovalenko, I., Faris, J., Barton, K., Tilbury, D.M., 2020. A Requirements Driven Digital Twin Framework: Specification and Opportunities. IEEE Access 8, 107781–107801.

[29] Martinelli, A., Mina, A., Moggi, M., 2019. The Enabling Technolgies of Industrie 4.0: Examining the seeds of the fourth industrial revolution. Industrial and Corporate Change (30).

[30] VDMA, RWTH Universität Aachen, IW Consult GmbH, 2022. Industrie 4.0-Readiness-Check: Where does your business stand? Check your readiness for Industry 4.0! https://www.industrie40-readiness.de/?lang=en. Accessed 19 September 2022.

[31] Deutsches Institut für Normung e. V., 2022. Normen und Standards - Industrie 4.0. https://www.din.de/de/forschung-und-innovation/themen/industrie4-0/normen-und-standards. Accessed 19 September 2022.

[32] Adolphs, P., Auer, S., Bedenbender, H., Billmann, M., Hankel, M., Heidel, R., Hoffmeister, M., Huhle, H., Jochem, M., Kiele-Dunsche, M., 2016. Struktur der Verwaltungsschale: Fortentwicklung des Referenzmodells für die Industrie 4.0-Komponente. Ergebnispapier der Plattform Industrie 4.0.

[33] Fuller, A., Fan, Z., Day, C., Barlow, C., 2020. Digital Twin: Enabling Technologies, Challenges and Open Research. IEEE Access 8, 108952–108971.

[34] Stevens, G., Bossner, P., Esau, M., Neifer, T., 2022. Data Science Canvas: Ein Instrument zur Operationalisierung von Daten. https://www.kompetenzzentrum-usability.digital/kos/WNetz?art=News.show&id=985. Accessed 19 September 2022.

[35] Blechschmidt, J., 2021. Quick Guide Trendmanagement: Wie Sie Trendwissen in Ihrem Unternehmen wirksam nutzen, 1st ed. Springer Heidelberg, Berlin, Heidelberg, 116 pp.

Biography

Fabio Oettl (*1994) is a research assistant at the Digital Manufacturing Group at the University of Augsburg since 2019. From 2013 to 2018 he studied Industrial Engineering. His main research focuses is one the identification and evaluation of application fields of the digital twin and their introduction in companies.

Sebastian Dietl (*1988) researches the applications fields of the digital twin. His focus is on the bidirectional data exchange of components with different protocols. From this he develops IoT applications such as dashboards, stream processing, condition monitoring, anomaly detection and predictive maintenance.

Christian Göltl (*1983) has been Product Manager at the Weiss Group since 2018. He is responsible for drive technology, software and digitalization. His focus is on creating smart Weiss products and new business models. He is member of VDMA IAS working group and the TwinStore community.

Daniel Müssig (*1993) has been Development Engineer - Advanced Development at the Weiss Group since 2018. His focus is on creating smart solutions for existing as well as new products in digitization. With his studies in Mechanical Engineering he connects the gathered data with the mechanical products.

Johannes Schilp (*1976) has been Chair of Digital Manufacturing since 2015. He is also head of the processing department at the Fraunhofer Research Institution for Casting, Composite and Processing Technology and member of scientific networks like WG MHI and automation research groups (VDMA).

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Why Companies Fail With Objectives And Key Results: An Analysis Of Implementation Frameworks

Clara Herkenrath[1], Gerrit Hoeborn[1], Volker Stich[1]

[1] *FIR Institute for Industrial Management at RWTH Aachen University, Aachen, Germany*

Abstract

Objectives and Key Results (OKR) is an approach that focuses on the company's goals through trust-based agreements between leaders and employees. With the OKR framework in its original form, strategic business goals are aligned with the employees' active involvement, which promotes intrinsic motivation, transparency, commitment, and alignment. Inspired by the successes at Google and Intel and shaped by its use in the tech industry, the use of OKR increased across industries. Although companies within all sectors use the OKR framework, numerous implementation efforts fail. The challenges of practitioners are not fully addressed in the development of implementation concepts for OKR. One main reason is that these challenges are not taken into account in scientific publications. The paper aims to investigate to what extent existing OKR frameworks need to be adapted to provide companies with suiting implementation guidance. Firstly, OKR is placed in the context of academically widely discussed Performance Management Systems (PMS). Secondly, criteria for successful PMS implementation are identified and used as a baseline for analyzing existing OKR implementation concepts. A systematic literature review shows the current state of research, identifying existing OKR implementation concepts from practice and theory. The OKR implementation concepts identified are systematically mapped to the series of identified criteria for PMS implementation. It is shown that the existing OKR frameworks do not address the described criteria necessary for a successful implementation of PMS, thus the adaptation of existing OKR implementation concepts is required.

Keywords

Objectives and Key Results (OKR); Performance Management Systems; Implementation Concepts, Success Factors; Digital Leadership

1. Introduction

Ongoing globalization and digitalization, as well as the associated dynamics of the economic environment, cause that companies are constantly faced with new challenges [1]. Companies must react to the accompanying speed and unpredictability of the market environment to remain competitive. This requires continuous adaptation [2]. Performance management systems (PMS) are a key instrument used by companies to continuously adapt to the dynamics of the environment. PMS offer approaches to encompass activities and processes aimed at managing employee contribution to achieve corporate goals [3]. A wide variety of PMS address different perspectives of the organization, such as the perspective of strategy implementation building on the Management by Objectives approach developed by Peter Drucker in the 1950s the Objectives and Key Results (OKR) framework was developed to incorporate operationally feasible strategic planning. Characterized by Andrew Grove and John Doerr, the OKR framework was designed and established in practice at Intel and Google. The framework of Doerr [4] and Niven and Lamorte [5] covers the fundamental idea, theoretical foundation, and underlying principles of OKR, rather than explicit individualized

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implementation paths. Implementation in practice and the associated challenges are dealt upon superficially. Despite the great popularity of OKR [6], many companies fail in its implementation and as an result decide to abandon the method that was supposed to assist in the implementation of the strategy [7]. As the OKR framework gains popularity, its practical application is becoming more relevant for research, focusing on the question of strategy implementation in companies. In this context, the crucial question is why companies fail with OKR. Among the reasons, organizational factors and the unmet expectation on the framework are stressed. This paper focuses on the implementation phase, as it is precisely in during the launch phase that companies turn away from the OKR framework. The central research question of this publication is therefore defined as follows:

Do existing OKR implementation frameworks address the needs of organizations for successful OKR implementation?

To answer this question, first this paper positions OKR within performance management theory by analysing its interrelationship along the PMS implementation framework according to Ferreira and Otley [8] with the fundamental OKR theory. Subsequently, a systematic literature review is conducted to identify existing state-of-the-art approaches to OKR implementation. Through this, a holistic picture of the current state of research can be ensured. The differences between the OKR implementation frameworks and gaps in existing OKR implementation frameworks are identified by analysing them according to the success factors for the implementation of PMS by Grünbichler and Klučka [9]. Based on the analysis a recommendation for the design of a holistic OKR implementation framework is derived.

2. Theoretical Foundation

Along with its increasing popularity and application in practice, the OKR framework has gained increasing importance in research. By actively engaging employees, the **Objectives and Key Results** framework focuses on strategy implementation. According to Doerr [4], the strategy is derived from the overarching mission, vision and purpose. In this process, breaking down the objectives and key results from the purpose paves the way for an intrinsically motivated performance. Not only does the OKR framework led to specifying which goals are to be achieved, it also specifies how success can be quantified. For this purpose, the goal-setting process is reflected in a V-shape, initially from the top down and subsequently from the bottom up, including feedback from employees. this encourages transparent communication at all levels. Niven and Lamorte [5] define OKR as „*a critical thinking framework and ongoing discipline that seeks to ensure employees work together, focusing their efforts to make measurable contributions that drive the company forward*".

Understanding of **Performance Management Systems** in theory and practice, due to the different perspectives, can differ greatly. Among the numerous PMSs, varying degrees of depth, methods of execution, and audiences are addressed and executed with a variety of tools [10]. What the different types of PMS have in common is that they enable companies to measure and manage corporate success effectively and efficiently [11]. At this point, it is important to note that the field of performance management in research is a complex, intertwined field in which research is increasingly ambiguous and different studies are contradictory. The industry's perspective on PMS is strongly influenced by the concept of output in everyday work. Heterogeneity in the conceptual understanding of PMSs in the industrial sector is reflected by the application focus, such as IT-based holistic control for steering positioning or targeting more traditional Controlling tools [12]. Industry's perspective in practice follows its own dynamics and distinguishes less distinctively between the instruments of measuring customer-driven project success and evaluation of project success by employees [13]. Besides the systems and the system elements, the research perspective focuses on the theoretical framework and the classification in existing sciences on the multidimensional measurement of performance [10]. According to Krause [14], performance management encompasses all activities that are aimed at optimizing the organization while constantly updating the expertise and social skills of the participants at the same time as minimizing the financial, material, time, emotional and social costs.

3. State of the Art

A systematic literature review following the framework for literature reviewing of vom Brocke et al. [15] was conducted to identify OKR implementation frameworks and to analyze them based on their applicability. Therefore, search strings were specified, along which four data bases were examined for existing OKR frameworks. The four digital databases used for the literature review in this thesis are Scopus, Springer Link, IEEE Xplore, and Google Scholar. The search strings are summarized in table 1.

Table 1: Search commands for the literature review

Database	Search string
SCOPUS	ALL ("objectives and key results" AND "implementation" AND "methods") AND PUBYEAR > 2010
Springer Link	"objectives and key results" AND implementation AND methods AND framework
IEEE Xplore	("objectives and key results" OR ("Full Text & Metadata":"objectives and key results" AND "Full Text & Metadata":"implementation" AND "Full Text & Metadata":"method"))
Google Scholar	"objectives and key results" AND "implementation" AND "methods" AND "framework"

The search strings were used to screen the identified sources using three quality gates, summarized in Figure 1. To focus on the relevant search result, quality gate criteria Q1 targets the period from 2010 to 2022. Additionally, Q2 selects publications focusing on OKR and the underlying methodology. Following on from this, quality gate Q3 identifies sources that provide an overarching framework of the implementation of OKR. Publications were extracted that highlight the process of OKR, such as the OKR cycle, rather than a framework for implementation.

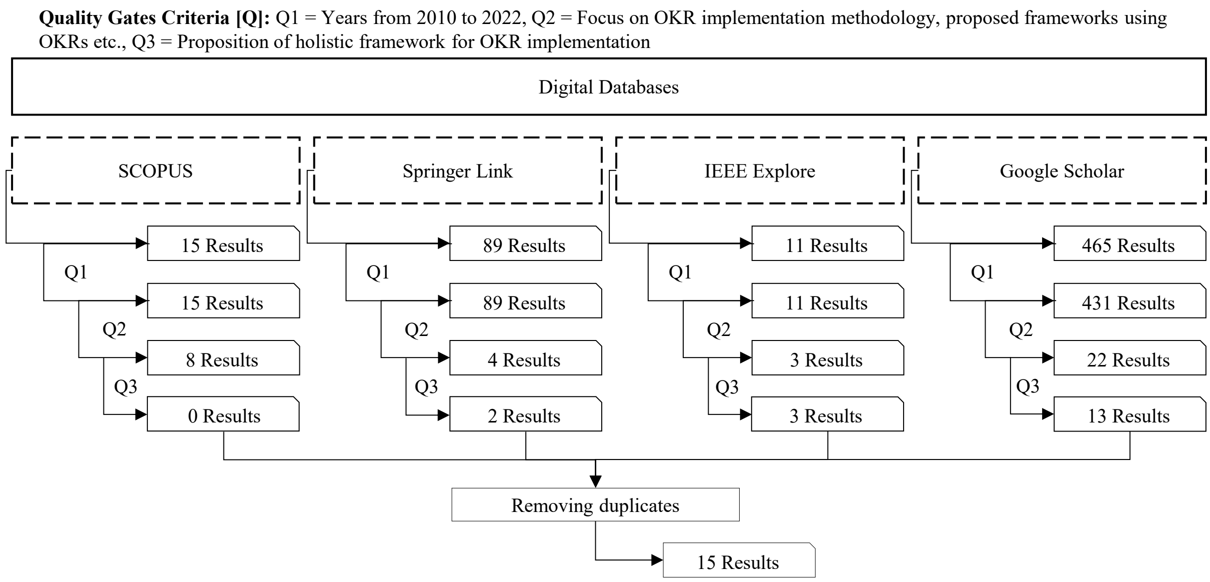

Figure 1: Summary of the literature selection process

In total, the four databases analyzed along the search strings yielded 580 results. Based on the quality gate criteria, 15 relevant OKR implementation frameworks can be identified following duplicate screening. It is striking that the ORK frameworks consider the foundation theory both as a stand-alone strategy implementation approach [4], and from a tool-driven perspective as a component of a combination of tools, on a par with e.g. scrum [16] or Big Data [17]. Following the research question, the 15 OKR frameworks identified are evaluated for sufficiency based on the PMS implementation criteria. These include the following 15 sources [24,17,18,4,25,21,19,26,27,5,22,16,20,28,23].

The study design addresses the relevance of the research question to practice. Using the systematic literature review, existing OKR implementation frameworks are identified which are applied in this form. In order to examine whether these frameworks support the successful introduction of OKR, their applicability is analyzed in the next step. Along the three phases of planning, application, and reporting for the successful introduction of PMS, the different perspectives of the OKR implementation frameworks are examined. Given that the practical application of the OKR implementation frameworks is crucial for the organizational success of the management system, the OKR implementation frameworks are analyzed on the basis of 16 dimensions. This extensive analysis shows how each OKR implementation framework addresses which implementation dimension. As a result of this analysis, it is possible to determine where there is a need to expand the OKR implementation frameworks.

4. Results

First, the OKR framework, widely discussed in practitioners, is placed in the PMS literature for the purpose of research assessment. Based on these findings, the identified OKR frameworks are examined for their sufficiency by analysing them along the core introduction phase for PMS. This systematic analysis identifies blind spots in the introduction systems.

4.1 Relations of PMS and OKR

This chapter of the paper examines the central question of to what extent the OKR framework intersects with the research perspective on PMS. Therefore, PMS are defined, and the characterizing elements holistically identified. Further, the characterizing elements of PMS are matched with the characterizing elements of OKR to evaluate the overlap. Ferreira and Otley [8] present a holistic approach of the structure and functioning of PMS with its performance management system framework. It is based on the respective literature, such as the 5 questions according to Otley [29] and the Levers of control frameworks according to Simons [30]. The framework constructs 12 level according to definition and questions, which provide holistic understanding of PMS. To position the OKR framework in PMS research, the foundational OKR frameworks of Doerr [4] and Niven and Lamorte [5] are analyzed in relation to the 12 levels of the performance management framework according to Ferreira and Otley [8], illustrated in table 2. The relation within the levels of the PMS and the OKR framework are evaluated according to the intensity indices of Probst and Gomez [31]. The intensity of effect, ranges from *o no intensity*, *+ low intensity*, *++ strong intensity* to *+++ very strong intensity,* based on the approach of vom Brocke [32]. If all 12 levels are addressed by the OKR concept it can be deducted that OKR is a PMS.

Table 2: Evaluation of relation within the levels of the PMS and the OKR framework

Levels of Performance Management System [8]	**OKR Framework of Doerr [4, p. 10-27, 60-66, 82, 126, 143–148, 163,179,184-187] and Niven and Lamorte [5, p. 13-22, 78-86, 97-114, 151-155, 170–171]**	**Evaluation [32]**
How is the organizations *vision and mission* brought to the attention of managers and employees?	Alignment with the with organization's mission, vision and North Star value forms the center of interest. OKR to promote purposeful work, common direction of organization 's vision and effort.	+++
What are the *key success factors* that are believed to be central to the organization's overall future success?	The implementation of the organizational strategy, which is implemented by OKR in day-to-day work, is identified as a critical factor for the success of the organization, conviction and buy-in at the top to drive alignment are crucial	+
What is the *organization structure* and what impact does it have on the design and use of performance management systems (PMSs)	Organizational units form the communication level of OKRs, resulting in OKR identifying unclear responsibilities. Open and visualize all parts of an organization, to each level of every department, is necessary.	++
What *strategies and plans* has the organization adopted that it has decided will be required for it to ensure its success?	Goal planning and reflection to progress are updated in the organizational units agile and short-term. The structure of the goal setting process is characterized by the continuous performance management.	+++

What are the organization's *key performance measures* deriving from its objectives, key success factors, and strategies and plans?	Employees track progress and check-in on all levels during OKR-Cycle by paring qualitative objectives and quantitative key results they are committed to.	++
What level of performance does the organization need to achieve for each of its *key performance measures*?	Modern goal setting promotes cross-functional connectivity, peer-to-peer and team-to-team, not scaling beyond the leadership team's capacity, structure and clarity, psychological safety, meaning at work, dependability, impact of work.	+
Are *performance evaluations* primarily objective, subjective or mixed?	Measuring Output by focusing on „What" and „How" with quarterly evaluation, bottom-up and top-down.	++
What *rewards system* is conducted by achieving performance targets	OKR promotes intrinsic motivation of employees, particularly purpose-driven motivation with non-financial incentives, failure to achieve OKRs result in future oriented planning are qualitative with focus on the capacity-planning.	+
What specific *information flows systems* and *networks* has the organization in place to support the operation of its PMSs?	Through joint qualitative and quantitative goal setting bottom-up and top-down in the organization, transparent communication across the hierarchical levels is promoted, language harmonization is developed, and silo behavior is prevented.	+
What *type of use* is made of information and of the various control mechanisms in place?	New information needs are addressed obliquely, the definition of goals by qualitative Objectives and quantitative Key Results is based on a vision-based leadership.	+
How have the *PMSs* altered in the light of the *change* dynamics of the organization and its environment?	Objectives and key results are modified on an agile quarterly basis and aligned with the dynamic requirements of the organization and the environment. The OKR cycle is adapted to the organization's needs and continuously adjusted.	+++
How *strong and coherent* are the links between the components of PMSs and the ways in which they are used?	The comparison between annual performance management and continuous performance management is discussed and OKR is classified. Measuring the impact of the strategy implementation is carried out separately from the operational project management.	+

For the analysis of the OKR framework on the theoretical basis of Niven and Lamorte [5] and Doerr [4], a high level of overlap with the framework of performance management systems according to Ferreira and Otley [8] is evident. Among the 12 levels, PMSs use is the lowest fit. Three levels stand out due to their high impact intensity: vision and mission, strategy, and plans, and PMSs change. For both employees and employers, the vision and mission are the focus of attention of the OKR method. Regarding strategy and plans in the OKR method, emphasis is placed on the way to encourage effective communication and transparency. Transformation and its dynamics have been included in the broader framework, summarized in the PMS change. The analysis shows that, from a research perspective, OKR can be grouped among the PMS. Engelhardt and Möller [12] identify OKR as a system part of performance management. In line with the results of the analysis presented above, it is classified along the lines of the St. Gallen Performance Management Model (SPMM) as a comprehensive, normative performance management system with a focus on strategy implementation. Based on the analysis stated above, OKR will be referred to as a PMS.

4.2 Analysis of OKR implementation Framework

Due to the variety of PMS approaches, existing PMS implementation concepts focus on different angles. With the aim of highlighting the different key elements and comprehensiveness of the identified OKR implementation frameworks, an analysis of their scope and depth is conducted along the PMS implementation framework. Various approaches have been developed to understand the dimensions of a successful PMS implementation. The SPMM, designed by Möller et al. [12], offers an approach to guide companies through the introduction of PMS with a heavily focused controlling-related perspective. Building on these implementation models as well as other models and empirical surveys, Grünbichler and Klučka developed a three-phase model that provides a holistic framework for a PMS implementation. The authors extend their model to focus on further management approaches such as knowledge, risk, change, communication, and project management that are relevant for a successful PMS implementation. [9] Given the cross-disciplinary approach, Grünbichler and Klučka's [9] approach is used to evaluate OKR implementation frameworks. The planning phase includes all criteria that address the preparation of the implementation, whereas the application phase covers the practical implementation of the PMS. The reporting phase is dedicated to the overall evaluation of the implementation process [9]. The results of the analysis of the OKR implementation frameworks are shown in table 2. It presents the success criteria for a PMS implementation which were derived using the three-phase model. The table reviews the extent to which the PMS implementation success criteria are reflected in the OKR implementation frameworks. The qualitative analysis results of the 15 OKR implementation frameworks are broken down into three different stages: full overlap (full ball), partial overlap (half ball), no overlap (empty ball), see figure 2.

PMS success criteria	OKR implementation framework														
[9] p.50-53	[5] p.9-170	[4] p.27-187	[19] p.136-138	[22] p.441-443	[26] p.104-110	[21] p.2-7	[25] p.2-6	[28] p.272-283	[18] p.142-151	[17] p.677-680	[20] p.i-28	[23] p.1-4	[24] p.51-54	[16] p.10-13	[27] p.212-215
Phase 1: Planning															
Sensitize management for need of PM	◑	●	○	○	●	○	○	◑	○	○	○	○	◑	◑	○
Define/ concrete vision, objectives & strategies	●	●	●	●	●	○	○	●	◑	○	○	○	●	●	○
Knowledge management	○	○	●	●	○	○	○	○	○	○	◑	◑	○	○	◑
Allocation of resources	○	○	○	○	○	○	○	○	◑	○	○	◑	○	○	○
Define key objectives in consideration of vision	●	◑	◑	●	◑	○	◑	●	◑	●	●	◑	●	◑	◑
Define KPIs for all areas	◑	◑	◑	○	◑	○	◑	○	○	◑	●	○	○	○	●
Risk management	○	○	○	○	○	◑	○	○	◑	○	◑	◑	○	○	○
Phase 2: Application															
Adapt management system	◑	●	◑	○	◑	◑	○	●	○	○	◑	○	●	○	●
Change management	◑	◑	●	◑	○	○	○	●	○	○	◑	○	◑	○	◑
Pilot project	●	●	○	○	○	◑	○	○	○	○	○	○	○	○	●
Communication management	●	●	●	●	◑	◑	○	●	○	○	◑	○	●	◑	◑
Implement measures & KPIs	◑	◑	○	○	●	○	○	●	○	●	●	●	○	○	○
Phase 3: Reporting															
Raise acceptance	◑	◑	○	◑	◑	○	○	◑	○	◑	○	◑	○	○	○
Evaluate project implementation	○	○	○	◑	●	○	◑	○	○	●	○	○	◑	○	○
Evaluate communication	○	○	○	○	○	○	○	○	○	●	○	○	○	○	○
Reviewing objectives, KPIs & measures	●	●	○	○	●	○	◑	◑	○	◑	○	●	◑	●	●

Legend Full overlap ● Partial overlap ◑ No overlap ○

Figure 2: Analysis of OKR implementation frameworks according to the phases of the PMS implementation

For the analysis of the different OKR frameworks, the three phases structure was used, initially starting with the **planning phase**. The planning phase includes all steps that are necessary before implementing a PMS to ensure further success. This phase defines the responsibilities of team members, their objectives, and the schedule. A closer look at the planning phase reveals that none of the OKR implementation frameworks cover all seven PMS success criteria. Seven [24,18,4,25,26,5,20] out of fifteen OKR implementation frameworks cover four criteria of the planning phase, thus reflecting the highest overlap, mainly focusing on strategy, goal setting and KPIs. On the other hand, further criteria as knowledge and risk management are less discussed. The frameworks of Higgins and Madai [21] addresses only one criterion (*risk management*) and Rahmah et al. [22] and Cao [17] cover two success criteria which also focus on goal setting and KPIs, showing the lowest overlap. The detailed analysis shows that the criterion *define key objectives in consideration of vision* is most frequently represented in the OKR implementation frameworks, within fourteen of fifteen publications. The only exception is the OKR framework by Higgins and Madai [21], which does not address this criterion. In the planning phase the OKR implementation frameworks primary concentrate on goal setting in the light of the overall vision and strategies. In contrast, *allocation of resources* and *risk management* as well as *sensitize management for need of PM* are rarely mentioned. For successful implementation of OKR, the management level must embody and embrace OKR. The leadership team must be convinced of the method so that a successful and long-term implementation is guaranteed. A lack of resource planning for the entire implementation process and a lack of risk management could trigger implementation barriers. Accordingly, it is recommended to define all necessary resources, in terms of time, personnel and consequently budget, in advance of implementation to increase planning certainty. Risk management can help to ensure that implementation risks are identified, evaluated, and corrected at an early stage.

The **application phase** aims to integrate the KPIs within the PMS, resulting in changes of organizational structure, incentive system and processes. In addition, the KPIs need to be included in the overall reporting to systematically control the objectives during the year. In the application phase, the OKR implementation frameworks by Niven and Lamorte [5] and Doerr [4] cover all of the five success criteria, whereas *pilot project* and *communication management* have a complete fit. The criterion a*dapt management system* is fully addressed by Doerr [4] and partly considered by Niven and Lamorte [5]. Both, van Oijen [23] and Heinäluoma et al. [25] do not refer to *pilot project*, whereas van Erp et al. [28] does not go into more detail about *implement measures & KPIs*. It is noticeable that Rahmah et al. [22] and Berntzen et al. [24] do not consider any of the success criteria and the implementation frameworks of Cao [17] and Koldyshev et al. [26] only refer to the criterion *implement measures & KPI*s. In the application phase, it is noticeable that the frameworks especially map the PMS criteria of *communication management*, *adapt management system,* and *change management*. Accordingly, there is a high level of awareness that the implementation process requires an adaptation of the previous management system. Organizational structures and processes as well as the general incentive system need to be adapted accordingly. Communication is also considered important, ensuring that all involved parties are informed sufficiently [18,21]. In contrast, the measure of introducing a pilot project is only considered by four authors [4,21,5,28]. With the help of a pilot project, problems can be identified at an early stage and appropriate measures can be taken to increase the success of an organization-wide rollout.

The **reporting phase** serves to review the PMS implementation. Here, it is evaluated whether the KPIs are suitable, the communication fulfills its purpose, and the PMS has been accepted by the employees. Within the reporting phase solely the paper by Cao [17] includes all four implementation criteria *raise acceptance, review objectives, KPIs & measures* and *evaluate communication*. In contrast, four OKR implementation frameworks [24,18,25,21] make no reference to any of the success criteria in the third phase. Five OKR implementation frameworks [17,25,27,22,20] *evaluate project implementation* in more detail, with a high degree of overlap. *Evaluate communication*, on the other hand, is only addressed in the paper by Cao [17]. Accordingly, a high focus is placed on the evaluation of the achievement of objectives. To *evaluate communication*, on the other hand, is only addressed by one paper and therefore does not have an overall priority. The evaluation of whether and to what extent *communication* within the implementation process was sufficient can contribute significantly to the success of the overall implementation.

It can be stated that the OKR implementation frameworks cover the PMS success criteria differently. Across the three phases, the publications by Niven and Lamorte [5] and Doerr [4] each address eleven of overall sixteen success criteria, thus showing the highest overlap. It is noticeable that those OKR implementation frameworks cover the same success criteria, with different degrees of intensity. Whereas Rahmah et al. [22] covers only criteria of the planning and reporting phase, the focus of the paper by Higgings and Madai [21] is on the application phase and the paper by Berntzen et al. [24] is limited to the planning phase. Each OKR implementation framework sets different priorities and often focuses on a specific phase. The implementation framework of Cao [17] covers two of six criteria in the planning phase, whereas only one criterion is covered in the application phase. In the reporting phase, on the other hand, all criteria are partially or fully covered. The implementation frameworks of Niven and Lamorte [5] and Doerr [4] cover success criteria within all three phases, but important success criteria are still missing which can put a successful implementation at risk. In the planning phase, the criteria *knowledge management*, *allocation of resources* and *risk management* are not covered in both frameworks, and in the reporting phase the success criteria *evaluate project implementation* and *evaluate communication* are not considered. Overall, there is a stronger focus on the application phase, compared to the planning and reporting phase. Each OKR implementation framework covers individual implementation criteria but none of them covers all PMS implementation criteria. Consequently, a holistic and comprehensive framework for implementing the OKR is not available in the literature.

5. Discussion and Conclusion

In a first step, this paper has positioned OKR within the field of PMS. A systematic literature review was conducted to identify the state-of-the-art OKR implementation frameworks, applied in practice. The identified OKR frameworks were put into a comparison to the holistic PMS implementation framework and their underlying success factors of Grünbichler and Klučka [9] to answer the research question if existing OKR implementation frameworks address the need of organizations for successful OKR implementation. The analysis shows that none of the OKR frameworks cover all PMS implementation success criteria. It is striking that the OKR implementation frameworks address the application phase, in contrast to the planning and reporting phase. Furthermore, the identified OKR frameworks mainly cover goal setting and goal achievement factors, which can be measured using specific KPIs. Soft factors that are difficult to measure, such as sensitizing management or knowledge management are less often covered, which equally contribute to implementation success. Thus, a practical and comprehensive OKR implementation framework, therefore addressing the success factors for PMS implementation. Based on the overall findings it can be deduced that there is a critical need for a central OKR implementation model that incorporates all key success criteria of practical relevance. Consequently, consisting of organization- and industry-independent success criteria which include both hard and soft factors. Applying a three-phase model of prior planning, actual application and following reporting helps to specify and monitor the implementation process and may contribute to a successful implementation. Nevertheless, each implementation process requires adaptions depending on company specifics.

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References

[1] Buchholz, U., Knorre, S., 2017. Interne Kommunikation in agilen Unternehmen. Springer Fachmedien Wiesbaden, Wiesbaden, 46 pp.

[2] Bergfors, V., 2022. Sich schneller dem permanenten Wandel anpassen. Digitale Welt 6 (2), 72–73.

[3] Demartini, C., 2014. Performance Management Systems. Springer Berlin Heidelberg, Berlin, Heidelberg, 215 pp.

[4] Doerr, J.E. (Ed.), 2018. Measure what matters: How Google, Bono, and the Gates Foundation rock the world with OKRs, International ed. ed. Portfolio/Penguin, New York, New York, 306 pp.

[5] Niven, P.R., Lamorte, B., 2017. Objectives and key results: Driving focus, alignment, and engagement with OKRs. John Wiley & Sons, Inc, Hoboken, New Jersey, 224 pp.

[6] Teipel, P., Alberti, M., 2019. Vision und Strategie verwirklichen mit OKR. Controlling & Management Review (5), 34–39.

[7] Maasik, A., 2018. Objectives and Key Results: The Book: The advanced guide to using OKRs.

[8] Ferreira, A., Otley, D., 2009. The design and use of performance management systems: An extended framework for analysis. Management Accounting Research 20 (4), 263–282.

[9] Grünbichler, R., Klučka, J., 2019. Die Einführung eines Performance Management-Systems: Ein integriertes Implementierungsmodell für kleine und mittlere Unternehmen. CAMPUS 02 - Fachhochschule der Wirtschaft FH-Studienrichtung Rechnungswesen & Controlling, Graz, 78 pp.

[10] Bititci, U., Garengo, P., Dörfler, V., Nudurupati, S., 2012. Performance Measurement: Challenges for Tomorrow*. International Journal of Management Reviews 14 (3), 305–327.

[11] Cocca, P., Alberti, M., 2010. A framework to assess performance measurement systems in SMEs. International Journal of Productivity and Performance Management 59 (2), 186–200.

[12] Möller, K., Wirnsperger, F., Gackstatter, T., 2015. Performance Management–Konzept, Erfahrungen und Ausgestaltung einer neuen Disziplin. Controlling 27 (2), 74–80.

[13] Chowdhury, S., Hioe, E., Schaninger, B., 2018. Harnessing the power of performance management. McKinsey & Company, April 5.

[14] Krause, O., 2006. Performance Management: Eine Stakeholder-Nutzen-orientierte und Geschäftsprozess-basierte Methode. Zugl.: Berlin, Techn. Univ., Diss., 2005, 1. Aufl. ed. Deutscher Universitäts-Verlag, Wiesbaden, 307 pp.

[15] vom Brocke, J., Simons, A., Niehaves, B., Riemer, K., Plattfaut, R., Cleven, A., 2009. Reconstructing the Giant: On the Importance of Rigour in Documenting the Literature Search Process, in: , 17th European Conference on Information Systems (ECIS).

[16] Sowkasem, C., Kirawanich, P., 2021. A Deliverable Delay Management of Software Development in Railway Project using an OKR-Based Scrum Process, in: 2021 The 4th International Conference on Software Engineering and Information Management. ICSIM 2021: 2021 The 4th International Conference on Software Engineering and Information Management, Yokohama Japan. 16 01 2021 18 01 2021. Association for Computing Machinery, New York,NY,United States, pp. 10–16.

[17] Cao, R., 2021. Research on Teaching Evaluation System of Higher Vocational Colleges Based on OKR and Big Data, in: IEEE the 16th International Conference on Computer Science & Education (ICCSE 2021). August 17-19, online conference. 2021 16th International Conference on Computer Science & Education (ICCSE), Lancaster, United Kingdom. 8/17/2021 - 8/21/2021. IEEE, Piscataway, NJ, pp. 676–680.

[18] Charoenlarpkul, C., Tantasanee, S., 2019. A Proposed Employee Development Program from Objectives and Key Results: A Case Study of SG Group of Companies. ABAC ODI Journal Vision. Action. Outcome 6 (2), 133–151.

[19] Klanwaree, N., Choemprayong, S., 2019. Objectives & key results for active knowledge sharing in IT consulting enterprises: A feasibility study. Proceedings of the Association for Information Science and Technology 56 (1), 441–444.

[20] Trinkenreich, B., Santos, G., Barcellos, M.P., Conte, T., 2019. Combining GQM+ Strategies and OKR: Preliminary Results from a Participative Case Study in Industry, in: Franch, X., Männistö, T., Martínez-Fernández, S. (Eds.), Product-Focused Software Process Improvement. 20th International Conference, PROFES 2019, Barcelona, Spain, November 27–29, 2019, Proceedings, 1st ed. 2019 ed. Springer, Cham, pp. 103–111.

[21] Higgins, D., Madai, V.I., 2020. From Bit to Bedside: A Practical Framework for Artificial Intelligence Product Development in Healthcare. Advanced Intelligent Systems 2 (10), 2000052.

[22] Rahmah, A., Sukmasetya, P., Syaiful Romadhon, M., Adriansyah, A.R., 2020. Developing Distance Learning Monitoring Dashboard with Google Sheet: An Approach for Flexible and Low-Price Solution in Pandemic Era, in: 2020 International Conference on ICT for Smart Society (ICISS). 2020 International Conference on ICT for Smart Society (ICISS), pp. 1–6.

[23] van Oijen, P., 2020. Driving Value Creation Through Proper Design of Goal Realization Frameworks. Journal of Creating Value 6 (2), 271–285.

[24] Berntzen, M., Stray, V., Moe, N.B., 2021. Coordination Strategies: Managing Inter-team Coordination Challenges in Large-Scale Agile, in: Gregory, P., Lassenius, C., Wang, X., Kruchten, P. (Eds.), Agile Processes in Software Engineering and Extreme Programming. 22nd International Conference on Agile Software Development, XP 2021, Virtual Event, June 14–18, 2021, Proceedings, 1st ed. 2021 ed. Springer International Publishing; Imprint Springer, Cham, pp. 140–156.

[25] Heinäluoma, E., Lannoo, K., Parlour, R., 2021. Anti-money laundering in the EU: Time to get serious. Centre for European Policy Studies, Brussels, 57 pp.

[26] Koldyshev, M.V., Stoliaruk, K.S., Shpynkovskyi, O.O., Mital, O.H., Yamnenko, H.Y., Dovban, I.M., 2021. HR Management Efficiency Facotor and Their Impact on Creation of a commercial innovative product. Journal of Management Information and Decision Sciences 24 (6), 1–8.

[27] Mangipudi, M.R., Prasad, K., Vaidya, R.W., 2021. Objectives and Key Results for Higher Educational Institutions–A Blended Approachas Part of Post Covid-19 Initiatives for Keeping the Institutions Abreast of the Industry Innovations, Create Future Leaders and Build the Nation. Pacific Business Review International 13, 46–56.

[28] van Erp, T., Rytter, N.G.M., Sieckmann, F., Larsen, M.B., Blichfeldt, H., Kohl, H., 2021. Management, Design, and Implementation of Innovation Projects: Towards a Framework for Improving the Level of Automation and Digitalization in Manufacturing Systems, in: 2021 9th International Conference on Control, Mechatronics and Automation (ICCMA). 2021 9th International Conference on Control, Mechatronics and Automation (ICCMA), Belval, Luxembourg. 11/11/2021 - 11/14/2021. IEEE, [S.l.], pp. 211–217.

[29] Otley, D., 1999. Performance Management: A Framework for Management Control Systems Research. Management Accounting Research 10, 363–382.

[30] Simons, R., 1995. Control in the Age of Empowerment. Harvard Business Review (73), 80–88.

[31] Probst, G.J.B., Gomez, P. (Eds.), 1993. Vernetztes Denken: Ganzheitliches Führen in der Praxis, 2., erw. Aufl., Nachdr ed. Gabler, Wiesbaden, 341 pp.

[32] vom Brocke, J. Referenzmodellierung. Dissertation, 2., unveränderte Auflage ed.

Biography

Clara Herkenrath holds an M.Sc. RWTH degree in Civil Engineering and Business Administration from the RWTH Aachen University. She is currently doctoral candidate at the FIR Institute for Industrial Management. Her specific focus is in the area of the digital leadership and organization design for the manufacturing industry.

Gerrit Hoeborn, M.Sc. M.Sc., is head of the business transformation department at RWTH Aachen University. He joined the department after his studies in industrial engineering at the RWTH Aachen University and Tsinghua University. His research focus is business transformation and digital business strategies.

Prof. Volker Stich is head of the Institute for Industrial Management (FIR) at the RWTH Aachen University since 1997. Prof. Dr.-Ing. Volker Stich worked for the St. Gobain Automotive Group for 10 years and led the management of European plant logistics. In addition, he was responsible for the worldwide coordination of vehicle development projects.

4th Conference on Production Systems and Logistics

Evaluation Of Business Model Innovation Towards Industry 4.0 Via Cross-Industry

Mohammadhossein Chitsazzadeh[1] , Eva Walbroel[1], Roman Senderek[1], Volker Stich[1]
[1]FIR e. V. an der RWTH Aachen, Aachen, Germany

Abstract

Innovation is one of the key drivers of growth, development, and profitability, which increases competitive advantages and has recently been moving towards industry 4.0 technologically. This motivates companies to update their business models (BM) towards industry 4.0. Moreover, there is a technique with the primary characteristics for achieving this motivation called "cross-industry innovation". Cross-industry innovation is a new method of innovation that concerns the creative translation and imitation of existing solutions from other industries for responding to the needs of the current market, sectors, areas, or domains. The challenge is to find out how far managers can rely on that to innovate their BM towards Industry 4.0. The aim of this study was to investigate the application of cross-industry innovation for designing industry 4.0 BM and explore the extent to which companies can rely on it as it has not been used for this purpose previously. This study utilized a database analysis to compare cross-industry innovation practices with industry 4.0 BM's characteristics in terms of value proposition, value creation, and value capture levels. In addition, some interviews were conducted with companies that had previously implemented cross-industry innovation to validate and generalize the results. The results indicated that cross-industry innovation practices can better fulfil flexible and dynamic networks, connected information flows, high efficiency, high scalability, and high availability in terms of value creation as well as variabilization of prices and costs in terms of value capture. Therefore, it demonstrated that cross-industry innovation was a more dependable and applicable strategy for designing the BM of Industry 4.0 than current practices.

Keywords

Business Model Innovation; Industry 4.0; Cross-Industry Innovation; Value Creation; Value Capture

1. Introduction

Companies are moving towards providing customers with more detailed and tailored value offerings due to the competitive pressure of mature markets [1]–[3]. They are also constantly renewing their business models (BM) for entering and competing in new markets [4], [5]. For these purposes, established companies try to introduce value innovations and create new business models to change the competitive game in their favor [6]. From a technological point of view, business models are transferring to the fourth industrial revolution. This new revolution is not well understood by companies because it is novel and there have not been many reliable signs or results of it. Besides, this transformation is time-consuming. In this case, finding a way that could help the managers innovate their BMs while staying competitive and transferring to Industry 4.0 is necessary. [7]

While the literature on Business Model Innovation (BMI) has grown over the years, evaluations of BMI procedures and best practices, as well as BM-related discussions of Industry 4.0, are scarce. The literature examines the characteristics of Industry 4.0 BMs, assesses how firms approach BMI in the context of Industry 4.0, finds best practices, and compares them to Industry 4.0 BM characteristics (or "requirements"

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in reverse). It demonstrated how a systematic BMI process may supplement existing processes for product or service development, as well as how a specialized BMI process might improve innovation performance during Industry 4.0 and beyond. However, it is not possible to provide a success factor-based approach for investigating BMI activities and processes in a large sample of companies that could yield fundamental results and cover all the differences between companies. Furthermore, it is not possible to cover the effect of these differences because of the specific behavior of companies. Moreover, by investigating the papers in the Business Information System, some other challenges can be found, such as a lack of knowledge and a lack of employee readiness in companies for innovating in the BMs towards Industry 4.0. [8] For this purpose, this research seeks a new methodology in BMI that could be applied to different companies and industries for innovating in BMs towards Industry 4.0. This methodology should be tailored to each company while meeting the characteristics of Industry 4.0 and related goals.

Searching the sources and reviewing related papers on BMI and innovation leads to the discovery of a new innovation methodology known as "cross-industry innovation." This methodology, basically works by taking inspiration from other industries that are facing similar problems and trying to adapt and implement it in our own industry. It has been structured and developed in 2015 by Ramon Vullings and Marc Heleven [9]. This methodology has never been applied to design the BM towards industry 4.0 before, however, it shows some promise of applicability at the first sight. It integrates different sources of inspiration, such as products, services, BMs, etc., and adapts them to the company's needs, to show some early results of that innovation in another company. For investigating the usage of cross-industry innovation for designing the BM toward industry 4.0, a comparison of its practices with existing best practices of the BMI was implemented, and the practices were mirrored with industry 4.0 characteristics. For this purpose, nine interviews were conducted with companies and the founders of cross-industry innovation. These companies used cross-industry innovation to steer their BMs toward new technologies. Finally, an interview with the founders was devised to validate and generalize the findings.

These considerations lead to the following question being formulated:

- How far can we rely on cross-industry innovation for designing the BM of Industry 4.0 and replace it with traditional practices?

It is important to identify the aims of the study, which reflect the logical processes as follows:

- Monitoring the usage of cross-industry innovation for the BMI of Industry 4.0
- Comparing cross-industry innovation with current practices for BMI of industry 4.0
- Identifying the constraints to improving the use of cross-industry innovation

The goal of the research is to introduce cross-industry innovation as an optimal and systematic way for designing the business model of industry 4.0 in companies and to cover a large number of companies in different industries for business transformation.

2. Literature review

2.1 Business Model Innovation

Foss & Saebi [10] defined BMI as "designed, novel, nontrivial changes to the key elements of a firm's business model and/or the architecture linking these elements". Therefore, BMI process is a change phenomenon which can lead to a business innovation process [11], [12]. BMI redefines the essence of the company value proposition, changing the nature of products and services and how they should be delivered to customers. This provides an opportunity to establish a long-term competitive advantage and differentiate from competitors. BMI investigates the various stages that businesses go through to. It also identifies the organizational capabilities and processes required to support innovation [13]–[15]. In the literature, several scholars began examining BMI led by new ventures, which, in their early phases of development, frequently experience change and innovation [15]. Besides, some others considered large corporations the focus of BMI since they needed to change and evolve their businesses [16].

2.2 Industry 4.0

The term "Industry 4.0" was first coined by the German government to promote manufacturing computerization and refers to the fourth industrial revolution (the digital revolution) [17]. Industry 4.0 thus refers to providing devices with sensors through which they are given the capability to communicate. In the last decade, the expression has included more spheres like transportation, healthcare, utilities, etc. It includes a series of smart connected objects and a network connectivity architecture that enables them to exchange information and become active participants [18]. This has the result of creating a network of things that can communicate with each other without the need for human help. The expanded capabilities of smart, connected products, as well as the data generated by them, have unleashed a new era of competitiveness, exposing businesses to new opportunities and threats [19]. Finally, combining these three extended capabilities enables autonomous product operations, self-coordination of the unit with other units and systems, autonomous product upgrades and personalization, and self-diagnosis and servicing. Leminen et al. [20] stated that the diffusion and growth of Industry 4.0 suggest possibilities for the redesign of the business model, which refers to value co-creation and redesigning value propositions in the field of Industry 4.0, as claimed by Mejtoft [21]. Industry 4.0 is shifting business models because of three main fundamental properties of digital technologies: the exact transmission of the signal, the infinite replication of the signal without degradation, and, once the investment in the network infrastructure has been made, the zero (or almost zero) marginal cost of this replication. These features are enabled by ubiquitous digital technology and improve the scalability of operations, facilitating the combination of new and old business processes [20]. In other words, it connects industries and communities to create opportunities. The numerous potentialities have been appreciated by the market, and the global Industry 4.0 market was valued at $170 billion in 2017 and is predicted to expand to $561 billion by 2025 [22].

2.3 Cross-industry Innovation

Nowadays, innovation is seen as one of the main driving forces for growth, development, and profitability. The problem is that most innovations are limited to the recombination of existing knowledge or technology that has been developed within the company, or at least within our own industry. According to various studies, most of the innovation sources are internal ones and partners within our own industry are among the most important sources of innovation. It is hard to generate major innovations as most products, services, and business models have largely been shaped by the mind-set of their respective industries and most industries are quite mature. Furthermore, the innovation between partners is considered a source of threat instead of opportunity. Drivers of innovation such as technology diffusion, shorter innovation cycles, worker mobility across industries, and global knowledge availability have simplified and expedited access to external innovation sources. Cross-industry is a new method of innovation that is about creative translation and imitation of existing solutions from other industries to meet the needs of the current market, sector, area, or domain. Such solutions can be technologies, patents, specific knowledge, capabilities, business processes, general principles, whole business models, or a combination of them [9]. Furthermore, using external knowledge in our own enterprise—cross-industry innovation—can be used as a tool for transferring our own technology to other industries for innovation. While the outside-in process leads to higher innovativeness, the inside-out process generates additional turnover with relatively little effort [9]. Businesses frequently search across industry boundaries and execute cross-industry innovation while striving for breakthrough innovations. Successful cross-industry innovation requires the integration of external partners with diverse perspectives, mind-sets, and educational backgrounds who are motivated to contribute to the development of novel ideas, concepts, techniques, and technologies [23].

3. Methodology

3.1 Research Design

Given the theory restrictions found after the literature review, we decided to investigate some specific case studies for the development of inductive theory (Figure 1). Case study building theory can be defined as an approach for research involving the development of theoretical buildings, suggestions, and/or midrange theories based on case empirical evidence with the help of one or many instances [24]. Simultaneously, case studies can be described as strong, empirical descriptions, typically based on a range of information sources, of specific phenomena cases [25].

3.2 Data Collection

Data was gathered through 9 structured interviews conducted in accordance with previously distributed interview instructions with companies and founders of cross-industry innovation. The primary filter to case selection was to focus and deepening on those companies which innovate designing their business models towards new technologies by cross-industry innovation. It was decided to consider all of them as primary cases and ask their CEOs or related managers to participate in an interview via different communication paths (i.e., email, LinkedIn, and the company website) in order to extract and obtain the desired data from their companies. The interview guidelines were divided into three sections that covered the interviewees' grasp of Industry 4.0, their BMI approach and cross-industry innovation methodologies. Its structure is based on Zellner's model of business process components [26]. This paradigm separates a trigger (the event that initiates the process), activities and flow (a task (process) undertaken to achieve set goals and their sequence), organization (department, unit, or individual performing the activity), and resources (methods or tools supporting the activities).

3.3 Data Analysis

Our data analysis follows qualitative research methods [27]–[29]. We employ an inductive approach, evaluating and then interpreting the facts as Spiggle suggests [30]. According to this method, data analysis encompasses categorization, abstraction, comparison, dimensionalization, integration, iteration, and refutation. We began by mirroring the Industry 4.0 BM characteristics with cross-industry practices, and we put them together in a table to understand that which practices could meet more the requirements for designing a BM for industry 4.0. The process will be followed by comparison of the best practices of BMI to cross-industry innovation practices in the joint table (Table 1). In this table, the almost same practices were placed in front of each other to obtain better comparison. The final results were iterated and changed if needed with the cross-industry innovation founders.

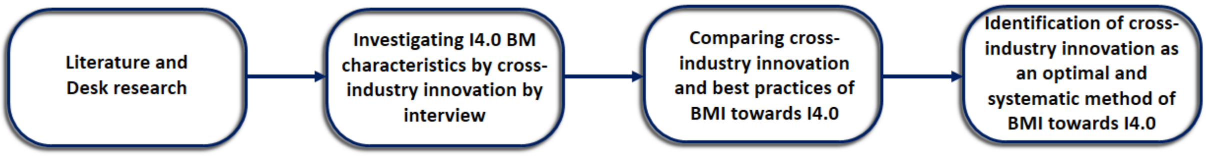

Figure 1- Research process (I4.0 is Industry 4.0)

4. Results and Discussion

In this section, we show our findings utilizing Zellner's business process components [26]. These also aided in organizing our data collection procedure. We began by describing the opportunities that initiate a BMI process, then defined its typical actions and tasks, remarked on organizational challenges, and discussed the resources (tools) used to support these activities.

4.1 Cross-industry innovation process

The main cross-industry innovation processes are cross-industry canvas, looking sideways by questioning and getting inspiration from another industry, and getting insights from desk research, interviews, and company visits.

From a value creation point of view, the innovation process can be controlled by using Cross-Industry Canvas. This connects information at different levels, which can improve efficiency and scalability.

The first company could innovate its BM by cross-industry canvas to reduce services to just the necessary ones, making efficient use of infrastructure, maximum use of assets, yield management, and no frills with

regard to other industries. Their source of innovation for these achievements was a systematic scan of markets, questioning their cost model and services with a price-elastic demand curve and high potential to increase customer integration. It results in making many successful and promising new business models.
It does not necessarily require inventing a new value for the design of VPs through cross-industry innovation. It is possible to find value in other industries by questioning. Take looking sideways with defined questions about our problem to aid in finding already implemented solutions. Finding various types and types of inspiration is critical due to the wide range of industries.
The second company, which made fleet management decisions regarding building tools, ensures that building tools in use through service contracts are in optimal condition. Their source of innovation was automotive fleet management, which focuses on long-term service contracts instead of selling cars.
The strong market research in this methodology results in focusing on customers at different levels and providing tailored services. Then, synchronization of the services is achieved by adapting the concepts of other industries to their target customers.
The third company could increase rail worker safety by cooperating with lead users to produce a dirt-resistant jacket. The new technology discovered through questioning and inspiration from another industry, as well as insights through desk research, interviews, and company visits, was the root of their creativity.
The fourth company invented the first Internet-compliant sewing machine that could directly download the sewing patterns to facilitate the machines. Their source of innovation was driven by customer requests on their website, which were gotten from desk research.
The cross-industry innovation process in these companies resulted in increasing the flexibility of the process, overcoming the experience gap, and reducing development time. Therefore, the main goals of our innovation process for BMI towards Industry 4.0 are completely achieved and perform better compared to other practices due to the nature of cross-industry innovation. Furthermore, all participants in our study believe that the cross-industry innovation process offers new value propositions and advancements in value-creating structures.

4.2 Cross-industry innovation at the organizational level

Significant disparities in the organizational anchoring of BMI processes were discovered. BMI is frequently sponsored by high management. In most organizations, the BMI project lead is either a technology manager with a background in research and innovation or a business manager, such as a member of the business unit management, product management, or business development departments. According to interviewees, governance is a success factor, however, we don’t have any special policy in cross-industry innovation at the organizational level of the company and it should be provided by other practices. The main cross-industry innovation method at the organizational level is using open sources of innovation from different industries and remixing your industry which provides a wide range of inspiration for innovation. The variability of industries and methodologies resulted in different values with different costs and prices. In this case, it is possible to observe the results of their pricing methodologies and try not to repeat their mistakes. Furthermore, the resulted pricing policy is better and more flexible than the original industry's policy.

The fourth company added sensors to the sewing machine's pressure foot, which measure and regulate speed, resulting in consistent stitches for beginners as well. Their source of innovation came from their cooperation with another company, which uses the same technology for producing optimal computer mouse devices.

The fifth company made it possible to plan sanitary installations with enormous cost savings of up to six digits. Their source of innovation was their collaboration with another company that uses the same technology for power plant planning.

The sixth company found a new method to connect glass fibers without using mechanical pressure by using adhesion technology. Their source of innovation was their collaboration with another company that works in the chemicals industry.

At this level, the cross-industry innovation strategy resulted in openness, pragmatism, and entrepreneurial thinking, which are the primary goals of BMI toward Industry 4.0. However, it was not possible to expand roles and duties at the organizational level, so other methods must fill the void.

4.3 Cross-industry innovation resources and toolkits

BMI necessitates the use of specialized resources and tools. Their development and deployment appear to be dispersed across firms today. The spectrum extends from having no specific BMI toolkit at all to having a sophisticated and IT-supported solution in place. Osterwalder's BM Canvas [31] is a popular tool for structuring BM ideas, and Gassmann's BM Patterns [32] is a tool for creative assistance. Most interviewees complain that these tools are too high-level, too restricting within the limitations they provide, and lack consistency across the process. Cross-industry innovation, on the other hand, has a large range of particular toolkits for VP and VCr, such as the transfer map, 21 methods, and so on. Experimenting with the outcomes and applying the lessons learnt is another approach of cross-industry innovation that is utilized by all firms to evaluate their innovation processes.

The first company used management toolkits for the efficient use of infrastructure, the maximum use of assets, and yield management. The toolkits aid in the production of value and the reduction of time in accordance with the company's aims. As a result, it expedites the launch of the product or service and assists it in reaching the target market.

The seventh company used a transfer map to use new technologies to become a successful automotive supplier and security process service provider. Their own military aircraft division was source of innovation based on internal experimentation and data.

Cross-industry innovation tools and resources support companies in optimizing their innovation processes and making new decisions. Moreover, they create a structure for the innovation process that guides companies during the process.

4.4 Cross-industry innovation practices for BMI towards Industry 4.0

Table 1 contrasts the properties of BMs for Industry 4.0 (rows) with cross-industry innovation practices (right columns) and BMI best practices (left columns) to summarize our findings and observations [33]. We identified essential BMI competencies that are relevant across most dimensions by highlighting significantly best practices for developing Industry 4.0 BMs (marked as "X" at the intersections in the table) and cross-industry innovation practices (marked as "✓" at the intersections in the table).

Table 1 illustrates that cross-industry innovation practices can support more characteristics on their own compared to other practices that are already applied separately in companies. As previously stated, all objectives were met, particularly the reduction of development time and product-service distinction in contrast to other techniques. However, we don’t have any special policy on cross-industry innovation at the organizational level of the company, and it should be provided by other practices. The results indicated that cross-industry innovation practices can better fulfill flexible and dynamic networks, connected information flows, high efficiency, high scalability, and high availability in terms of value creation, as well as variabilization of prices and costs in terms of value capture. At the final step, the results were iterated in an interview with cross-industry innovation founders to ensure their validation and generalization. They had seen more companies that used these methodologies for these purposes; therefore, they guaranteed the validation of these results with a larger number of companies.

It is understood, both theoretically and empirically, that cross-industry innovation methods can match the features of industry 4.0 at many levels of its BM, including value proposition, value creation, and value capture. Furthermore, cross-industry innovation techniques outperformed current BMI best practices in terms of meeting the aims of Industry 4.0 BM. They can be considered at several levels of the organization,

Table 1: Existing and cross-industry practices

BMI Best Practices	Industry 4.0 BM Characteristics: High product/service differentiation/ customization	End-customer focus, B2B2C	Comprehensive Service business	Synchronized product/service combinations/ VAS	Value chain integration, consolidated control	Flexible and dynamic VCr networks	Connected information flows	Close (End-) customer relations, B2B2C	Short time-to-market	High efficiency	High scalability	High availability, preventive maintenance	Value appropriation from data/digital structures	Variabilization of prices and costs	Cross-industry Practices
Agile, iterative, proactive and open BMI process	✓ X	✓ X	✓ X	✓ X	✓ X	✓ X	✓ X	✓ X	✓ X	✓	✓	✓	✓ X	✓ X	BMI by Cross-industry Canvas
Inter-departmental and cross-entity collaboration Intra-industry knowledge transfer	✓ X	✓ X	✓ X	✓ X	✓ X	✓ X	✓ X	✓ X	✓ X	✓ X	✓ X	✓ X	✓ X	✓ X	Looking sideways by questioning and inspiration from another industry for finding the answer in them
Feedback loops with customers	✓ X	✓ X	✓ X	✓ X	✓	✓	✓ X	✓ X	✓ X	✓			✓ X		Getting insights from desk research, interviews and company visits
Open organization with dedicated BMI or I4.0 team with interdisciplinary staffing and partner	X	X	X	X	X	X	X	X	X	X	X	X	X		Not a specific organizational strategy at high levels of innovation
Entrepreneurial culture with freedom and responsibility	✓ X	✓ X	✓ X	✓ X	✓ X	✓ X	✓	✓ X	X	✓	✓	✓	✓ X	✓ X	Open source of innovation from different industries and remix your industry
Dedicated BMI toolkit (BM structuring + VP modelling framework)	✓ X	✓ X	✓ X	✓ X	✓ X	✓ X	✓ X	✓ X	✓ X	✓	✓	✓	✓ X	✓	Special toolkits for VP and VCr like transfer map, 21 ways and etc.
Ecosystem analysis methodology tools and networking skills	✓ X	✓ X	✓ X	✓ X	✓ X	✓ X	✓ X	✓ X		✓	✓ X	✓	✓ X	✓	Experimenting the results and Adapting the lessons learned

✓= Identified cross-industry practices that are supportive or critical for this issue / X = Identified existing practices that are supportive or critical for this issue such as process, organization, and resources and tools for attaining goals. However, it lacks a high-level organizational strategy for innovation and should be supplemented by other techniques.

The first drawback of the findings is that the information was gathered through a small number of interviews and one specific actor role. In the future, it would be beneficial to work on large-scale databases with a broader collection of informants. This allows for a more in-depth examination of the phenomenon. Another disadvantage is the lack of quantitative data, which necessitates assigning weights to features in order to make appropriate practice comparisons.

5. Conclusion

We can extract knowledge and make original additions to the existing literature even if it is based on particular case studies. These studies helped obtain a detailed picture of cross-industry innovation practices so that they could be used more efficiently. Furthermore, structuring and organizing these studies helps managers control their processes while using cross-industry practices. Moreover, these findings allow us to learn how cross-industry collaboration can help companies at various stages of their innovation process.

The current study has some consequences in practice. Our findings show that managers and entrepreneurs of established companies and start-ups can innovate their business models by pursuing an Industry 4.0 strategy through cross-industry innovation. By innovating their BM and orienting to Industry 4.0, they can disrupt the market and compete with the blue ocean approach.

Management practices can be accounted for as an example that was not mentioned in cross-industry innovation. They should dedicate a group for BMI and Industry 4.0 with interdisciplinary skills. Also, the managers should do sponsorship and create an open environment for the organization to do partnership and collaboration. Finally, it should be noted that a successful implementation of cross-industry innovation can be performed by selecting and integrating additional innovation strategies and working on them concurrently.

According to the findings, cross-industry innovation techniques can better fulfill flexible and dynamic networks, connected information flows, high efficiency, scalability, and availability in terms of value creation, as well as pricing and cost variability in terms of value capture. As a result, it revealed that cross-industry innovation was a more reliable and applicable technique than present practices for developing the BM of Industry 4.0.

References

[1] T. S. Baines, H. W. Lightfoot, O. Benedettini, and J. M. Kay, “The servitization of manufacturing: A review of literature and reflection on future challenges,” *J. Manuf. Technol. Manag.*, vol. 20, no. 5, pp. 547–567, 2009, doi: 10.1108/17410380910960984.

[2] J. Vandermerwe, S., & Rada, “Servitization of business: Adding value by adding services.,” *Eur. Manag. J.*, pp. 314–324, 1988.

[3] P. Wise, R., & Baumgartner, “Go downstream: The new profit imperative in manufacturing.,” *Harv. Bus. Rev.*, pp. 89–96, 2000.

[4] V. Sabatier, V. Mangematin, and T. Rousselle, “From Recipe to Dinner: Business Model Portfolios in the European Biopharmaceutical Industry,” *Long Range Plann.*, vol. 43, no. 2, pp. 431–447, 2010, doi: https://doi.org/10.1016/j.lrp.2010.02.001.

[5] S. Winterhalter, M. B. Zeschky, and O. Gassmann, “Managing dual business models in emerging markets: an ambidexterity perspective,” *R&D Manag.*, vol. 46, no. 3, pp. 464–479, Jun. 2016, doi:

https://doi.org/10.1111/radm.12151.

[6] W. C. Kim and R. Mauborgne, “Fair process: managing in the knowledge economy.,” *Harv. Bus. Rev.*, vol. 75, no. 4, pp. 65–75, 1997.

[7] A. G. Frank, G. H. S. Mendes, N. F. Ayala, and A. Ghezzi, “Servitization and Industry 4.0 convergence in the digital transformation of product firms: A business model innovation perspective,” *Technol. Forecast. Soc. Change*, vol. 141, no. January, pp. 341–351, 2019, doi: 10.1016/j.techfore.2019.01.014.

[8] A. Calabrese, M. Dora, N. Levialdi Ghiron, and L. Tiburzi, “Industry’s 4.0 transformation process: how to start, where to aim, what to be aware of,” *Prod. Plan. Control*, vol. 0, no. 0, pp. 1–21, 2020, doi: 10.1080/09537287.2020.1830315.

[9] R. Vullings and M. Heleven, *Not invented here cross-industry innovation*. 2015.

[10] N. J. Foss and T. Saebi, “Fifteen Years of Research on Business Model Innovation: How Far Have We Come, and Where Should We Go?,” *J. Manage.*, vol. 43, no. 1, pp. 200–227, 2016, doi: 10.1177/0149206316675927.

[11] A. Cavallo, A. Ghezzi, and B. V. Ruales Guzmán, “Driving internationalization through business model innovation,” *Multinatl. Bus. Rev.*, vol. 28, no. 2, pp. 201–220, Jan. 2020, doi: 10.1108/MBR-11-2018-0087.

[12] L. Massa and C. L. Tucci, “Business model innovation,” 2014.

[13] K. Girotra and S. Netessine, “Business model innovation for sustainability,” *Manuf. Serv. Oper. Manag.*, vol. 15, no. 4, pp. 537–544, 2013, doi: 10.1287/msom.2013.0451.

[14] B. Demil and X. Lecocq, “Lecocq, X.: Business Model Evolution: In Search of Dynamic Consistency. Long Range Planning 43, 227-246,” *Long Range Plann.*, Apr. 2010, doi: 10.1016/j.lrp.2010.02.004.

[15] P. P. McDougall and B. M. Oviatt, “New venture internationalization, strategic change, and performance: A follow-up study,” *J. Bus. Ventur.*, vol. 11, no. 1, pp. 23–40, 1996, [Online]. Available: https://econpapers.repec.org/RePEc:eee:jbvent:v:11:y:1996:i:1:p:23-40.

[16] L. Achtenhagen, L. Melin, and L. Naldi, “Dynamics of Business Models – Strategizing, Critical Capabilities and Activities for Sustained Value Creation,” *Long Range Plann.*, vol. 46, pp. 427–442, Dec. 2013, doi: 10.1016/j.lrp.2013.04.002.

[17] European Commission, “Digital Transformation Monitor Germany: Industrie 4.0,” *Digit. Transform. Monit.*, no. January, p. 8, 2017, [Online]. Available: https://ec.europa.eu/growth/tools-databases/dem/monitor/content/germany-industrie-40.

[18] S. Haller, S. Karnouskos, and C. Schroth, *The Internet of Things in an Enterprise Context*, vol.)5468. 2008.

[19] J. E. H. Michael E Porter, “How smart, connected products are transforming competition,” *Harv. Bus. Rev.*, vol. 92, no. 11, pp. 64–88, 2014.

[20] S. Leminen, M. Rajahonka, M. Westerlund, and R. Wendelin, “The future of the Internet of Things: toward heterarchical ecosystems and service business models,” *J. Bus. Ind. Mark.*, vol. 33, no. 6, pp. 749–767, 2018, doi: 10.1108/JBIM-10-2015-0206.

[21] T. Mejtoft, “Internet of Things and Co-creation of Value,” Oct. 2011, doi: 10.1109/iThings/CPSCom.2011.75.

[22] F. B. Insights, “The global industry 4.0 market is projected to grow from $130.90 billion in 2022 to $377.30 billion by 2029, at a CAGR of 16.3% in forecast period, 2022-2029... Read More at:- https://www.fortunebusinessinsights.com/industry-4-0-market-102375,” 2021. https://www.fortunebusinessinsights.com/industry-4-0-market-102375.

[23] E. Enkel and O. Gassmann, “Creative imitation: Exploring the case of cross-industry innovation,” *R D Manag.*, vol. 40, no. 3, pp. 256–270, 2010, doi: 10.1111/j.1467-9310.2010.00591.x.

[24] S. Civil *et al.*, “Web of Science [5.20] - Exportar serviço de transferência http://apps-webofknowledge.ez11.periodicos.capes.gov.br/OutboundServ...,” *Acad. Manag. Rev.*, vol. 1, no. 4, pp. 12–13, 2015, [Online]. Available: http://books.google.com/books?hl=en&lr=&id=in_rMFXR3agC&oi=fnd&pg=PA3&dq=Beyond+re+engineering&ots=IViSnfKCoY&sig=iJLx4ImlLpmeDdqx5FqhGTONdzw%0Apapers3://publication/uuid/FBAD3EAE-8DDB-4DEF-A0EE-50D39461F477%0Ahttp://search.ebscohost.com/login.aspx?direct.

[25] R. K. Yin, “Validity and generalization in future case study evaluations,” *Evaluation*, vol. 19, no. 3, pp. 321–

332, Jul. 2013, doi: 10.1177/1356389013497081.

[26] G. Zellner, "Towards a framework for identifying business process redesign patterns," *Bus. Process Manag. J.*, vol. 19, no. 4, pp. 600–623, 2013, doi: 10.1108/BPMJ-Mar-2012-0020.

[27] A. L. Glaser, B. G./Strauss, *The discovery of grounded theory strategies for qualitative research*. 1967.

[28] K. M. Eisenhardt, "Building Theories from Case Study Research," *Acad. Manag. Rev.*, vol. 14, pp. 532–550, 1989.

[29] A. M. Miles, M. B./Huberman, *Qualitative data analysis: an expanded sourcebook: Sage Publications*. 1994.

[30] S. Spiggle, "Analysis and Interpretation of Qualitative Data in Consumer Research," *J. Consum. Res.*, vol. 21, no. 3, p. 491, 1994, doi: 10.1086/209413.

[31] Y. Osterwalder, A./Pigneur, *Business Model Generation*. Hoboken: John Wiley & Sons, 2010.

[32] M. Gassmann, O./Frankenberger, K./Csik, *Geschätsmodelle entwickeln – 55 innovative Konzepte mit dem St. Galler Business Model Navigator*. 2013.

[33] C. Burmeister, D. Lüttgens, and F. T. Piller, "Business Model Innovation for Industrie 4 . 0 : Why the " Industrial Internet " Mandates a New Perspective on Innovation," pp. 124–152, 2016, doi: 10.5771/0042-059X-2016-2-124.

Biography

Mohammadhossein Chitsazzadeh earned a Master of Science in Management Engineering from the Polytechnic University of Milan, Italy, and the RWTH Aachen University, Germany. He was a project manager at FIR e. V. at RWTH Aachen. Currently, he is employed as a project manager and PhD candidate in the Advanced Systems Engineering group at the Heinz Nixdorf Institute.

Eva Walbroel has been project manager in the department Smart Work at the Institute for Industrial Management at the RWTH Aachen University (FIR at the RWTH Aachen University) since 2022. She is a psychologist in the field of work, cognitive and social psychology. Her experience, which she has gained in personnel recruitment and personnel development in a manufacturing company, has shaped her field of work.

Roman Senderek studied Economics and is responsible for the newly founded Smart Work department at FIR at RWTH Aachen, which deals with issues related to the design of customized teaching and learning solutions as well as human-oriented design that promotes learning in the digitized world of work.

Volker Stich has been the head of the Institute for Industrial Management (FIR) at RWTH Aachen University since 1997. Prof. Dr.-Ing. Volker Stich has worked for 10 years for the St. Gobain-Automotive Group and led the management of European plant logistics.

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Cascading Scenario Technique Enabling Automated And Situation-based Crisis Management

Stefan Leachu[1], Jokim Janßen[1], Natalie Gdanitz[2], Merlit Kirchhöfer[3], Sabine Janzen[2], Volker Stich[1]

[1] *Institute for Industrial Management (FIR) at RWTH Aachen, Aachen, Germany*
[2]*German Research Center for Artificial Intelligence (DFKI), Saarbrücken, Germany*
[3]*Bundesanstalt Technisches Hilfswerk (THW), Bonn, Germany*

Abstract

Crises are becoming more and more frequent. Whether natural disasters, economic crises, political events, or a pandemic - the right action mitigates the impact. The PAIRS project plans to minimize the surprise effect of these and to recommend appropriate actions based on data using artificial intelligence (AI).
This paper conceptualizes a cascading model based on scenario technique, which acts as the basic approach in the project. The long-term discipline of scenario technique is integrated into the discipline of crisis management to enable short-term and continuous crises management in an automated manner. For this purpose, a practical crisis definition is given and interpreted as a process. Then, a cascading model is derived in which crises are continuously thought through using the scenario technique and three types of observations are classified: Incidents, disturbances, and crises. The presented model is exemplified within a non-technical application of a use case in the context of humanitarian logistics and the COVID-19 pandemic. Furthermore, first technical insights from the field of AI are given in the form of a semantic description composing a knowledge graph. In summary, a conceptual model is presented to enable situation-based crisis management with automated scenario generation by combining the two disciplines of crisis management with scenario technique.

Keywords

Crisis Management; Supply Chain; Humanitarian Logistics; Scenario Technique; Scenario Pattern; Operations Planning; Resource deployment; Knowledge Representation

1. Introduction

Since 2020, the cascading effects of global crises are more perceptible as ever before. As the COVID-19 pandemic unfolded, actors in all sectors all over the world could observe as the implications of the pandemic rippled across all domains down into the everyday life of citizen. Originally being a medical domain topic, the pandemic for instance very quickly influenced air traffic due to global restrictions on international mobility. This effect alone caused large implications on the global labor market, tourism sector and caused major supply chain disruptions [1]. Besides the economic impact, the pandemic also had numerous political and social consequences. Amongst others the medical sector, education, digitization, ways of working and the cultural sector underwent major shifts and triggered interdependencies and long-term implications which are not all yet apparent. In this complexity, it becomes increasingly difficult for affected groups and actors to keep track of available information and to differentiate between relevant and irrelevant information. Methods to reduce complexity are needed and to decide on expedient actions to anticipate and minimize the effects of crises regarding their individual situation.

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In the PAIRS (Privacy-Aware, Intelligent and Resilient crisiS Management) research project, a scenario-based crisis management platform is being developed in which hybrid AI methods are used to detect and anticipate the development of crises and to identify adequate measures for each actor.

In this paper, a concept for cascading scenario technique is presented and applied to one of the project's use cases in the field of humanitarian logistics. Existing crisis management research and scenario technique are highlighted as the underlying approach to enable situation-based crisis management with automated scenario generation. First technical insights are given on how to use the model within the development of a service for operations planning of the German Federal Agency for Technical Relief (German abbr. 'THW'), an organization that acts upon crisis scenarios. We thereby apply a knowledge representation of THW's operations in the form of a semantical description that enables to create a knowledge graph serving as foundation for further technical approaches (e.g., machine learning, planning methods) in order to generate actions and planning recommendations.

2. Fundamentals of scenario technique

For long-term strategic planning, institutions use the scenario technique to make a socio-economic forecast and take appropriate preparatory measures [2–4]. The aim of the scenario technique is the generation of several scenarios (cf. Figure 1). Each of these scenarios is intended to show hypothetical consequences to draw attention to possible decision-making processes of the actors concerned [2,4].

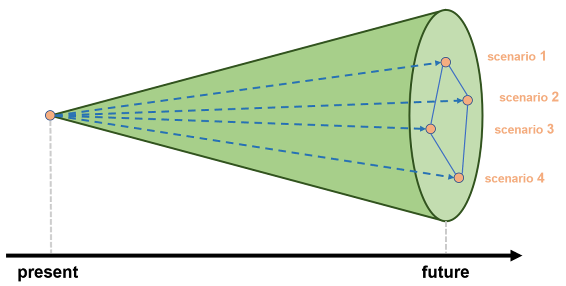

Figure 1: A scenario funnel projecting 4 different scenarios from a particular starting point

A scenario can be seen as a bundle of the most diverse characteristics of the influencing factors. The characteristics of an influencing factor can be interpreted as a spectrum between best/worst cases, which increases in magnitude on a scale like a funnel over time. This phenomenon of drifting apart of the best/worst cases is called scenario funnel. Once a wide variety of scenarios have been modelled, cluster analyses and plausibility checks are used to assess the probability of occurrence of the scenarios. A good result from a scenario analysis is not one that shows a high density and overlap with respect to other scenarios in a space. Rather, outliers should be identified as interesting cases and further examined to see how they can be controlled with decisions made by the actors. It should be emphasised that a larger number of scenarios leads to a better result but is also associated with greater effort. [2–6]

3. Related work to scenario technique in crisis management

To demonstrate the potential of continuous and automated scenario generation in crisis management, a literature review was conducted to identify the status of the use and degree of automation of scenario technology in crisis management. Aspects as the general time horizon of predictions with scenario technique and software for automated scenario generation are analyzed.

3.1 Time horizon of prediction using scenario technique

Up to now, the scenario technique is mainly used for strategy planning, which is an iterative process in business area [3]. The methods are generated in scenario projects to help strategy development. This process is designed to make a forecast from day X of the project. The time period of the forecast varies but is between 5-15 years [3,4,7]. The recommendations for action refer to an implementation solution, the realisation of which take at least 3 years. It can be seen that the timeline of the scenario generation is chosen very wide and is not observed in the short term. Study [8] analyzes the application of scenario technology in the real economy. They surveyed almost 300 companies with annual sales of more than 250 million euros. Results show 70% of the interviewed companies not using scenario techniques with a concrete plan of action for possible scenarios.

3.2 Software tools for scenario generation

Nowadays, software solutions are used to help generating scenarios. Big players are presented in the following section.

Inka 4 [9] is a software solution, which is very close to the process of scenario technique described above. The methodology is based on a consistency matrix analysis in which scenarios are formed through independent weighting and selection of the influencing factors. However, the software solution represents little to hardly any automation, let alone AI. In addition, the program is very limited in its accuracy by the data fed in by the actors themselves. Reaction measures are also left out, which ultimately offers relatively little added value for the user.

The Scenario Manager from ScMI [10] is a software solution that generates scenarios for an initially defined environment. It focuses strongly on key factors that are selected in a consortium. With the help of these factors, projections and development possibilities are presented, which should generate a landscape of scenarios through a consensus evaluation. The solution uses an automated instance to delineate core dimensions of the scenarios. However, this product only focuses on core dimensions determined from key factors. It lacks a large database that raises external trends, unless the user identifies these.

3.3 Software tools for crisis management

Available risk assessment and management software solutions tend to function in isolation. Even the functionality of "supply chain risk management" (SCRM) tools, such as, SAP Ariba [11] and Resilinc [12], is limited as they mainly use data from internal company systems for their analyses. Resilinc is a supply chain specialized company with software solutions focused on risk analysis. The resilience assessment is based on the data without AI. The focus here is strongly on the processing and visualization of the collected data. Resilinc does not base its crisis management on the scenario technique, but simply establishes the probability of suppliers being affected by certain events, which then have an impact on their own supply chain. Other tools, such as DHL Resilience 360 [13], can pull data from various sources to identify supply chain disruptions; however, these are usually focused on logistics metrics without any further utilization (e.g., capacity of affected companies). Traditional methods such as crisis management [14], risk management [15] and security management (e.g., probabilistic risk assessment (PRA)) are used. Projects that offer a holistic overview of the situation usually require the engagement of specialized consulting firms. The resulting long response time would preclude such an approach within a crisis.

Strategic scenario planning has not yet been integrated into crisis management, so that different crisis scenarios based on cross-company data along the value chain have not yet been generated on a situational and continuous basis. This means that one of the most important aspects for crisis management, collaboration along the supply chain, is not ensured [16].

3.4 Summary

Scenario technique is used in strategic planning with a wide timeline. The proportion of automation in these software solutions is low, especially in the sections of the scenario field analysis, and is associated with a high level of effort for the user. There is no possibility to generate new scenarios automatically based on already created scenarios. Moreover, scenario technique is not used in crisis management yet, so that there is no possibility to generate new scenarios on situational and continuous basis. Therefore, it is necessary to investigate a solution that results in a continuous crisis management through the permanent cycle of scenario generation to enable the generation of situational basis. The needed concept for this solution is presented in the following.

4. Cascading model on scenario technique for continuous crises management

For the continuous anticipation of crises, a continuous model is developed, which is based on the fundamentals of scenario technique. The goal is to enhance the one-time planning with looping scenario technique, e.g., in strategy departments, by continuously generating new and dependent scenarios.

The basis for this is the concept of resilience specifically in crises. The goal is to return to a stable state in which the ability to act is made possible [17]. As described by STICH ET AL. [17], in the disturbance curve of performance, it can be seen how an unstable state at the beginning develops immediate consequences. The affected actors differ depending on the maturity of the crisis: First, the consequences are felt in the direct circle of the individual affected, also called a micro crisis (e.g., a corporate crisis). If this crisis affects multiple actors and has many interdependencies, then it is called a macro crisis (e.g., economic crisis).

Both classes of crisis arise from a chain of events and can be interpreted as a process (cf. Figure 2).

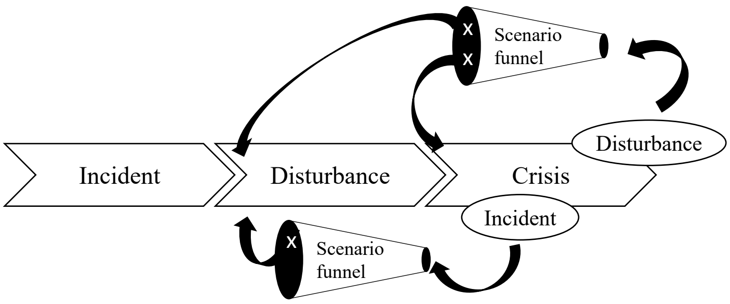

Figure 2: Looping scenario technique based on the 3-step process of crises.

Based on the interpretation of STICH ET AL. [17] and BSI [18], this means that crises are motivated by *incidents* which grow to *disturbances* leading to *crises*. Thereby, *incidents* are events of any kind, which do not lead to a deviation from the normal state. *Disturbances* are unplanned and unforeseeable deviations from a planned course or condition. *Crises* are a continuing, varying degree of deviation from the normal state of things. It can have various causes with specific unavoidable consequences. In principle, the effects of crises can only be influenced to a limited extent since the outcome is influenced by the actions of all actors. The aim of countermeasures is to return to a permanent stable state and thus secure essential processes and the continued existence of the system.

Using the existing scenario technique, the two concepts of the 3-step process of crises as well as the scenario technique can be mapped together. This means, that the generation of a new scenario can start in any of the listed stages of the 3-step process of crises (cf. Figure 2). In other words, every event (incident, disturbance, crisis) in each stage can be used as an input for the one-time generation of multiple scenarios so that the output results in a later state, e.g., an incident as input to the scenario funnel results in two scenarios which outputs a disturbance and another one a crisis (cf. Figure 2 upper funnel).

The model presented here is intended to allow this one-time starting in the phases continuously, so that a chain of incidents, disturbances and crises can be integrated in the generation of the scenarios. This creates a loop in the generation of scenarios (cf. Figure 2). We describe this model as cascading.

Exemplified, Figure 2 shows an incident developing to a disturbance and afterwards to a crisis (main process arrow). In that crisis again new events happen (labeled ovals) which are interpreted in this example as a possible disturbance and an incident (bubbles next to crisis). Based on each of this disturbance and incident, the scenario technique (scenario funnel) is used to generate new and multiple scenarios. For example, the upper disturbance in Figure 2 leads again to a possible disturbance or/ and to a crisis.
Essential here is that the output of the scenario funnel (i.e., one of multiple scenario) can contribute directly as an incident, disruption, or crisis, depending on its magnitude. In other words, this is the impact of the event on the scenario generation. For example, every occurring incident in a crisis can be interpreted as a new input for the generation (cf. Figure 2).

This loop breaks the singularity in the scenario planning. Each occurring result (output of the scenario generation) acts again as an input. This continuity can be represented and interpreted as a tree (cf. righthand side in Figure).

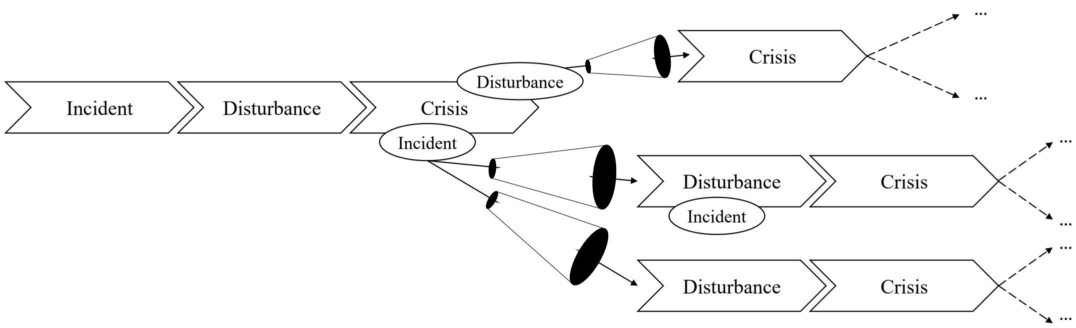

Figure 3: Looping scenario technique based on the 3-step process of crises illustrated in a tree diagram

In Figure , the process arrows indicate the development of e.g., an incident to a disturbance, whereas a simple arrow with funnel shows the application of the scenario technique to generate new scenarios, in which a new process evolves.

This overall looping corresponds to the underlying idea of the PAIRS research project. Each branch (cf. 3-step crisis as process) is a new event or a different interpretation of it for e.g., another group of actors, so that crises can also be generated, considered, and analyzed across different actors.

5. Application

The German Federal Agency for Technical Relief (German abbr. 'THW') acts upon mentioned crisis scenarios (e.g., floods, Ukrainian war, pandemics). As agency of the German Federal Ministry of the Interior and Community, responsibilities of the THW include technical assistance in civil protection, in disaster relief, public emergencies as well as major accidents nationally and internationally [19]. In collaboration with the THW, the PAIRS project specified a humanitarian logistics use case in order to support daily operations at the THW by means of AI.

In the following the humanitarian logistics use case is described. Thereby, the COVID-19 crisis is used as a concretisation of the use case to illustrate the non-technical application (cf. 5.2) of the cascading model, which is the first step for explanation of a crisis. Section 5.3 then transfers the COVID-19 example into a semantic description via a technical mapping, that enables an AI-based operations planning approach in the future.

5.1 Use Case description: Operations Planning

The personnel infrastructure of the THW consists of 80,000 volunteers and 2000 full-time employees working in 668 local sections, modular units are deployed in a flexible manner in real-time [19]. The operational options catalogue of the THW includes hazards and requirements due to natural disasters, transport accidents, or other occurrences concerning civil safety [20]. Additionally, the THW's domestic operations include logistics-related options, i.e., emergency supply of communities with critical and daily needed resources, setting up and operating logistic bases and the emergency repair or maintenance of critical infrastructures (e.g., electricity, sewage disposal, supply of fuel or drinking water). Missions also include other logistic related tasks as the transport of resources used for construction and technical support of emergency shelters or catering for task forces [19][20]. In the context of a crisis, resources need to be delivered as soon as possible for humanitarian reasons. Therefore, the resource delivery needs to be optimized. As every task and operation is different, the allocation of staff including the mapping of special capabilities poses an additional challenge. Operations must be characterised according to (1) tactical units required, (2) time horizon, (3) the assumed duration of the operation, and (4) required resources (e.g., vehicles, technical devices, consumables, other operational resources). Depending on scope, severity and urgency of the operation, planning and design is performed manually by local associations, national associations or the THW's headquarter. A manual assignment of personnel, tasks, resources, and logistics cannot always be carried out in the most efficient manner. Supporting THW's operations with an AI-based approach therefore reduces time and costs for all participants within the planning process.

5.2 Non-technical application of the cascading scenario model

To illustrate cascading scenarios within an unfolding crisis from THW perspective, the model is exemplified based on the COVID-19 pandemic. It will be evident, how the model can be used as a useful analysis tool to extricate single strings of the crisis and to pinpoint options for action in a multicausal, dynamic and complex situation. For this purpose, few iterations of the 3-step process will be singled out in a narrating manner, visualised in Figure .

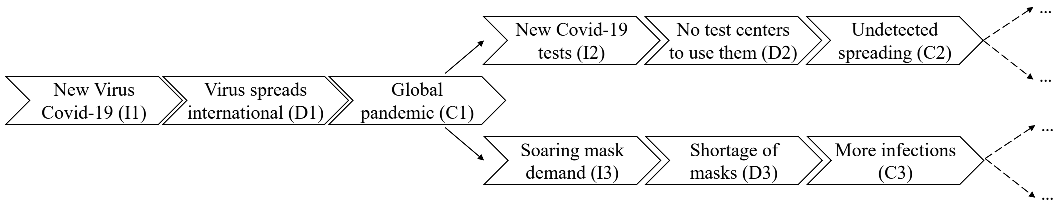

Figure 4: Exemplified cascading crisis model in the THW use case.

In late 2019, a new coronavirus named COVID-19 emerges (*incident I1*). The virus spreads internationally infecting people (*disturbance D1*), turning into a global pandemic (*crisis C1*). Deriving from this, new branches of the crisis can be followed. One branch describes the development of new COVID-19 tests (*incident I2*) to contain the spreading of the virus. These first tests can only be used by professionals in testing centres, for which the infrastructure is missing (*disturbance D2*). Missing test centres have the effect, that the spreading of the virus continues without being detected (*crisis C2*). Another branch deriving from the first iteration describes a soaring demand of hygienic protective equipment like masks, gloves or sanitiser (*incident I3*). We will focus here on masks as an example. This sudden rise in the mask demand is followed by a mask shortage (*disturbance D3*) which leads to more infections (*crisis C3*). Subsequently to *crisis C1* (pandemic) and *crisis C3* (more infections), the hospitalisation rate increases (*incident I4*) which leads into a shortage of hospital beds (*disturbance D4*). Without countermeasures, a shortage of hospital beds results into a rise of death cases (*crisis C4*). Following the shortage of masks, another branch includes the sudden procurement of large quantities of masks by the government (*incident I5*). But without a fitting infrastructure to distribute them quickly (*disturbance D5*), the result once again is more infections (*crisis C5*).

Applying the cascading scenario model in this manner from the perspective of one actor in the crisis, the actor can pinpoint the critical points of action they can take. In this example, the THW can systematically analyse with which of their operational options they can influence which disturbances to not turn into crises or to reduce the impact of the crisis. In this case, the operational options of the THW allow to take actions as operating central logistics centres to distribute protective equipment and to build an infrastructure distributing them to regional focal points (*disturbance D5*). Further actions include building new test centres (*disturbance D2*) and the support in distributing hospitalised patients to hospitals with free capacities (*disturbance D4*).

5.3 Technical transfer of the cascading scenario model

The goal in THW use case is to develop a service generating planning and design recommendations for THW's operations supported by AI. One approach that serves as basis for the development of such a service can be found in previous research. AISOP thereby conceptualizes a model for AI-based scenario planning within crisis management that is instantiated within the energy domain [21]. AISOP uses four essential components to (1) describe and learn, (2) anticipate, (3) monitor and (4) respond to occurring crises events. For the first component, the model uses semantically enhanced Scenario Patterns that provide detailed background information on crisis scenarios, in particular information on crisis identifier, context, location, reason, the impact of the event, potential actors, measures, used resources, data sources and historical events [21]. The model proposes to link interrelated historical crisis situations using JSON-LD, which then serves as basis for applying further methods (e.g., predictive analytics), on the resulting knowledge graph network of historical crisis scenarios [27].

By applying the general idea of a cascading crisis as exemplified in chapter 5.2 on a technical processable semantic description such as Scenario Patterns, we lay the foundation for applying AI to our logistics-driven use case. Cascading crisis scenarios and their tree like structure are therefore transferred and represented within a respective knowledge graph network. Incidents, disturbances, and crisis events (cf. Figure 2) each represent a scenario described by filled Scenario Patterns. The resulting knowledge graph (cf. Figure 5) can be used to run analytical operations, e.g., to identify critical scenarios within the graph interlinking to many subsequent events.

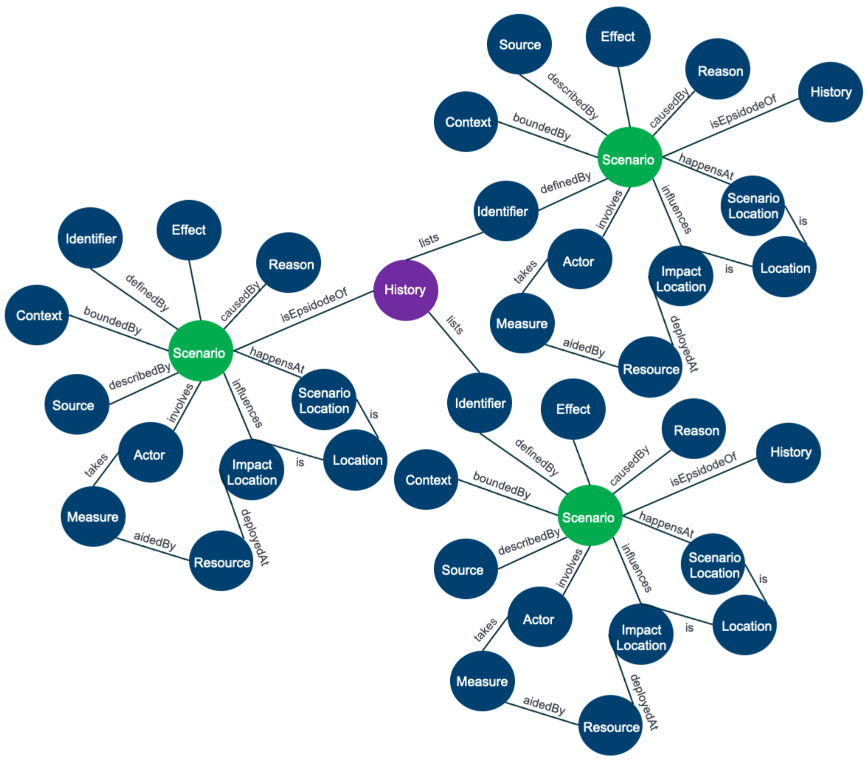

Figure 5: Exemplified Knowledge Graph Instance of a cascading crisis

To generate Scenario Pattern instances operationalized in JSON-LD for an operations-based knowledge graph, we used historical THW operations within Germany between 2012 and 2022 as data basis, as well as historical data from THW's logistic centres. We matched the two datasets based on locations and date and mapped corresponding attributes within the data sets onto the entities of the Scenario Pattern. The following table (cf. Table 1) hereby shows an example for a mask shortage event, as described within disturbances D3 or D5 of section 5.2.

Table 1: Mapping of THW's data attributes onto the Scenario Pattern's structure

Scenario Pattern Entity	Attribute in Scenario Pattern	Mapping of data attributes by THW	Example
Identifier	Title, ID, Timestamp, Category	TypeOfEvent, * , Start	**"Title":** " CRITICAL (disruption/transport/logistics)", **"ID":** "OP_2020-21-04T06:30_Julius-Leber-Kaserne", **"Timestamp_start":** "2020-27-04T06:30:00+00:00", **" Category ":** "Disruption"
Context	ScenarioDescription, Data, InfluentialFactors	Description, *, *	**"ScenarioDescription":** "Low stock emergency reserve masks ", **"Data":** ["THW Operation data", "THW Logistics centre data"], **"InfluentialFactors":** "Corona Virus"
Source	Organization	*	**"Organization":** ["THW"]
ScenarioLocation	Country, Region	Country, Federal state	**"Country":** "Germany", **"Region":** "Berlin"
ImpactLocation	City, Region	City, District	**"City":** " Julius-Leber-Kaserne", **"Region":** "Berlin"
Reason	Precondition	Service Project	**"Precondition":** "Corona Virus"
Effect	Postcondition, Duration	Task, Duration	**"Postcondition":** "Restocking masks", **"Duration":** "13:30 h"
Actor	ActorRole, NumberOfActors, Skillset	Federal state association, Regional association, NumberOfActors, *	**"ActorRole":** ["Federal state association Berlin, Brandenburg, Sachsen-Anhalt", "Regional association Berlin", "THW volunteers"], **"NumberOfActors":** [9],**"Skillset":** ["THW basic education", "Truck transportation"]
Measure	Actionstep	Task	**"Actionstep":** ["Logistics (Transportation of consumables)"]
Resource	Equipment, NumberOfEquipment	ORMasks	**"Equipment"**:["OR masks"], **"NumberOfEquipment"**: ["54300"]
History	Identifier_ID	*	**"Identifier_ID":** [" OP_2020-21-04T06:30_Julius-Leber-Kaserne"]

We added the *Category* attribute within the Scenario Pattern entity *Identifier* to categorize the scenario accordingly to our cascading model. The categorization can be automatically filled based on number of subsequent events within the resulting knowledge graph network. Attributes within the Scenario Pattern for which no mapping to THW's data exists (highlighted with *), can also be filled in an automized manner (e.g., Identifier.ID, History.Identifier_ID), or based on statical input (Source). The filled Scenario Pattern's structure can be seen in Figure 6. In the future, we are planning to use cascading crisis scenarios as presented by applying further related research on the resulting operations-based knowledge graph. Apart from works that apply predictive analytics [21] or inductive knowledge [23,22] on knowledge graph networks, we are also considering graph-analysis [24] and planning-based approaches [25] in order to generate appropriate planning and action recommendations for THW.

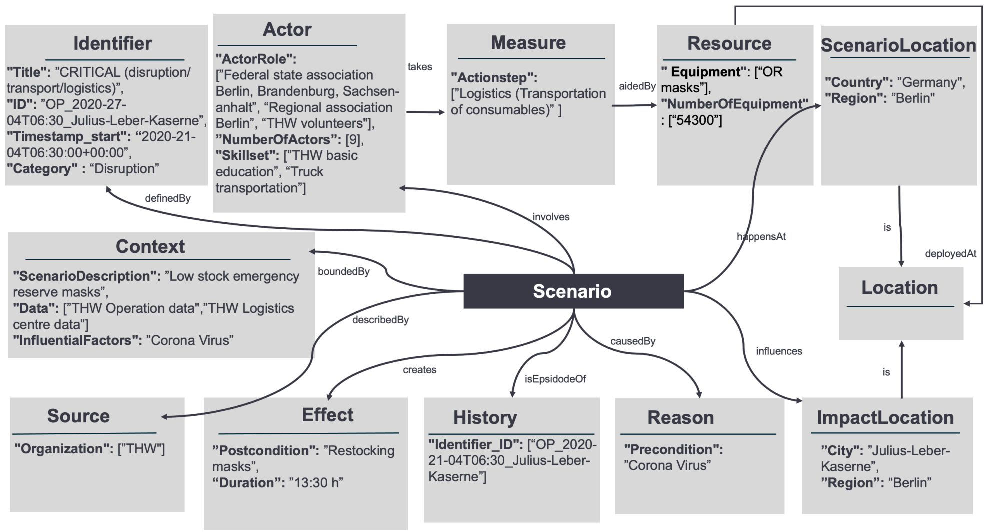

Figure 6: Filled Scenario Pattern structure based on THW data

6. Conclusion

In this paper, we expand the unique singularity in scenario generation. For this purpose, the scenario technique was applied to a crisis generation process to generate events, disturbances as well as crises continuously and interdependently for different affected actors. This is done in a cascading manner in the form of a loop, where in every iteration scenario technique is applied. Furthermore, a crisis tree with influences can be generated by the dependency, which supports the visualization. Moreover, we transferred these trees into a first technical approach to semantically describe cascading crisis scenarios within the structure of Scenario Patterns using JSON-LD and laid the foundation to apply an AI-supported scenario planning approach. In the future, we plan to use the resulting operations-based knowledge graph to develop a service that supports THW's Operation Planning by generating planning recommendations and to realize it within a proof of concept.

The presented concept of cascading crises enables a deeper understanding of crisis situations and further automatization regardless of the contextual industry. It serves as the underlying approach for automated industrial crisis management throughout the overall Supply-Chain in the context of PAIRS. Within this work we showed an application within the logistic context. The model and the applied semantical description within the Scenario Pattern enable a knowledge representation of information and data about crises, that can further be applied on data of various contexts also within the PAIRS project, such as investigated use cases in the energy or health domain. Resulting knowledge graph networks can be used as input for generating action and planning recommendations or for the prediction of crisis events.

Acknowledgements

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References

[1] OECD, 2022. Environmental impacts of the war in Ukraine and prospects for a green reconstruction, 1–9.

[2] Bishop, P., Hines, A., Collins, T., 2007. The current state of scenario development: an overview of techniques. Foresight 9 (1), 5–25.

[3] Bradfield, R., Wright, G., Burt, G., Cairns, G., van der Heijden, K., 2005. The origins and evolution of scenario techniques in long range business planning. Futures 37 (8), 795–812.

[4] Gausemeier, J., Fink, A., Schlake, O., 1996. Szenario-Management: Planen und Führen mit Szenarien, 2., bearb. Aufl. ed. Hanser, München, 390 pp.

[5] Gräßler, I., Scholle, P., Thiele, H., 2020. Scenario Technique, in: Vajna, S. (Ed.), Integrated Design Engineering. Interdisciplinary and Holistic Product Development, 1st ed. 2020 ed. Springer International Publishing; Imprint Springer, Cham, pp. 615–645.

[6] Vajna, S. (Ed.), 2020. Integrated Design Engineering: Interdisciplinary and Holistic Product Development, 1st ed. 2020 ed. Springer International Publishing; Imprint Springer, Cham, 799 pp.

[7] Piller, F.T., Hilgers, D. (Eds.), 2013. Praxishandbuch Technologietransfer: Innovative Methoden zum Transfer wissenschaftlicher Ergebnisse in die industrielle Anwendung, 1. Auflage ed. Symposion, Düsseldorf, 222 pp.

[8] Krystek, U., Herzhoff, M., 2006. Szenario-Technik und Frühaufklärung: Anwendungsstand und Integrationspotenzial. Z Control Manag 50 (5), 305–310.

[9] Inka 4, 2022. INKA 4 Szenariosoftware. https://szenariotechnik.com/. Accessed 4 November 2022.

[10] ScMI, 2022. Scenario-Manager™. https://www.scmi.de/en/software/scenario-manager%E2%84%A2. Accessed 4 November 2022.

[11] Ariba, S.A., 2022. SAP-Ariba-Lösungen. https://www.ariba.com/de-de. Accessed 10 October 2022.

[12] Resilinc, 2022. Resilinc End-to-End Supply Chain Risk Management Solutions. https://www.resilinc.com/. Accessed 4 November 2022.

[13] Resilience 360 DHL, 2022. https://www.resilience360.dhl.com/. Accessed 10 October 2022.

[14] Tenckhoff, B., Siegmann, S., 2019. Krisenmanagement, in: , Vernetztes Betriebssicherheitsmanagement. Springer Vieweg, Berlin, Heidelberg, pp. 271–314.

[15] Kumamoto, H., Henley, E.J., 2000. Probablistic risk assessment and management for engineers and scientists, 2nd ed. ed. Wiley-IEEE, Piscataway, NJ, 620 pp.

[16] PWC, 2013. Supply chain and risk management: Making the right risk decisions to strengthen operations performance.

[17] Volker Stich, Tobias Schröer, Maria Linnartz, Svenja Marek, Clara Herkenrath, Christian Hocken, Jonas Kaufmann, 2021. Wertschöpfungsnetzwerke in Zeiten von Infektionskrisen, 68 pp.

[18] Bundesamt für Sicherheit in der Informationstechnik. BSI-Standard 200-4, 234 pp.

[19] THW, 2022. Die Bundesanstalt Technisches Hilfswerk (THW) im Überblick. https://www.thw.de/SharedDocs/Downloads/DE/Hintergrund/THW_im_Ueberblick.pdf?__blob=publicationFile. Accessed 21 October 2022.

[20] THW, 2014. Katalog der Einsatzoptionen. https://www.thw.de/SharedDocs/Downloads/DE/Mediathek/Dokumente/THW/Einsatzoptionen-Katalog.html?noMobile=1. Accessed 21 October 2022.

[21] Sabine Janzen, Natalie Gdanitz Lotfy Abdel Khaliq, Talha Munir, Christoph Franzius, Wolfgang Maaß, 2023. Anticipating Energy driven Crises in Process Industry by AI based Scenario Planning, 10 pp.

Biography

Stefan Leachu (*1996) is a researcher at FIR at the Institute for Industrial Management RWTH Aachen University in the department of Information Management since 2021. With his degree in computer science, he enjoys linking the technical issues of various technologies with the value-added potential that can be achieved in the business world.

Jokim Janßen (*1993) works as a project manager and scientific assistant at the Institute for Industrial Management (FIR) at the RWTH Aachen since 2019. Before that, he gained experience in supply chain management at Miele & Cie. KG. In his current work as the group leader in supply chain management, he is managing projects in the context of digitalized supply chain management in research, consortia, and consulting projects.

Merlit Kirchhöfer (*1992) works as a research associate at the German Federal Agency for Technical Relief (THW) since 2021. As part of her degree in intercultural human resources management and communication management at Friedrich-Schiller University in Jena, she focused on organizational and work psychology. Her master thesis examined team resilience in the context of preparing hospitals for crisis situations.

Natalie Gdanitz (*1995) is a junior researcher at the German Research Center for Artificial Intelligence Saarbrücken with a degree in Business Informatics. While working at the department Smart Service Engineering under the directorship of Prof. Dr.-Ing. Wolfgang Maass, she focuses on industry and business-related topics and their ontological representation within the semantic web.

Dr.-Ing. Sabine Janzen is senior researcher and deputy head of the research department Smart Service Engineering at the German Research Center for Artificial Intelligence (DFKI). During her PhD in computer science, she worked on natural language interfaces for mixed motive dialogues. Now, Sabine investigates solutions for systematically designing and developing smart service systems; in this context, her research interests are AI architectures, intelligent user interfaces and Responsible AI.

Prof. Dr.-Ing. Volker Stich (*1954) has been head of the Institute for Industrial Management (FIR) at the RWTH Aachen University since 1997. Prof. Dr.-Ing. Volker Stich worked for 10 years for the St. Gobain-Automotive Group and lead the management of European plant logistics. In addition, he was responsible for the worldwide coordination of future vehicle development projects.

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Development Of A Data Concept For An Algorithm To Enable Relay Traffic For Trucks

Kira Frings[1], Max-Ferdinand Stroh[1], Sijmen Boersma[1], Volker Stich[1], Florian Wehling[2]
[1]*FIR – Institute for Industrial Management at RWTH Aachen University, Aachen, Germany*
[2]MANSIO GmbH, Aachen, Germany

Abstract

In road haulage, transports are interrupted by truck drivers to comply with driving and rest times. On long-distance routes, these interruptions lead to a considerable increase in transport time. Transport interruption can be avoided by so-called relay traffic: a vehicle (e. g. semi-trailer) is handed over to a rested driver at the end of the driving time. This type of transport requires a certain company size. In Germany, however, transport companies have 11 employees on average. Intra-company relay traffic is therefore not economically viable for most transport companies. To organize an intermodal transport across forwarding companies, long-distance routes need to be split into partial routes to divide them between freight forwarders and carriers. This paper presents a data concept for an algorithm to find the best possible route sections along a previously defined start and endpoint. The developed data concept includes order-specific data, forwarder-specific data, real-time traffic data, geographical data as well as data from freight forwarding software and telematics to be the basis for the route sectioning algorithm. In this paper, different data sources, external services and logistic systems are analyzed and evaluated. It is shown which data is needed and what the best ways are to select and derive this data from the different data sources.

Keywords

Relay Traffic; Route Sectioning Algorithm; Freight Forwarder; Carrier; Transport Order

1. Introduction

On long-distance routes, the driving and rest times truck drivers must comply with cause a considerable increase in transportation time [1]. The interruptions due to break times can be reduced by double staffing. However, double crews with two truck drivers are problematic and cost-intensive due to driver shortages as freight volumes increase [2]. Additionally, interruptions are not entirely avoided either since time as a co-driver does not count as rest time. In order to comply with driving and rest times, truck parking spaces are also occupied of which there is a shortage of around 23,300 on German highways according to BASt [3]. Furthermore, the parking-seeking traffic leads to CO_2 emissions, driving time overruns and frustration among truck drivers. Illegally parked trucks cause accidents, bother residents and encourage cargo robberies with damage running into billions [4]. Building more parking availabilities costs billions of dollars and, at the current rate of new construction, will not solve the problem for the next 20 years [5].

Transport interruption can be avoided by so-called relay traffic: a vehicle (e. g. semi-trailer) is handed over to a rested driver at the end of the driving time. While the driver who handed over the trailer can rest when his driving time is reached, the trailer continues his path with another driver. Therefore, relay traffic could

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help the parking problem because only the truck without the trailer needs to be parked. Nevertheless, this type of transport requires a certain company size since a network of drivers in different regions is needed. In Germany, however, 73% of the forwarding companies have less than 100 employees. On average, a transport company has 11 employees [6]. Intra-company relay traffic is therefore not economically viable for most transport companies. There is a need for an intelligent algorithm which is capable of planning this more complex method of transportation. So far, there is no solution for the organization of relay transport across forwarding companies. An explanation of this relay traffic transport system can be seen in Figure 1. For example, one delivery goes from Antwerp to Istanbul and the other way around. Instead of one driver driving all the way, the route is split into five sections. In this case the driver who starts in Antwerp only drives to a switching point near Frankfurt and drives back home with the trailer destinated for Antwerp. This principle repeats itself in the other five sections for the other drivers.

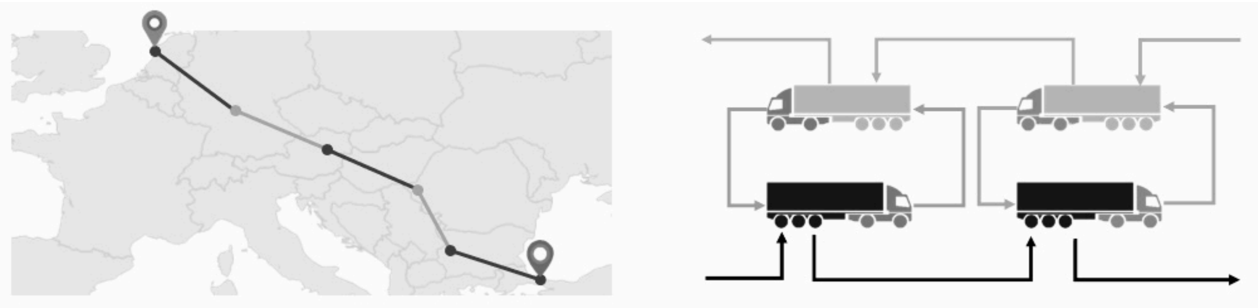

Figure 1: relay traffic transport system

2. Motivation

For the relay traffic transport system to function, a complex algorithm must be developed. The goal of the algorithm is to cleverly divide the complete route into smaller sections. Each section should be small enough to comply with the truckdriver's driving time. When the truckdriver finishes the section and arrives at the switching point for the trailer, the next truckdriver is already prepared and starts with the next section. For the algorithm to produce this output, it needs to take diverse types of data into account. Examples of this would be transport orders to consider the right start and endpoint, truck routing data to determine the estimated time of arrival and real-time traffic information to potentially adjust the estimated time of arrival. To clarify the data, which is needed for the algorithm to function properly, the goal of this research is to develop a data model for the algorithm. To create a basis for this data model, the status quo of truck transportation in Europe will be analyzed. By reviewing data about transportation management systems (TMS), routing software and possible switching points, it is examined which useful data already exists. Additionally, in the chapter "State of Research", it is clarified which vehicle routing problems and route sectioning algorithms already exist for other purposes, and if these can be adapted or function as a basis for the still to be developed algorithm. Moreover, the real time traffic data, which is an essential part of the algorithm, will be investigated to review the different traffic data gathering methods.

2.1 Truck transportation in Europe

2.1.1 Transportation management system (TMS)

TMS is a software that integrates supply chain management and plays a central role in logistic transportation. The TMS software allows freight forwarder and carriers to observe and control logistical operations. Hereby, the software integrates the different stages that make up freight transportation processes and contributes to the execution and control of the activities [7]. A TMS forms the logistical platform that enables freight forwarders and carriers to plan resulting transport requirements from procurement, distribution and returns management on available transport capacities. Scheduled tours can then be optimized and monitored until delivery [9]. These TMS functionalities can be divided into three groups [8].

- Planning and execution: determine the ideal transport mode, optimized route, and cargo consolidation for better use of vehicle capacity.
- Monitoring and control: provide real-time status information of vehicles and cargo transported by GPS tracking.
- Auditing and support to commercial negotiations stores a history of approved freight rates that seek to simplify the process of freight auditing.

Generally, all freight forwarder and carrier data e. g. transport mode, consolidation of different types of cargo, free driving time of truck drivers or order information is stored in a TMS. Which freight forwarder and carrier data will be needed for the data model of the algorithm will be further elaborated at 4.2.1

2.1.2 Routing software

Most vehicle routing issues are related to practical transportation issues. Each vehicle routing problem frequently has a unique solution that satisfies a particular set of constraints and goals considering the inherent variations in real-world environments that exist. Vehicle routing issues have typically been attempted using a variety of methods, from precise algorithms to heuristics [8].

For plotting the route for truck drivers, the routing software must consider truck specific parameters like permissible clearance height, maximum weight, speed limits and environmental zones [9]. To calculate the costs, truck, gasoline costs or the hourly rate of the driver are an essential part of the transport costs and must be considered and optimized by the routing software [9]. To compare the different routing software providers, various important aspects of truck routing software have been compared, as seen in Table 1.

Table 1: Comparison routing software

Table	PTV-Group	Google	Impargo	TomTom (Europe)	here
Price (Per Month/ per user)	49	Subscription	19,90	Subscription	Subscription
API Connection	✓	✓	✓	✓	✓
Route planning	✓	✓	✓	✓	✓
Traffic forecast	✓	✓	✗	✓	✗
Route cost calculation	✓	✗	✓	✗	✓
Truck navigation	✓	✗	✓	✓	✓
Realtime ETA sharing	✓	✓	✓	✗	✓
Offer calculator	✓	✗	✓	✗	✗

2.1.1 Possible switching points

For the relay traffic transport system to function, the algorithm needs a list of switching points spread through Europe. The switching points must contain a combination of parking spaces for trucks along with trailer changing areas. For the transport system to work, there will be several characteristics these spots must fulfill. Next to parking spaces and trailer switching areas, the switching points need to be near to the highway to prevent a costly and environmentally unfriendly detour. Furthermore, the switching points need to be a secured area in case the drivers arrive at different times and the trailer is unsupervised. Suitable are highway service areas, industrial areas, and premises of logistical companies. Public highway parking spaces are not applicable, because of parking shortage, safety reasons and costly detours. In Germany, there are 35.000 trucking parking places missing [3][4]. Especially at night, the parking places are overcrowded and leave no space for a trailer change. Moreover, public parking spaces are located at one lane of the highway, one of the trucks would have to take a costly detour to change the highway direction.

2.2 State of the Research

2.2.1 Vehicle routing problem

The term "Vehicle routing problem" (VRP) refers to a class of combinatorial problems where customers are to be served by several vehicles. [10], among others, have developed some well-known models for vehicle routing issues. [8] identifies three categories of vehicle routing issues which are linked to routing problems of truck transportation: “Truck and trailer routing problem” (TTRP), “Vehicle scheduling problem” (VSP) and “Vehicle routing problem with time windows” (VRPTW) [8].

[11] presents the TTRP (a variation of VRP) problem, which takes into account the fleet size of trucks and trailers in the model [11]. In the solution, there are three distinct types of routes: (1) routes where a truck travels alone; (2) routes where a truck and trailer are required; and (3) routes where a trailer is only needed at specific sub-tours. The goal is to reduce both the fleet's overall cost and distance traveled [8]. In contrast to the VRP, the needed route sectioning algorithm mandates that trucks visit switching stations to pick up the trailer. The route sectioning algorithm, which determines the switching stations for picking up or parking the trailer, could possibly be used for the route sectioning algorithm. Especially as the TTRP allows the outsourcing of tasks [11]. For example, the trailer could be dropped off at a switching point for another truck (of another hauling company) to be picked up again.

The vehicle scheduling problem (VSP) made the assumption that multiple trips could be taken to complete the routing to various sites [12]. Each journey consists of a pair of predetermined sources and destinations, each one identified by the beginning and ending times. The goal is to reduce the number of vehicles, the cost associated with deadheading trips (gas, driver, etc.), and the amount of time each vehicle is idle. The restrictions for this model include the travel distance and time required for routine maintenance and refueling, as well as the limitation that some tasks can only be performed by a particular type of vehicle. Contrary to the vehicle routing issue, the trips data is the only factor that determines whether a customer is visited more than once or not at all [8]. Although trips in the VSP are comparable to the idea of an order in a relay traffic system, the complexity of trailer type constraints is not present in the VSP. For the relay traffic algorithm to be designed, the trailer type constraint is an important aspect, because it must be ensured, that the transported trailer can be picked up by the planned vehicles.

Another variation of the well-known vehicle routing problem is the vehicle routing problem with time windows (VRPTW). In this problem, a set of constrained vehicles must be routed from a central depot to a group of geographically dispersed customers with predetermined time windows and known demands. The time window can be described as a single-sided or double-sided window. The pickup points typically state the dates by which they must be served in single-sided time windows traveled [8]. However, in a double-sided time window, the nodes impose both the earliest and latest service times. There will be a waiting period if a vehicle arrives before the node's earliest service time. Since a vehicle can only service fewer nodes if the waiting time is longer, this penalizes the transport management through either an increase in the number of vehicles or direct waiting costs. [13] lists a few of VRPTW's more recent publications. [14]'s surveys on the VRPTW that are available. The VRPTW offers the opportunity to include time windows into the algorithm. This could be used for the time windows at the switching points.

2.2.2 Route sectioning algorithms

A route sectioning algorithm first plots a route from a start to an endpoint and then divides the route into several sections, depending on the requirements defined in the algorithm. [9] developed a software which determines which truck should undertake which demand and how this truck should select the roads and make a schedule for the drivers. Their objective was to find the best route with scheduling including the optimal parking and refueling locations into the route [9]. Furthermore, [15] have also developed a heuristic route sectioning algorithm, which is designed to optimize the routing of heterogeneous electric vehicles. The algorithm optimizes the delivery routes and calculates where to recharge the battery [15]. The algorithm has two similarities with the algorithm proposed in this paper. Firstly, the charging points can be compared with the switching points. Both are previously determined points which can be used when needed. Secondly the remaining energy level of the battery can be compared with the free driving time left of the truck driver. Both must be considered when planning the optimal charging or switching point. Additionally, the algorithm developed by [16] shows the same similarities in their algorithm. They have developed an efficient heuristic algorithm for the alternative-fuel station location problem [16]. In Table 2 the three proposed algorithms have been compared with important aspects of the algorithm to be created. None of the mentioned algorithms focuses on relay traffic and the corresponding trailer exchange. Until now, no algorithm is equipped with the function of finding the optimal switching points for the trailers to be exchanged. Nevertheless, the approaches have shown aspects which could be used for the development of the algorithm.

Table 2: Comparison route sectioning algorithms

Table	Truck routing [9]	Electric vehicle [15]	Alternative-fuel [16]
Rout sectioning	✓	✓	✓
Designed for Europe	✓	✗	✓
Designed for Trucks	✓	✓	✗
Realtime Traffic	✓	✗	✗
Relay Traffic	✗	✗	✗

2.2.3 Real-time traffic data

Different data collection techniques can be used to collect and pre-process traffic data with different technical aspects and operational characteristics. Studies show that traffic data collection through crowdsourcing provides reliable travel time estimates with reasonable accuracy [17]. Google Maps is the only provider of this type of crowdsourcing. Mobile phone users all around the world utilize GPS data through the Google Maps application. Furthermore, Google Maps has access to local municipality data trough contacts such as road-specific information, road types, road works and speed limits. The combination of this information results in accurate traffic data. In a test the traffic data provided by Google Maps are compared with a traffic dataset collected through sensors installed on different road segments in the city of Paris. Google Maps traffic data achieved an overall accuracy of 95.8% in fluid traffic situations [18]. These test results show that the right use of crowdsourcing together with local municipality data can produce accurate traffic data which is needed for the algorithm.

3. Methodology

In this paper, a data model for an algorithm to enable relay traffic for trucks is developed by applying the systematic mapping study [19]. A systematic mapping study is conducted to get a comprehensive overview on a particular research topic and identify research gaps. The result of a systematic mapping study is a visual summary with various classification categories [20]. The procedure in [19] was followed, including the five phases of (1) planning of the study, (2) search execution, (3) selection of primary studies, (4) data extraction and classification, (5) analysis and mapping (see Figure 2). In the following, the five phases are descripted.

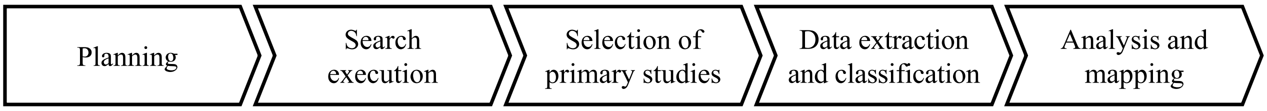

Figure 2: Approach for systematic mapping study

1. Planning: The planning phase exists of five steps:
    a. Definition of research question: How can a data model for an algorithm to enable relay traffic for trucks be descripted and where can the data be derived?
    b. Definition of the scope: Developing a data model for a platform approach by analyzing the algorithm procedure and identifying suitable data sources
    c. Establishment of search strategy: Only qualified journals are considered. In case of services and data which can be purchased, the offer of service and data providers are included.
    d. Establishment of selection criteria: For the journals, only recent papers in renowned logistic journals are selected. The offers of service and data providers still need to be marketed and purchasable.
2. Search execution: In this step, the search is executed based on the previously defined search strategy
3. Selection of primary studies: The primary studies are afterwards selected based on the selection criteria
4. Data extraction and classification: The classification scheme consists of the different steps the algorithm is performing and the different data that is needed for each step. Moreover, the different data sources are defined in detail.
5. Analysis and mapping: A concept for a data model is build and analyzed based on the findings from the previous steps

4. Results

4.1 Routing sectioning algorithm for relay traffic

The route sectioning algorithm to enable relay traffic determines which switching points are possible and comply with the driver's driving time. First, a route from a start to an endpoint is plotted based on the freight forwarder's transport order and truck routing data. Subsequently, it is the algorithms task to define route sections with suitable switching points for the trailer to be exchanged. When the switching points are defined, the route sections are plotted again for navigation purposes. Real-time traffic data is used to define the estimated time of arrival and potentially adjust the earliest starting and latest arrival times. Figure 3 shows the data model of the route sectioning algorithm for relay traffic including the needed data and results for each step.

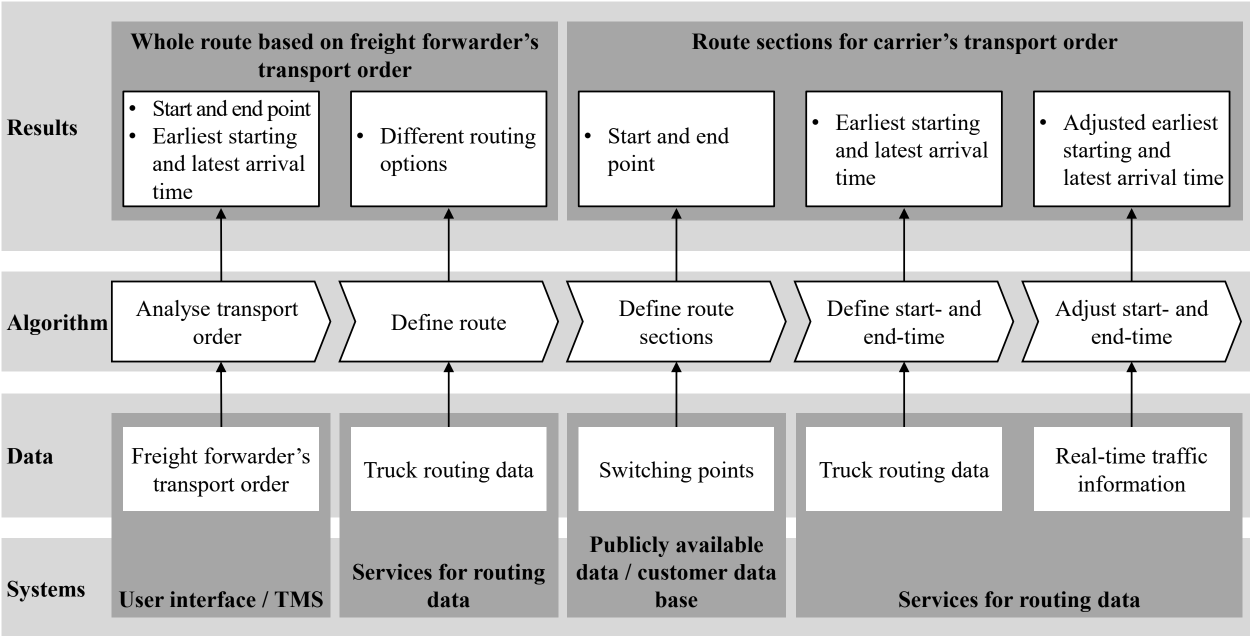

Figure 3: Route sectioning algorithm for relay traffic

4.2 Data model for sectioning algorithm

As a result of the systematic mapping study, the indispensable data input for the algorithm to function was identified. Transport orders, truck routing data, switching points and real-time traffic data have been researched to locate the most important aspects of these datasets for the algorithm.

4.2.1 Transport orders

Within this algorithm, there are two types of transport orders. The freight forwarder's transport order and the carrier's transport order. The freight forwarder's transport order contains the whole route defined by the shipper, who hired the freight forwarder to move a cargo from a given start to an endpoint in a given time. The freight forwarder's transport order can then be broken down to several carrier's transport orders, which consist out of route sections from the freight forwarder's transport order. From the freight forwarder transport order, the starting and arrival times as well as the start and endpoints must be integrated into the algorithm to then let the algorithm define the route sections with its switching points. The output of the algorithm is the carrier's transport order including the route sections and the corresponding starting and arrival times.

4.2.2 Truck routing data

Truck routing data is different from car routing data since additional information (e. g. tunnel heights and maximum load) is needed. Therefore, normal routing systems like Google Maps cannot be used. Research has shown that there are multiple providers of truck routing software's, as seen in Table 1 and **Error! Reference source not found.**. Furthermore, it shows how many of the chosen aspects are provided. The PTV-Group is the only provider who provides all the information needed. The truck routing data is particularly important for defining the route and scheduling transportation orders. With the truck routing data, the algorithm can define the expected starting and arrival times for the carrier's transport orders.

4.2.3 Switching points

The switching points are an essential part for the relay traffic algorithm to work properly. Without the right trailer changing areas the system cannot function efficiently. Therefore, a list of possible switching points for the algorithm to choose from must be created. In case there is no list with possible switching points from the freight forwarder or carrier database, three alternative options were identified. With great organizational efforts parking spaces at industrial areas or premises of logistical companies could function as switching points. The most promising solution however are highway service areas. Because here the relay traffic transport system and the highway service areas could form a symbiosis. The highway service could organize a trailer changing area in exchange for a switching fee. Furthermore, the parking problem could be dramatically reduced. Because when the trailer continuous its trip and only truck itself needs a parking space, up to three trucks would fit on a parking space previously used for a truck with trailer. This would reduce the truckdrivers searching time for a parking space and simultaneously benefit the highway service area. The service area could host up to three times more trucks and truck drivers.

4.2.4 Real-time traffic data

The use of real-time traffic data for planning optimal routes is indispensable [21]. The algorithm needs to have access to real-time traffic data for it to plan a route and to intelligently determine the switching points. Furthermore, this traffic data is important for reliable estimated time of arrival (ETA) predictions, so the forwarder and the other truckdriver know when the trailer will arrive or be delayed. The research has shown that that the right use of crowdsourcing together with local municipality data can produce very accurate traffic data with ich needed for the algorithm [21]. Although google maps provides no routing data for trucks, the traffic data could be very useful for the algorithm [21]. With usage of accurate traffic data, the algorithm will be able to adjust starting and arrival times based on changing traffic situations to determine accurate ETAs for the switching points. Because of the crowdsourcing capabilities of Google Maps, they deliver the most reliable real-time traffic data.

5. Conclusion and outlook

Within this paper, a data model for an algorithm to enable relay traffic for trucks was developed. In the first step, the existing data within transport management systems, routing software and switching points was described. Afterwards, the status quo of route sectioning algorithms and real-time traffic data was analyzed and approaches which could be used for the development of the algorithm were identified. With the application of a systematic mapping study, a concept for a data model was build. The data model is based on the different steps performed by the algorithm and shows data sources, the needed data and the results for each algorithm step. The main data typed needed for the algorithm are transport orders, truck routing data, switching points and real-time traffic data.

In the future, the algorithm could be enhanced by enlarging the requirements for finding the best switching points. The following adjustments were identified:

- An additional requirement would be to minimize the transport costs.
- Moreover, not only the maximum driving time of the truck driver could be considered, but the left amount of free driving time.
- Furthermore, the transported cargo could be an additional parameter for the algorithm. The information about dangerous goods and weight of the cargo could be added, since dangerous goods must be known, so possible road limitations can be prevented. The weight of the cargo is important for economic reasons, if small detours must be made to reach the switching point, the truck with the smallest weight should make the biggest detour.
- Additionally, should the traffic situation change, the algorithm could not only change the ETA and inform the second drivers, but be capable of changing the existing switching points so both drivers arrive at approximately the same time.

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References

[1] Bundesamt für Güterverkehr, 2020. VERORDNUNG (EG) Nr. 561/2006 DES EUROPÄISCHEN PARLAMENTS UND DES RATES, 24 pp. https://eur-lex.europa.eu/legal-content/DE/TXT/PDF/?uri=CELEX:02006R0561-20200820&qid=1603348974472&from=DE. Accessed 19 October 2022.

[2] Bundesministerium für Verkehr und digitale Infrastruktur, 2020. Fahrermangel im deutschen Straßengüterverkehr: Strukturelle Treiber und verkehrspolitischer Handlungsbedarf, 21 pp.

[3] Irzik, M., Habermann, M., Löhe, U., Treichel, H., 2019. Lkw-Parksituation im Umfeld der BAB 2018: Bundesweite Erhebung der Lkw-Parksituation an und auf BAB in Deutschland in den Nachtstunden, Bergisch Gladbach. https://www.bmdv.bund.de/SharedDocs/DE/Anlage/StB/bast-erhebung-lkw-parksituation-im-umfeld-der-bab-2018.pdf?__blob=publicationFile. Accessed 19 October 2022.

[4] Huster, F., 2018. DSLV Pressemeldung: Jährlich 1,3 Milliarden Euro Güterschäden durch Ladungsdiebstahl, Berlin, 2 pp.

[5] Ertl, A. Lkw-Parkplätze sind Mangelware: Trotz Mangel an Lkw-Parkplätzen scheitern Planungen oft an Einsprüchen – eine Übersicht über bundesweit bestehende und geplante Anlagen. https://www.eurotransport.de/artikel/parkleitsysteme-und-kompaktparken-in-testphase-lkw-parkplaetze-sind-mangelware-10891415.html. Accessed 19 October 2022.

[6] DSLV Deutscher Speditions- und Logistikverband e. V., 2022. Zahlen Daten Fakten aus Spedition und Logistik, 44 pp.

[7] Santos, J.R., Piva, S.S., 2021. Transportation Management System (TMS) Use in the Automotive Parts Industry, in: Oliveira, G.G.d., Seixas, A.C.M.d., Kemper, G., Saotome, O., Iano, Y. (Eds.), Proceedings of the 6th Brazilian Technology Symposium (BTSym'20): Emerging Trends and Challenges in Technology, vol. 233. Springer, Cham, pp. 72–79.

[8] Tan, K.C., Chew, Y.H., Lee, L.H., 2006. A hybrid multi-objective evolutionary algorithm for solving truck and trailer vehicle routing problems. European Journal of Operational Research 172 (3), 855–885.

[9] Csehi, C.G., Farkas, M., 2017. Truck routing and scheduling. Cent Eur J Oper Res 25 (4), 791–807.

[10] Dantzig, G.B., Ramser, J.H., 1959. The Truck Dispatching Problem. Management Science 6 (1), 80–91.

[11] Chao, I.-M., 2002. A tabu search method for the truck and trailer routing problem. Computers & Operations Research 29 (1), 33–51.

[12] F. Baita, R. Pesenti, W. Ukovich, D. Favaretto. A comparison of different solution approaches to the vehicle scheduling problem in a practical case. Computers & Operations Research 2000, 1249–1269.

[13] van Breedam, A., 2002. A parametric analysis of heuristics for the vehicle routing problem with side-constraints. European Journal of Operational Research 137 (2), 348–370.

[14] Desrosiers, J., Dumas, Y., 1995. Time Constrained Routing and Scheduling 1995, 35–139.

[15] Zhao, M., Lu, Y., 2019. A Heuristic Approach for a Real-World Electric Vehicle Routing Problem. Algorithms 12 (2), 1–19.

[16] Tran, T.H., Nagy, G., Nguyen, T.B.T., Wassan, N.A., 2018. An efficient heuristic algorithm for the alternative-fuel station location problem. European Journal of Operational Research 269 (1), 1–27.

[17] Tahmasseby, S., 2015. Traffic Data: Bluetooth Sensors vs. Crowdsourcing—A Comparative Study to Calculate Travel Time Reliability in Calgary, Alberta, Canada. JTTE 3 (2).

[18] Arai, K., Kapoor, S., Bhatia, R. (Eds.), 2019. Intelligent Systems and Applications: Proceedings of the 2018 Intelligent Systems Conference (IntelliSys) Volume 1, 1st ed. 2019 ed. Springer International Publishing; Imprint: Springer, Cham, 1426 pp.

[19] Petersen, K., Vakkalanka, S., Kuzniarz, L., 2015. Guidelines for conducting systematic mapping studies in software engineering: An update, Information and Software Technology.

[20] Salama, M., Bahsoon, R., Bencomo, N., 2017. Managing trade-offs in self-adaptive software architectures: A systematic mapping study.

[21] Mostafi, S., Elgazzar, K., 2021. An Open Source Tool to Extract Traffic Data from Google Maps: Limitations and Challenges, in: The 2021 International Symposium on Networks, Computers and Communications (ISNCC 2021). October 31-November 2, 2021 - Dubai, UAE. 2021 International Symposium on Networks, Computers and Communications (ISNCC), Dubai, United Arab Emirates. 10/31/2021 - 11/2/2021. [IEEE], [Piscataway, New Jersey], pp. 1–8.

Biography

Kira Frings (*1995) works as a project manager and scientific assistant at the Institute for Industrial Management (FIR) at the RWTH Aachen since 2021. Before that, she gained experience in requirements engineering and agile project management at the energy and software start-up envelio GmbH as a product owner and product manager.

Max-Ferdinand Stroh (*1991) is a researcher at FIR at RWTH Aachen University since 2017 in the department Information Management. He is head of the department Information Management. His scientific work is focused on the practical application of AI, smart products, and IT-OT-Integration.

Sijmen Boersma (*1995) pursues his Master´s degree (M.Sc.) in Production Engineering at the RWTH Aachen. He has been working at the Institute for Industrial Management (FIR) since 2021 as a research assistant with focus on information technology management to identify, evaluate and configurate digital technologies to innovative solution concepts.

Prof. Dr.-Ing. Volker Stich (*1954) has been head of the Institute for Industrial Management (FIR) at the RWTH Aachen University since 1997. Prof. Dr.-Ing. Volker Stich worked for 10 years for the St. Gobain-Automotive Group and lead the management of European plant logistics. In addition, he was responsible for the worldwide coordination of future vehicle development projects.

Florian Wehling (*1991) leads the technical development at MANSIO GmbH since 2022. Prior to that, he gained experience in software development at other startups. In 2017, he completed his computer science studies at RWTH Aachen University with a Master’s degree (M.Sc.).

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A Cognitive Assistance System To Support The Implementation Of Machine Learning Applications In Manufacturing

Jannik Rosemeyer[1], Laurenz Beck[1], Joachim Metternich[1]
[1]*Institute of Production Management, Technology and Machine Tools, TU Darmstadt, Otto-Berndt-Straße 2, 64287 Germany*

Abstract

Despite the increasing spread of digitalisation in manufacturing, humans will still play an important role in future production environments. Evidently, their role will change from physical to rather cognitive tasks, such as decision-making or control and monitoring of processes. A suitable medium that can support employees in interpreting the data generated are machine learning (ML) applications. Nevertheless, recent studies show that the knowledge required to implement an ML solution is not available in a large number of companies. In order to close the knowledge gap and subsequently prepare human operators for the implementation and use of ML applications, it is highly relevant to provide proper assistance. For this reason, the present publication aims to develop a cognitive assistance system that supports shop floor managers in implementing ML use cases in manufacturing (referred to as CAS-ML). The CAS-ML concretizes a previously published procedure model with additional steps as well as learning material and is realized as a software thereupon. Finally, the CAS-ML is evaluated by operative employees and tested on an open-source data set.

Keywords

Machine learning; Operator 4.0; Cognitive assistance system, Shop floor manager; Vocational education

1. Introduction and problem definition

In recent years, the number of Industry 4.0 applications in manufacturing environment has increased strongly [1], thereby offering previously unrealizable insights into production processes in real time. Yet, human operators remain a central part of manufacturing halls [2]. Noteworthy, their jobs will change from rather physical to rather cognitive tasks [3] such as decision-making, control and monitoring of processes [4]. A possible mean to support them in interpreting the data generated by Industry 4.0 technologies are machine learning applications (MLA) [5], which yield the advantage to evaluate large data in a short time. Nevertheless, a gap between potentials and actual ML dissemination – especially in small and medium enterprises (SMEs) – can be identified due to a lack of ML competences, a lack of IT infrastructure, a lack of data as well as a rather unstructured project management [6–8]. Concerning competences, a general change has been taking place in times of digitalization from information knowledge about individual processes to action knowledge and thereby acting in unknown scenarios [9]. Besides, many competences such as problem-solving competences can hardly be developed in non-formal settings such as seminars [10]. Indeed, practitioners asked by [8] declared that the transfer from knowledge gained in ML seminaries to industrial problems to be complex. This transfer obstacle in combination with the general shift of required competences in digitized manufacturing environments displays the need to realize suitable learning materials to train workforces for their changing roles [2]. In terms of vocational education, literature agrees that a promising approach to prepare employees for future challenges at work is the concept of work-integrated

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learning [11]. For the sake of enabling work-integrated learning, cognitive assistance systems are considered to be a supportive technology [3,12].

Hence, the goal of this paper is the development of a software-based cognitive assistance system to support the integration of machine learning (CAS-ML) in manufacturing environments. To mitigate the hurdle of transferring knowledge gained to industrial problems, the aim is to enable competence development with respect to MLA in a work-integrated manner. It has to be noted that the focus of this paper lies on ensuring guidance, which in return limits the competence development. Since especially SMEs lack designated ML departments [6], the focus of this paper is on shop floor managers who possess the knowledge to select data sources as well as parameters and are therefore seen as essential for successful MLA implementation [13].

The remainder of this paper is structured as follows: chapter 2 provides the theoretical background needed to understand most relevant terms used and gives an overview over similar publications. In chapter 3 the development of the CAS-ML is described. Chapter 4 displays the evaluation of the CAS-ML with potential users. Finally, chapter 5 summarizes the paper and yields an outlook to further development steps.

2. Theoretical background and related work

In the following, the most important terms introduced in chapter 1 will be described further before delivering the state of the art in cognitive assistance systems for the implementation of ML in manufacturing.

2.1 Theoretical background of the paper

The term machine learning describes the capability of a computer or a program to automatically improve itself in the execution of a certain activity through the experience gained in the past. The term experience refers in particular to the data that the computer receives as feedback from processes. For this purpose, ML methods make extensive use of statistical methods to analyze data, detect errors within the data, and make and test hypotheses regarding the data. [14]

According to Dehnbostel [11] the term "work-integrated learning" displays a scenario where learning takes place in the process of working or where learning place and workplace are identical. Most frequently, learning is ensured by active participation in real work processes. Thereby, learning incorporates cognitive, affective and psycho-motorical tasks. Learners are i.e., assisted by coaches or so-called communities of practice [15]. Another learning method in terms of work-integrated learning is the combination of informal and formal learning, e.g., by integrating learning bays or e-learning materials into real processes. In sum, learning takes place self-directed, experimental and situated. [16] As indicated above, the model within this paper follows principles which have been described in this sub-section (for more details please see below).

To meet the emerging changes in the range of tasks in manufacturing environments and thereby aid humans in processing and retrieving new information in similar situations, CAS are required to support workforces in diagnosis, situational awareness, decision-making and planning [12]. In consequence, CAS are digital systems that help its users with information processing and thereby enable learning in real time based on end devices like as smartphones and tablets or extended reality. In addition, they are capable to generate guidelines for actions, steps, and processes. [17]

2.2 Related work

Villanueva Zacarias et al. [18] describe a software consisting of four modules that supports the implementation of ML algorithms in manufacturing. The framework thereby facilitates the cooperation of different stakeholders (domain experts, IT specialists, data engineer and data scientist) that are required in the implementation process. In this context, domain experts are obliged with the specification of the task and the final evaluation. In return, a data engineer and a data scientist are responsible for data analysis and algorithm selection, respectively. Final validation is performed on a predictive quality use case. In terms of SMEs the exchange of several stakeholders is not applicable due to the frequent absence of data engineer and data scientist.

Frye et al. [19] develop a software that includes a holistic ML-pipeline based on the CRISP-DM for the integration of MLA in manufacturing and extend this with a final certification of the AI solution developed in the process. To support data pre-processing and hyperparameter tuning, the authors provide a rule-based expert system that proposes solutions based on domain knowledge and past data. A collaboration between domain experts, IT specialist and data scientists is facilitated by the framework. Just like previously described, the lack of data scientists prevents SMEs from using such software systems.

Garouani et al. [20] describe a software application that allows non-ML experts to select and design ML algorithms such that they are adapted best possible to their needs. For this, they make use of automated machine learning and explainable AI (XAI). The platform then enables the choice between algorithm and hyper-parameter combination. Additionally, the authors deliver a mechanism to increase the explainability of results. The platform was lately tested in the field of predictive maintenance. Despite the integration of XAI, little emphasis is laid on the user and his knowledge development in terms of MLA. In contrast, respective know-how is presumed.

Fischbach et al. [21] develop a software application for implementing an MLA in cyber-physical production systems. Central part of the architecture is a cognitive module that processes the goals defined by the user, selects suitable algorithms and lastly creates a configuration for the execution of a processing pipeline. An evaluation is conducted against different performance criteria. For realization, several technologies such as Docker containers are used. Validation is finally performed on a use case from a learning factory. A description of the roles of single stakeholders is not described in their paper. Likewise, it is assumed that data is already existent and can be included in the application.

As evident, several articles on research in this field were published in recent years. The approaches overcome the problem of unstructured project management by integrating a process model or transferring development steps to a software. Nevertheless, it can be noticed that the focus lies on technical aspects and technical developments, respectively or a collaboration between domain and ML expert is facilitated. A competence development among manufacturing domain experts as later users especially by means of work-integrated learning is only considered marginally. Yet, it is of high importance to familiarize them with the functionalities of MLA. Moreover, the obstacles of SMEs when implementing ML in practice described in chapter 1 are not considered in detail. As such, it is often assumed that a data scientist is employed and therefore available for working with the systems described above. Besides, little focus is put on data collection. Rather the authors suppose that data was collected previously.

3. A CAS for ML implementation

In this chapter, the concept as well as the software-based realization for the CAS-ML that guides practitioners in the development and implementation of an MLA for their manufacturing environment is pointed out. Therefore, foundations and assumptions are described first before an in-depth description of the CAS-ML is provided. The development of the CAS-ML follows the systematics described in ISO EN 9241-210 [22].

3.1 Foundations and context of use

In their research, the authors of [23] describe that employees' trust in MLA is a basic prerequisite for successful collaboration. To ensure trust and increase the likelihood that an ML project becomes successful, the involvement of employees in the design and implementation is therefore essential. In particular, they need to be trained accordingly. Additionally, the research results of [24] indicate that a step-by-step approach is a suitable level of detail for non-ML experts when providing assistance.

For this reason, the basis of the CAS-ML is the so-called Data Mining Methodology for Engineering Applications (DMME) [25]. The individual sections of the DMME are briefly introduced in the following.

- **Business Understanding** is about comprehensively defining the problem to be solved and to define a goal for the implementation of MLA. Additionally, a project plan which contains time frame, budget and potential stakeholders of the project is built up.
- **Technical Understanding** contains the formulation of technical goals based on the previously defined goals in Business Understanding and the development of a technical project plan with the target variables to be measured as well as the required technical infrastructure.
- **Technical Realization** includes the execution of the technical project plan while the main goal is to collect high-quality data.
- In **Data Understanding** companies gain an overview of the previously recorded data by analyzing it comprehensively and identifying potential data problems.
- The aim of the section **Data Preparation** is to preprocess data so that it can later be used within an MLA. It includes e.g., data filtering, feature generation, feature selection and normalization of data.
- **Modeling** contains the applications of an ML-algorithm to the preprocessed data.
- In the section **Evaluation** the performance of the ML-algorithm is evaluated with regard to the problem and general goal formulated in Business Understanding as well as the technical goal defined in Technical Understanding.
- **Technical Implementation** is about the application of the ML algorithm within the real process and ensuring the long-term stability of the technical system.
- The section **Deployment** follows the target to maintain the functionality of the MLA.

The CAS-ML focuses on shop floor managers (production managers and team leaders with decision-making competence [26]) as a suitable hierarchy level for implementation of MLA due to their broad domain knowledge and decision-making competence [13,27]. The goal of the CAS-ML is to allow an easy implementation of MLA for this target group. Since the perception of the complexity of the CAS-ML depends on the prior knowledge and competence of a user, the following assumptions are made:

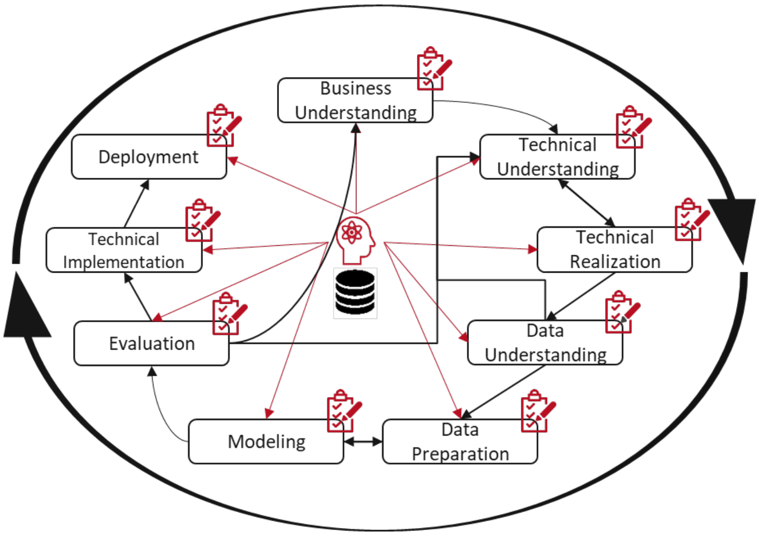
- A user has deep domain-knowledge in the subject of discrete manufacturing and can therefore assess whether a process known to him is in a normal or abnormal state.
- A user knows the basics of descriptive statistics (e.g., differ quantitative and qualitative variables, understand scale levels, interpret location measure and measure of dispersion) and programming (e.g., differ several data types (integer, float, string), understand tabular data) and is able to utilize sources of information outside the CAS-ML in case of upcoming ambiguities.
- A problem definition in manufacturing environment is available. Contrarily, its identification is not part of the CAS-ML nor are traditional solutions other than an MLA meaningful.
- Explicitly, it is assumed that a user does not have extensive knowledge in the field of ML.

The focus of the CAS-ML is on predictive maintenance (PM), as PM is among the most frequently regarded application areas in manufacturing [28]. In the first step, the CAS-ML is limited to milling machines as these are a common use case of PM [29] and have a high relevance for manufacturing environments. Extensions to further processes are planned in future development steps.

3.2 Usage requirements and Design solutions

In order to use the CAS-ML for work-integrated learning when implementing MLA, it has to fulfil a number of functionalities, which are described in the following.

Project management: Considering that ML projects often fail due to unstructured project management and with regard to the findings of [24], the CAS-ML includes a proven process model (DMME) and extends it by respective questions within each step. Thereby a user is lead systematically and generating guidelines for actions, steps, and processes. The underlying concept of the CAS-ML is shown in Figure 1. Therein, the steps displayed in black are taken from the DMME. The lists marked in red represent the single questions made in the steps and the head the learning materials attached.



Procedure within Technical Understanding (excerpt)

- Goals of Technical Understanding
- Definition of process (currently only “milling machine”)
- Definition of sensors, data type, communication standard, message-exchange protocol
- Definition of sampling rate
- Definition of data storage
- Definition of trigger signal

Figure 1: Underlying concept of the CAS-ML with specifications for Technical Understanding; own illustration based on [25]

Visual representation: As a suitable form of presentation, the CAS-ML is visualized by means of tablets. A prototypical implementation of the CAS-ML was realized in Python using the library PyQt5 for building the user-interface. The entries made by the user are saved within a non-SQL Database which makes it possible to interrupt the program and continue without losing any information. An exemplary visualisation of the CAS-ML is represented in Figure 2.

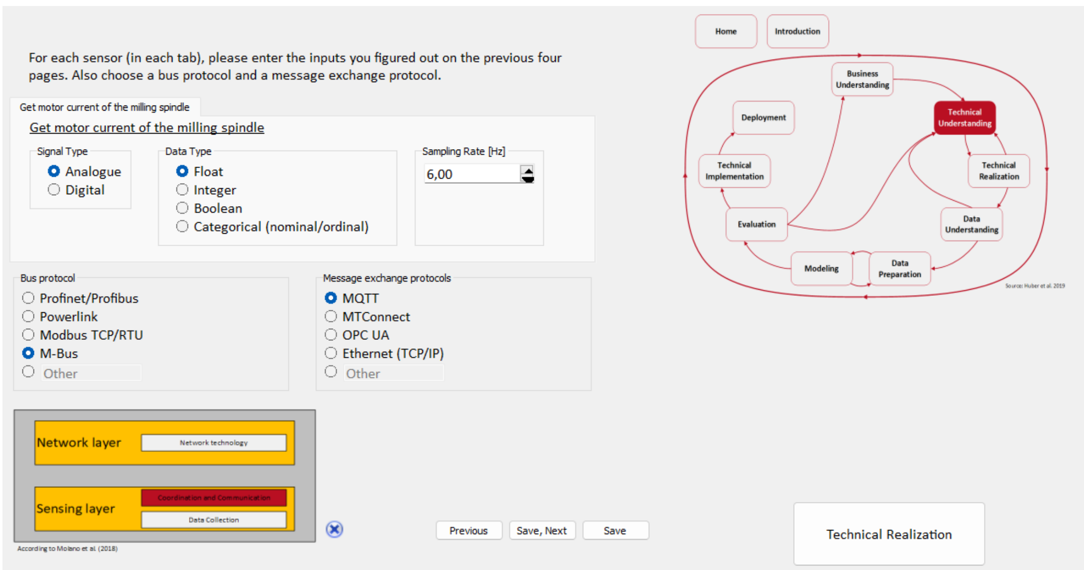


Figure 2: Exemplary visualisation of the CAS-ML (Technical Understanding)

Obstacles of SMEs: To mitigate the previously described obstacles, the CAS-ML focuses on the construction of appropriate sensors and IT infrastructure. By integrating a framework published by [30] which puts emphasis on sensors, their connection to the company's IT infrastructure and the storage of data as well as by the inclusion of best practices from research about PM on milling machines, users are guided through the process systematically. Likewise, the CAS-ML contains default settings for entries to simplify its use, which, however, can always be individualised by the user.

Use for work-integrated learning: As described, the CAS-ML is developed for work-integrated learning to train users accordingly for the integration and use of MLA. Thereby, users are involved both in the design and implementation. In this context, the CAS-ML aims to enhance users' capabilities for diagnosis and decision-making, respectively. For ensuring self-directed learning, digital learning materials [31,27] as well as background information is context-related included in the CAS-ML and can be consumed in the form of problem-pull [32]. Following the systematics of the DMME, backward steps are integrated allowing experimental learning. Since the CAS-ML can be used at specific use cases within production environment, situated learning is ensured. Thus, informal learning is made possible due to the proximity to production processes. Likewise, formal learning takes place through the provision of learning materials.

Within the first section **Business Understanding**, a user has to provide a problem definition before he can specify a goal for the MLA which is currently limited to PM. As stated before, the problem finding is not part of the CAS-ML. Based on the specified goal, suitable key performance indicators based on [33] are suggested to the user. Those can be used to later estimate and evaluate the effect of the MLA. In addition, colleagues who can support and accompany the user through the project have to be defined. Hence, it is specified according to [34] that in order to increase the probability of a successful implementation of PM colleagues from e.g., the departments of shop floor and maintenance management, IT and operative production has to be indicated. A learning by means of a community of practice is thereby made possible. At the end of the section, a summary of all inputs can be exported for forwarding purposes.

The second section **Technical Understanding** aims to create the conditions for MLA that do not exist in SMEs as described above. It starts with the selection of a machine type, which is currently limited to a milling machine. First, the technical goal to measure acoustic emission [35], vibration [36] and the motor current of the spindle [37] is automatically recommended by the CAS-ML. In order to define the technical infrastructure that is required for the implementation of the MLA, the user is guided by a framework based on [30] during the next steps. According to the technical goal, respective sensors are recommended by the CAS-ML within Data Collection. Within Coordination & Communication, the user is informed about the IT infrastructure required for data recording and can then select sensor-specific details such as signal and data type, as well as bus and communication protocols. The level Network Technology involves selecting a cloud service based on [38] that can be used for data storage and deciding to what extent edge computing should be used with regard to [39]. Insofar not yet available, it is suggested that the hardware is retrofitted. Just like in the section Business Understanding the end of the section is given in a summary of all inputs.

After the user has performed his data recording within the section **Technical Realization** and uploaded the data to the CAS-ML, he can analyse it exploratively in the section **Data Understanding**. Therefore, descriptive statistics methods are available and user-defined diagrams such as a boxplot, histogram and scatter-plot can be generated. In addition, missing values in the data can be displayed using the missingno library [40] and outliers can be removed using the method of interquartile range. In this context, the required information knowledge about processes by the users becomes significant. Based on existing domain-knowledge, the recorded data has to be interpreted and evaluated for later use in the model development. Also, it is particularly necessary for a user to have knowledge of descriptive statistics.

The first step of the section **Data Preparation** consists in editing missing values within the data. After the user has selected those columns of his data that contain meaningful sensor data within the second step, he must filter them. For this purpose, an auto-filter based on the interquartile range as well as a user-defined filter are available. The next step deals with labelling the data, which the user has to do graphically on the basis of observations made during the recording of the data. A graphical labelling provides the opportunity to include process knowledge more easily and thereby enhances data competences of the users. The labels are noted according to [41] in such a way that a worn-out state is labelled as positive and a non-worn-out state as negative. The user is then guided to select a sensor signal that he considers most promising for distinguishing normal and abnormal conditions. The features are calculated by the CAS-ML on the basis of this signal, with e.g., min., max., average, kurtosis and skewness in accordance with [42] and [43]. The calculated features are automatically evaluated using an ANOVA F-test [44]. The ten best features are recommended to the user for further use. Since normalization of the data leads to increased accuracy of the MLA [45], a min-max normalization according to [46] is applied in the last step of Data Preparation.

Within the **Modeling** section, the dataset is first divided into training and test data, with a ratio of 75-25 as the default ratio following [47]. Nevertheless, the user is given the opportunity to select a customized ratio. Next, a binary classification algorithm [41,48] is learned to distinguish normal and abnormal states. Here the user can choose between the application of e.g., random forest, k-nearest-neighbours and Gaussian Naïve Bayes, whereof the latter is selected as default due to its compromise between accuracy and computation speed [49]. After the learned algorithm has been applied to the test data, the user is presented with the result of the classification graphically. In addition, the user can display the performance indicators accuracy, recall and precision based on a confusion matrix [50]. If necessary, the user is given the opportunity to return to the algorithm selection and change his choice.

The **Evaluation** section allows the user to evaluate the results of the MLA with respect to the objectives defined in the Business Understanding and Technical Understanding sections, which are displayed again for this purpose. To the extent that the original goals were missed, users can go back to previous steps and make adjustments according to the systematics of the DMME. Within the last two sections **Technical Implementation** and **Deployment**, guidance is provided to the user to apply the MLA to the real process and maintain long-term functionality.

4. Evaluation of the CAS-ML

In order to assess users' acceptance and the usability of the first prototypical realization of the CAS-ML, it is finally evaluated by potential users from lower management (n = 9) using the Technology Acceptance Model (TAM) [51]. The evaluation serves as basis and inspiration for future development steps by revealing weaknesses in the current prototype from the user's point of view. As data for the evaluation the NASA milling data set was used [52]. Based on a given task, the users were asked to pass through the CAS-ML and provide the necessary information required therein. Finally, a digital questionnaire was provided. Following the systematics of the TAM, answers were given on a 7-point Likert-scale with anchor points "Strongly Agree", "Neutral", and "Strongly Disagree", whereby a rating of 4,0 can be regarded as an average value.

The answers indicate that the users perceived the CAS-ML as useful. Thus, they highlighted its use as usefulness at work (Ø = 5,89), working performance (Ø = 5,44) and work facilitation (Ø = 5,44). In contrast, the users expressed concerns regarding the usability. They especially marked the operation with the system (Ø = 4,78) and its customization to their needs (Ø = 4,78).

In light of the feedback by the testers included in the evaluation, the necessity of the CAS-ML is seen. Yet, an emphasis in future steps needs to be put on the usability whereby facilitating the ease-of-use and customization.

5. Summary and Outlook

In this paper, a cognitive assistance system to support the implementation of MLA, with special focus to predictive maintenance, in manufacturing environments was presented. It supports shop floor managers by providing a step-by-step instruction based on the DMME and concretizes where necessary. Additional learning content for each step was integrated that can be consumed context related. The CAS-ML offers the opportunity to learn foundations of MLA and important steps in the introduction process in a work-integrated manner, whereby allowing situated, self-directed and experimental learning and thus simplifying the transfer of knowledge gained to real industrial problems. As output, using companies exhibit higher competences in terms of machine learning, an improved IT infrastructure as well as data suitable for predictive maintenance. The CAS-ML was realized as a software application in Python and evaluated in terms of acceptance and usability by practitioners on an open-source data set.

Considering the assigned usability, the focus of future development steps is on a human-centered design such that the requirements of users are more deeply integrated and on facilitating learning. Besides, an extension to other machines such as a band saws or lathe as well as other use cases is planned. The existing prototype shall then be used in an industrial environment on real recorded data and in this context, users will be tested on competence development. Future development will also focus on the competence development through an interrogation of knowledge and action elements. Likewise, a division in tutorial and expert system is planned.

References

[1] Bitkom, 2022. Welche Bedeutung hat Industrie 4.0 für Ihr Unternehmen? https://de.statista.com/statistik/daten/studie/830769/umfrage/bedeutung-von-industrie-40-in-deutschland/. Accessed 9 August 2022.

[2] Hulla, M., Herstätter, P., Wolf, M., Ramsauer, C., 2021. Towards digitalization in production in SMEs – A qualitative study of challenges, competencies and requirements for trainings. Procedia CIRP 104, 887–892.

[3] Rauch, E., Linder, C., Dallasega, P., 2020. Anthropocentric perspective of production before and within Industry 4.0. Computers & Industrial Engineering 139, 105644.

[4] Gorecky, D., Mura, K., Arlt, F., 2013. A Vision on Training and Knowledge Sharing Applications in Future Factories. IFAC Proceedings Volumes 46 (15), 90–97.

[5] Peifer, Y., Jeske, T., Hille, S., 2022. Artificial Intelligence and its Impact on Leaders and Leadership. Procedia Computer Science 200, 1024–1030.

[6] Bauer, M., van Dinther, C., and Kiefer, D., 2020. Machine learning in SME: an empirical study on enablers and success factors, in: AMCIS 2020 proceedings - Advancings in information systems research. 26th Americas Conference on Information Systems. August 10-14 2020. Association for Information Systems (AIS), Atlanta, pp. 1–10.

[7] Ermakova, T., Blume, J., Fabian, B., Fomenko, E., Berlin, M., Hauswirth, M., 2021. Beyond the Hype: Why Do Data-Driven Projects Fail?, in: Proceedings of the 54th Hawaii International Conference on System Sciences, Hawaii. January 4-8, 2021, pp. 5081–5090.

[8] Metternich, J., Biegel, T., Bretones Cassoli, B., Tobias, Hoffmann, F., Jourdan, N., Rosemeyer, J., Stanula, P., Ziegenbein, A., 2021. Künstliche Intelligenz zur Umsetzung von Industrie 4.0 im Mittelstand: Expertise des Forschungsbeirats der Plattform Industrie 4.0. www.acatech.de/publikation/fb4-0-ki-in-kmu/. Accessed 11 October 2022.

[9] Erpenbeck, J., Sauter, W., 2013. So werden wir lernen!: Kompetenzentwicklung in einer Welt fühlender Computer, kluger Wolken und sinnsuchender Netze. Springer Gabler, Berlin, Heidelberg.

[10] Hartmann, E., 2015. Arbeitsgestaltung für Industrie 4.0: Alte Wahrheiten, neue Herausforderungen, in: Botthof, A., Hartmann, E.A. (Eds.), Zukunft der Arbeit in Industrie 4.0. Springer Vieweg, Berlin, Heidelberg, pp. 9–20.

[11] Dehnbostel, P., 2009. New Learning Strategies and Learning Cultures in Companies, in: Maclean, R., Wilson, D. (Eds.), International Handbook of Education for the Changing World of Work. Springer, Dordrecht, pp. 2629–2645.

[12] Romero, D., Bernus, P., Noran, O., Stahre, J., Fast-Berglund, Å., 2016. The Operator 4.0: Human Cyber-Physical Systems & Adaptive Automation Towards Human-Automation Symbiosis Work Systems, in: Nääs, I.A., Vendrametto, O., Mendes Reis, J., Gonçalves, R.F., Terra Silva, M., Cieminski, G. von, Kiritsis, D. (Eds.), Advances in production management systems. IFIP WG 5.7 International Conference, APMS 2016, Iguassu Falls, Brazil, September 3-7, 2016, vol. 488. Springer, Cham, pp. 677–686.

[13] Dacal-Nieto, A., Areal, J.J., Alonso-Ramos, V., Lluch, M., 2022. Integrating a data analytics system in automotive manufacturing: background, methodology and learned lessons. Procedia Computer Science 200, 718–726.

[14] Mitchell, T.M., 2010. Machine learning, International ed., [Reprint.] ed. McGraw-Hill, New York, NY.

[15] Lave, J., Wenger-Trayner, É., 1991. Situated learning: Legitimate peripheral participation. Cambridge Univ. Press, Cambridge.

[16] Dehnbostel, P., Schröder, T., 2017. Work-based and Work-related Learning: Models and Learning Concepts. TVET@Asia (9), 1–16.

[17] Mark, B.G., Rauch, E., Matt, D.T., 2021. Industrial Assistance Systems to Enhance Human–Machine Interaction and Operator's Capabilities in Assembly, in: Matt, D., Modrak, V., Zsifkovits, H.E. (Eds.), Implementing Industry 4.0 in SMEs. Concepts, examples and applications. Palgrave Macmillan, Cham, Switzerland, pp. 129–161.

[18] Villanueva Zacarias, A.G., Reimann, P., Mitschang, B., 2018. A framework to guide the selection and configuration of machine-learning-based data analytics solutions in manufacturing. Procedia CIRP 72, 153–158.

[19] Frye, M., Krauß, J., Schmitt, R.H., 2021. Expert System for the Machine Learning Pipeline in Manufacturing. IFAC-PapersOnLine 54 (1), 128–133.

[20] Garouani, M., Ahmad, A., Bouneffa, M., Hamlich, M., Bourguin, G., Lewandowski, A., 2022. Towards big industrial data mining through explainable automated machine learning. International Journal of Advanced Manufacturing Technology 120 (1-2), 1169–1188.

[21] Fischbach, A., Strohschein, J., Bunte, A., Stork, J., Faeskorn-Woyke, H., Moriz, N., Bartz-Beielstein, T., 2020. CAAI—a cognitive architecture to introduce artificial intelligence in cyber-physical production systems. International Journal of Advanced Manufacturing Technology 111, 609–626.

[22] International Organization for Standardization, 2019. Ergonomics of human-system interaction: Part 210: Human-centred design for interactive systems. Beuth Verlag GmbH, Berlin.

[23] Łapińska, J., Escher, I., Górka, J., Sudolska, A., Brzustewicz, P., 2021. Employees' Trust in Artificial Intelligence in Companies: The Case of Energy and Chemical Industries in Poland. Energies 14 (1942).

[24] Sjödin, D.R., Parida, V., Leksell, M., Petrovic, A., 2018. Smart Factory Implementation and Process Innovation. Research-Technology Management 61 (5), 22–31.

[25] Huber, S., Wiemer, H., Schneider, D., Ihlenfeldt, S., 2019. DMME: Data mining methodology for engineering applications – a holistic extension to the CRISP-DM model. Procedia CIRP 79, 403–408.

[26] Delbridge, R., Lowe, J., Oliver, N., 2000. Shopfloor Responsibilities Under Lean Teamworking. Human Relations 53 (11), 1459–1479.

[27] Rosemeyer, J., Bardy, S., Pinzone, M., Bosani, E., Schubert, T., Metternich, J., 2022. Towards artificial intelligence in production: A competence profile for shop floor managers. SSRN Journal.

[28] Peres, R.S., Jia, X., Lee, J., Sun, K., Colombo, A.W., Barata, J., 2020. Industrial Artificial Intelligence in Industry 4.0 - Systematic Review, Challenges and Outlook. IEEE Access 8, 220121–220139.

[29] Zonta, T., da Costa, C.A., da Rosa Righi, R., Lima, M.J. de, da Trindade, E.S., Li, G.P., 2020. Predictive maintenance in the Industry 4.0: A systematic literature review. Computers & Industrial Engineering 150 (6), 106889.

[30] Molano, J.I.R., Lovelle, J.M.C., Montenegro, C.E., Granados, J.J.R., Crespo, R.G., 2018. Metamodel for integration of Internet of Things, Social Networks, the Cloud and Industry 4.0. Journal of Ambient Intelligence and Humanized Computing 9 (3), 709–723.

[31] Bardy, S., Cibis, K., Hoppe, S., Schubert, T., Szuppa, S., Pinzone, M., Biscardo, G., Metternich, J., 2021. Human in the AI Loop: Teaching Shop Floor Workers Artificial Intelligence in Production. Proceedings of the 11th Conference on Learning Factories (CLF).

[32] Cachay, J., Abele, E., 2012. Developing Competencies for Continuous Improvement Processes on the Shop Floor through Learning Factories: Conceptual Design and Empirical Validation. Procedia CIRP 3, 638–643.

[33] DIN German Institute for Standardization, 2022. Maintenance-Maintenance Key Performance Indicators. Beuth Verlag GmbH, Berlin.

[34] Wagner, C., Hellingrath, B., 2019. Implementing Predictive Maintenance in a Company: Industry Insights with Expert Interviews, in: IEEE International Conference on Prognostics and Health Management (ICPHM). IEEE, pp. 1–8.

[35] Nahornyi, V., Panda, A., Valíček, J., Harničárová, M., Kušnerová, M., Pandová, I., Legutko, S., Palková, Z., Lukáč, O., 2022. Method of Using the Correlation between the Surface Roughness of Metallic Materials and the Sound Generated during the Controlled Machining Process. Materials 15 (3), 823.

[36] Popescu, T.D., Aiordachioaie, D., Culea-Florescu, A., 2022. Basic tools for vibration analysis with applications to predictive maintenance of rotating machines: an overview. The International Journal of Advanced Manufacturing Technology 118 (9-10), 2883–2899.

[37] Zschech, P., Heinrich, K., Bink, R., Neufeld, J.S., 2019. Prognostic Model Development with Missing Labels. Business & Information Systems Engineering 61 (3), 327–343.

[38] Hoffmann, J.B., Heimes, P., Senel, S., 2019. IoT Platforms for the Internet of Production. IEEE Internet of Things Journal 6 (3), 4098–4105.

[39] Zietsch, J., Weinert, N., Herrmann, C., Thiede, S., 2019. Edge Computing for the Production Industry A Systematic Approach to Enable Decision Support and Planning of Edge, in: 2019 IEEE 17th International Conference on Industrial Informatics (INDIN). IEEE, pp. 733–739.

[40] Bilogur, A., 2018. Missingno: a missing data visualization suite. Journal of Open Source Software 3 (22), 547.

[41] Paolanti, M., Romeo, L., Felicetti, A., Mancini, A., Frontoni, E., Loncarski, J., 2018. Machine Learning approach for Predictive Maintenance in Industry 4.0, in: 14th IEEE/ASME International Conference on Mechatronic and Embedded Systems and Applications (MESA). IEEE, pp. 1–6.

[42] Zhang, C., Yao, X., Zhang, J., Jin, H., 2016. Tool Condition Monitoring and Remaining Useful Life Prognostic Based on a Wireless Sensor in Dry Milling Operations. Sensors 16 (6).

[43] Caesarendra, W., Tjahjowidodo, T., 2017. A Review of Feature Extraction Methods in Vibration-Based Condition Monitoring and Its Application for Degradation Trend Estimation of Low-Speed Slew Bearing. Machines 5 (4).

[44] Stahle, L., Wold, S., 1989. Analysis of variance (ANOVA). Chemometrics and Intelligent Laboratory Systems 6 (4), 259–272.

[45] Raju, V.N.G., Lakshmi, K.P., Jain, V.M., Kalidindi, A., Padma, V., 2020. Study the Influence of Normalization/Transformation process on the Accuracy of Supervised Classification, in: Proceedings of the 3rd International Conference on Smart Systems and Inventive Technology (ICSSIT 2020). IEEE, pp. 729–735.

[46] Shalabi, L.A., Shaaban, Z., Kasasbeh, B., 2006. Data Mining: A Preprocessing Engine. Journal of Computer Science 2 (9), 735–739.

[47] Gholamy, A., Kreinovich, V., Kosheleva, O., 2018. Why 70/30 or 80/20 relation between training and testing sets: A pedagogical explanation 1209. https://scholarworks.utep.edu/cs_techrep/1209/. Accessed 10 September 2022.

[48] Traini, E., Bruno, G., D'Antonio, G., Lombardi, F., 2019. Machine Learning Framework for Predictive Maintenance in Milling. IFAC-PapersOnLine 52 (13), 177–182.

[49] Bahel, V., Pillai, S., Malhotra, M., 2020. A Comparative Study on Various Binary Classification Algorithms and their Improved Variant for Optimal Performance, in: 2020 IEEE Region 10 Symposium (TENSYMP). IEEE, pp. 495–498.

[50] Shobha, G., Rangaswamy, S., 2018. Machine Learning, in: Gudivada, V.N., Rao, C.R. (Eds.), Computational Analysis and Understanding of Natural Languages. Principles, Methods and Applications. Elsevier, Amsterdam, pp. 197–228.

[51] Davis, F.D., 1989. Perceived Usefulness, Perceived Ease of Use, and User Acceptance of Information Technology. MIS Quarterly 13 (3), 319–340.

[52] Agogino, A., Goebel, K., 2007. Milling Data Set. NASA Ames Research Center. https://www.kaggle.com/datasets/vinayak123tyagi/milling-data-set-prognostic-data/metadata.

Biography

Jannik Rosemeyer, M. Sc. (*1994) is PhD student and research assistant at the Institute of Production Management, Technology and Machine Tools (PTW) at Darmstadt University of Technology since 2020. His research interests include the introduction of ML applications as well as the competence development of production employees and shop floor managers for the use of ML applications.

Laurenz Beck, M.Sc. (*1998) is International Management Trainee at DAW SE. He holds a Master of Science in Industrial Engineering which he obtained at the Technical University of Darmstadt. His research interests are in lean production and data analytics.

Prof. Dr.-Ing. Joachim Metternich (*1968) is head of the PTW at TU Darmstadt since 2012. He is spokesman of the medium-sized digital competence centre Darmstadt, was president of the International Association of Learning Factories (IALF) from and is member of the scientific society for production technology (WGP).

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Energy-Flexible Job-Shop Scheduling Using Deep Reinforcement Learning

Mine Felder[1], Daniel Steiner[1], Paul Busch[2], Martin Trat[1], Chenwei Sun[1], Janek Bender[1], Jivka Ovtcharova[1]

[1]*FZI Research Center for Information Technology, Karlsruhe, Germany*
[2]*Karlsruhe Institute of Technology, Karlsruhe, Germany*

Abstract

Considering its high energy demand, the manufacturing industry has grand potential for demand response studies to increase the use of clean energy while reducing its own electricity cost. Production scheduling, driven by smart demand response services, plays a major role in adjusting the manufacturing sector to the volatile electricity market. As a state-of-the-art method for scheduling problems, reinforcement learning has not yet been applied to the job-shop scheduling problem with demand response objectives. To address this gap, we conceptualize and implement deep reinforcement learning as a single-agent approach, combining electricity cost and makespan minimization objectives. We consider makespan as an ancillary objective in order not to entirely abandon the timely completion of production operations while assigning different weights to both objectives and analyzing the resulting trade-offs between them. Our main contribution is the integration of the electricity cost-related objective. We present two innovative reward functions, which consider the dynamic electricity prices to select a job for the machine or allow the machine idle. The reinforcement learning agent finds optimal schedules determined by cumulative electricity costs for benchmark scheduling cases from the literature.

Keywords

Deep Reinforcement Learning; Production Planning; Job-Shop Scheduling; Demand Response; Energy Flexibility

1. Introduction

Sustainable energy consumption has become a critical issue of the industry concerning its massive energy demand and related emissions. The industry sector is accountable for the largest share of electricity consumption with 42% in 2018 compared to other sectors including household, commerce and transportation [1]. According to [2], the global greenhouse emissions caused by industrial processes reached a record level in 2021 with 2.54 Gt CO_2eq. Demand response (DR) is one of the mechanisms to tackle the growing energy and emissions problem of the the industry, which has a key role in energy management. With the help of smart grid devices, DR aims to improve electricity grid reliability, increase the demand for renewable energy, and cut energy-related emissions. Furthermore, DR motivates end-users to plan their consumption based on time-varying electricity prices in order to reduce their electricity bills [3,4].

Regarding the planning of electricity consumption of manufacturing, researchers have developed several approaches for integrating the DR aspect into the scheduling and utilized various scheduling techniques. Through rapid developments in artificial intelligence and machine learning, reinforcement learning (RL) has recently brought new ground for scheduling problems [4,5]. By continuously learning through interaction

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with the problem's environment, RL can create optimal, generic and rapid solutions for dynamic and complex problems [3]. These features make RL a convenient method for handling the dynamic characteristics of manufacturing as well as electricity markets.

Although numerous studies on the application of RL in scheduling problems are available, only a few have considered energy management aspects [4,6]. None of these studies address job-shop scheduling (JSS) intending to minimize electricity costs. Therefore, in this study, we work on developing a deep RL (DRL) methodology for JSS with electricity cost and makespan minimization objectives. Although yet to be published, [7] show a highly promising RL approach for JSS to minimize makespan. This paper presents how we successfully augmented their approach with DR aspects. To do this, we develop two different reward functions for two machine states: operating and being idle. This study considers makespan minimization as an auxiliary objective only to ensure the completion of production operations on time, whereas the electricity cost objective is assessed more in-depth. We give weights to both objectives to analyze the trade-offs in between and provide flexibility in the decision-making process of production planners. Our results show that the RL agent can reduce electricity costs with the help of our two reward functions.

The rest of the paper continues as follows: Section 2 explains the background behind this study, including JSS, DR, the related literature and RL. Section 3 provides our data and RL model. Section 4 presents the results of the model and discussion. Finally, section 5 gives a summary and an outlook for the future work direction.

2. Background

2.1 Job-Shop Scheduling

Among various scheduling problems, JSS is characterized as a combinatorial optimization problem, aiming to find an optimal solution from a finite set of feasible ones. Although the number of possible solutions is finite, JSS is one of the hardest manufacturing problems to solve, being identified as NP-hard (non-deterministic polynomial-time hard) [7].

JSS has two main components, which are jobs and machines. Each machine performs a specific processing step of a job, called an operation, in a specific sequence. There exist precedence constraints between operations. Machines can only execute one operation at a time until it is finished [8].

2.2 Demand Response

Due to limited transmission and storage opportunities for electricity, electricity supply and demand should always be in balance [9]. To keep balance, DR motivates alterations on the demand side in order to compensate for dynamic changes in electricity supply owing to diverse factors, including weather for renewable energy sources. In addition to balancing supply and demand, another goal of DR is to increase the electricity demand for times with large generation from renewable sources [10].

Without emission costs, electricity generation from renewables has lower marginal costs than conventional energy sources [11]. This cost advantage also makes DR attractive for consumers to save on their electricity bills. As the most significant electricity consumption sector, the industry could potentially benefit from DR to a great extent. Many studies have shown the applicability and advantages of industrial DR [4]. Nevertheless, according to [3], participation in DR is far less in the industry sector than residential and commercial sectors due to several barriers. The modeling of DR should consider complex and interdependent industrial processes and various electricity consumption profiles depending on equipment and job [12]. Another issue is potential risks for daily production, such as losses or penalties because of the shift in schedule [13]. Thus, the manufacturing sector approaches DR cautiously. That is why this study considers the timely completion of production tasks while scheduling DR.

2.3 Related Work

There have been numerous studies on scheduling problems, focusing on diverse objectives. This section presents the literature only dedicated to energy and makespan-related objectives applied to various scheduling problems (not only JSS). The applied methods can be categorized as heuristics, mathematical models and RL.

Heuristics applied to scheduling problems by previous studies include simulated annealing algorithm [14], particle swarm optimization [15], colony optimization [16], backtracking search algorithm [17] and genetic algorithm [18]. Overall, heuristics are preferable for their practicality, but they do not ensure globally optimal solutions and mostly offer near-optimal solutions [7,19].

Researchers focus on mathematical models to find the globally optimal solution for scheduling problems, such as mixed integer linear programming [20] and constraint programming [21]. However, compared to heuristics, these methods require complex mathematical expressions, precise modeling for each specific scheduling problem and much longer computational times [4].

The application of RL to scheduling problems has received much attention recently and is already utilized in a variety of optimization and decision-making problems [5]. [8,19,22] perform various RL algorithms intending to minimize the makespan. Regarding energy-relevant objectives, the authors of [4] utilize multi-agent DRL for the flow-shop scheduling problem to minimize the cost of energy and materials for manufacturing, while [6] use single-agent RL for rescheduling the production after a machine breakdown to minimize makespan and electricity consumption. However, until now, there have not been many studies for energy-flexible JSS using RL. With this study, we aim to fill this gap in the literature.

2.4 Reinforcement Learning

RL is a branch of machine learning, and its naming originates from psychological reinforcement theory, which explains the ability to shape personal behaviors by reinforcement and punishment [23]. Figure 1 illustrates the fundamental components of RL and the interaction in between. The main components include an agent and the environment in that the agent is located. In RL, the agent learns how to achieve a goal by interacting with the environment.

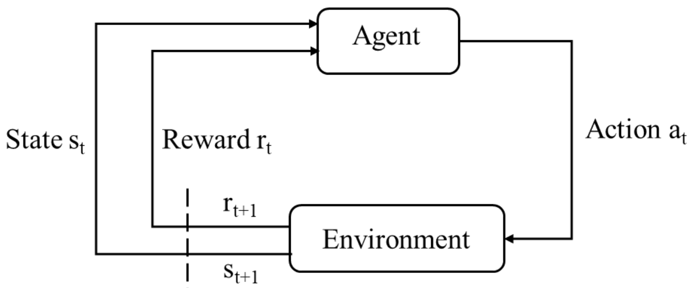


Figure 1: Representative deep reinforcement learning diagram (based on [4,24])

[24] states that the RL problem is based on an incompletely known Markov decision process where the agent partly observes the environmental state (s_t) and takes an action (a_t) regarding the observation. Taking an action (a_t) leads to a transition to the next state of the environment (s_{t+1}) and a numerical reward (r_{t+1}) from the environment. The RL agent tries to learn a policy that maps actions to the environmental states to maximize the numerical reward. The value function of the policy π is given by equation (1), which is the expected value (E) of discounted cumulative future rewards. In the equation, *R* stands for the set of rewards that the agent can obtain given that the state *s* at time *t*, while γ represents the discounting factor for future rewards [24].

$$V_\pi(s) = \mathrm{E}_\pi\left[\sum_{k=0}^{\infty} \gamma^k R_{t+k+1} | S_t = s\right] \quad (1)$$

A variety of RL algorithms have been developed so far, split into model-based and model-free algorithms. The main difference between the two categories is that model-based ones require modeling of state transition, whereas model-free ones do not. According to [5], due to the high computational effort for modeling state transition for a production environment, researchers preferred the model-free algorithms in scheduling problems more often, which are categorized as value-based and policy-based. Value-based algorithms try to learn state values V_π to find an optimal policy. In contrast, vanilla policy-based algorithms try to find an optimal policy by policy updates. Actor-critic methods, which are advanced policy-based algorithms, combine the advantages of these two methods by considering both the value function and policy update [25]. The main issue of actor-critic methods is to ensure a stable learning performance for the agent. As a DRL algorithm based on the actor-critic method, the proximal policy optimization (PPO) algorithm tries to ensure reliable learning performance by limiting policy updates with a hyperparameter called clipping parameter [26].

3. Methodology

We base our methodology on the work by [8], who build an RL environment to minimize makespan in the JSS problem. The following subchapters present our modifications on this JSS environment and the benchmark JSS datasets from the literature in order to integrate our primary objective of electricity cost minimization and to provide flexibility in production planning.

3.1 Data preparation

We implement our modified JSS model on the first ten instance datasets from [27]. The datasets are identical in size, including 15 machines and 15 jobs, each job has 15 operations. [27] gives processing times and machine numbers as the statistical data to describe an operation.

Our work in this stage includes the integration of external electricity data into the instance datasets. As external data, we add electricity demand per operation (kW) and the German day-ahead electricity prices (€/kWh). Electricity demand data is sampled from a discrete uniform distribution over the unit interval [1, 20] and given for each operation. We obtain the German day-ahead electricity prices from EPEX Spot through the Price API developed by aWATTar [28]. The data includes the prices between 11.10.2022 at 15:00 and 13.10.2022 at 00:00.

3.2 Modeling

In this stage, we enhance the JSS environment by considering energy-flexible scheduling. Specifically, the major modifications occur in the observation space and reward function, whereas the action space stays the same as the original version.

3.2.1 Action Space

The authors of [8] design the action space as the selection of a job for machines or keeping them idle, called "No-Op" by the authors. It is defined by the discrete space with the input $\{j_0, j_1, ..., j_{J-1}, \textit{No-Op}\}$. A boolean vector, representing the legal actions, eliminates ineligible actions, such as selecting finished or ongoing jobs or occupied machines, which is explained in Section 3.2.2. Additionally, the authors implement the "action masking" technique that equates the likelihood of taking illegal actions close to 0%. We employ these action-related settings without an alteration since our electricity cost objective does not require any change in the action space.

3.2.2 Observation Space

In the JSS environment from [7], the observation space of the agent includes seven attributes about required and leftover times for operations as well as idle times. Regarding our objective of electricity cost minimization, we add 2 new electricity-related attributes to the agent's observation space: the electricity demand of the operation and weighted electricity price. We weigh the hourly electricity price by the processing time because operations might take longer than one hour. The authors scale the majority of the attributes by the associated maximal values to treat them equally and benefit from the stability of the gradient calculation of the PPO network. We scale our two attributes accordingly. Table 1 shows all attributes of the observation space with explanations.

Table 1: Observation space attributes

State attribute	Description	Scaling Parameter	Range
s_1	Boolean parameter shows if jobs can be allocated to the machine	-	{0, 1}
s_2	Left over time for the currently performed operation	Longest operation time	[0,1]
s_3	Percentage of finished operations of a job	-	[0,1]
s_4	Left over time until total completion of a job	Longest job completion time	[0,1]
s_5	Required time until the machine is free	Longest operation time	[0,1]
s_6	Idle time since last job's performed operation	Durations of all operations	[0,1)
s_7	Cumulative idle time for the job in the schedule	Durations of all operations	[0,1)
s_8	Electricity demand of the operation	Largest electricity demand	[0,1]
s_9	Weighted electricity price	Highest electricity price	[0,1]

3.2.3 Reward Function

Equation (2) shows the original reward function from [8], which is an approach to minimize the makespan, calculated by taking the difference between the processing time of operation i of job j (p_{ij}), and idle times on machine m ($empty_m$), caused by selecting job j between old (s) and new states (s'). The authors scale the reward *R(s,a)* by maximum operation length.

$$\boldsymbol{R(s,a) = p_{ij} - \sum_{m \in M} empty_m(s,s')} \tag{2}$$

We develop two separate reward functions for selecting a job as the action and the "No-Op" action. Equation (3) represents the first reward function for the action for selecting a job. α represents the weight parameter for two objectives: makespan and electricity cost minimization. We integrate the electricity costs at the end of the formula. e_{ij} refers to the electricity demand of operation i of job j and π^h stands for the electricity price at hour h. p_{ij}^h represents the fraction of the processing time, which falls into each pricing hour. We scale the electricity costs by the largest electricity cost possible, which is the product of the highest electricity price and demand in the datasets. We subtract the weighted electricity costs from one, because the reward and electricity cost are inversely related. The agent receives less reward if it chooses an energy-intensive operation during an hour with a high electricity price.

$$R_1(s,a) = (1-\alpha)\left(p_{ij} - \sum_{m \in M} empty_m(s,s')\right) + \alpha\left(1 - \sum e_{ij}\, \pi^h p_{ij}^h\right) \tag{3}$$

For the "No-Op" action, the reward function given in equation (4) cannot have the operation-related parameters (e_{ij} and p_{ij}^h). Instead, we add only the electricity price to the reward function and scale by its maximum value. There is a different concept behind the reward function in equation (4) than in equation (3). On the one hand, the idle operation is not favorable for makespan minimization, because it can extend the total makespan. On the other hand, when the prices are high, it can be advantageous to not operate the machine to reduce the electricity cost. This concept is reflected in the change of the sign before the weight of the electricity minimization objective.

$$R_2(s,a) = (1-\alpha)\left(-\sum_{m\in M} empty_m(s,s')\right) - \alpha\left(1-\sum \pi^h\right) \quad (4)$$

4. Results and Discussion

We execute the PPO algorithm on a computer with AMD Ryzen 9 3950X CPU and 2 Nvidia Titan RTX GPU. We employ the same training time (10 minutes) and hyperparameters as [8].

Table 2 presents the results with all instance datasets. The results clearly show the antagonistic effect of α on the makespan and the electricity cost. Larger α values result in lower electricity costs and longer makespan. There are a few exceptions to this, such as the electricity costs of the datasets Taillard-03, Taillard-04 and Taillard-06. When we increase α from 0.5 to 0.8 for these datasets, we obtain higher electricity costs. In addition, incrementing α from zero to 0.2 provides shorter makespan values for the datasets Taillard-01 and between Taillard-05 and Taillard-09.

We obtain the significant difference, once we set α to 1, giving no focus on the makespan objective. Our reward functions provide an average 13% reduction in electricity costs when we focus fully on the electricity cost objective (α=1) compared to the model with full focus on makespan (α=0). Among the datasets, Taillard-09 has the biggest electricity cost savings with 18%. However, this rate may also depend on the electricity price data used for electricity cost calculation. The range of our price data lies between 0.2 and 0.49 €/kWh.

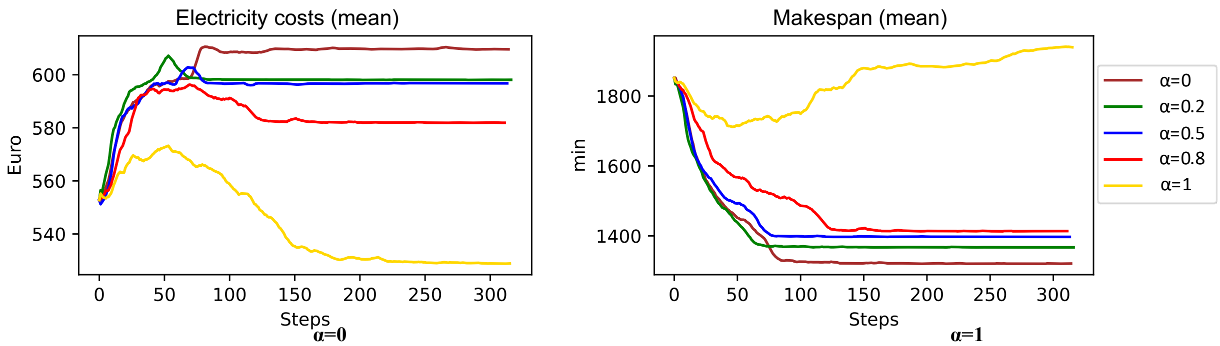
Table 2: Results in terms of electricity costs and makespan for the instance datasets with different weights

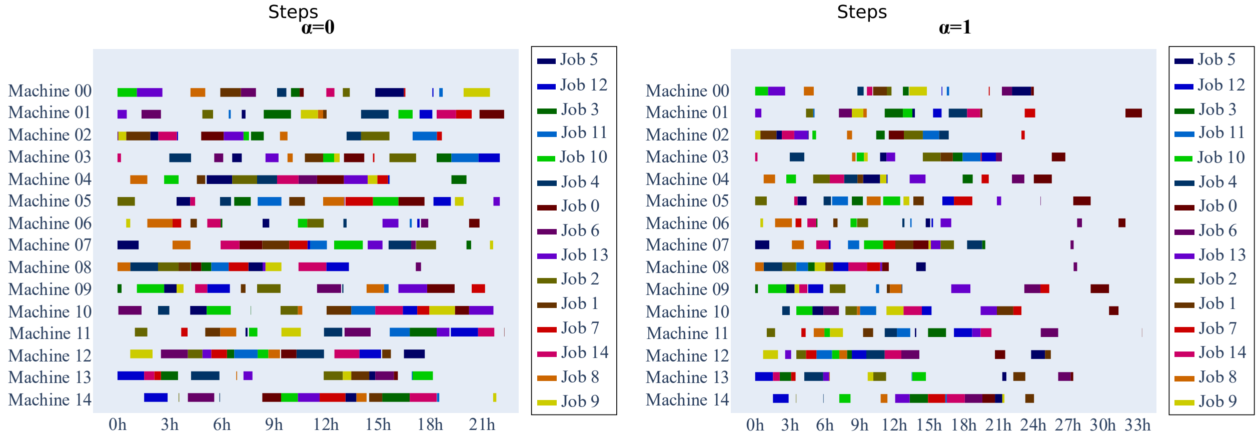
	Electricity costs (Euro)					Makespan (minute)				
Dataset	α=0	α=0.2	α=0.5	α=0.8	α=1	α=0	α=0.2	α=0.5	α=0.8	α=1
Taillard-01	687.20	671.63	659.08	651.38	574.37	1335.03	1310.48	1331.00	1343.05	1978.59
Taillard-02	589.64	572.66	572.15	539.43	497.22	1323.00	1323.00	1295.55	1421.28	1813.57
Taillard-03	596.35	595.96	581.99	583.99	546.44	1317.04	1333.01	1339.45	1338.11	1851.42
Taillard-04	608.01	597.18	579.19	582.67	536.16	1226.49	1264.63	1291.00	1333.80	1863.42
Taillard-05	587.55	574.10	556.34	549.01	507.46	1339.00	1309.04	1400.99	1427.38	1715.81
Taillard-06	569.59	546.69	545.10	553.94	495.90	1347.26	1325.25	1331.00	1366.76	1927.81
Taillard-07	608.94	620.05	607.67	600.00	566.02	1342.73	1294.12	1346.53	1412.49	1781.08
Taillard-08	598.03	599.66	596.70	594.88	497.15	1324.37	1319.08	1319.14	1349.10	2093.88
Taillard-09	620.32	594.84	597.37	581.84	511.03	1424.19	1392.53	1409.62	1506.72	2085.78
Taillard-10	609.57	598.08	596.76	581.88	528.85	1320.68	1367.03	1397.00	1413.77	1939.35

Figure 2 illustrates the evolution of makespan and electricity cost for the last instance data (Taillard-10) during the training with regard to α. At the beginning of the training, electricity costs are low since the agent has still jobs to finish. The costs rise as the agent assigns these jobs to machines. After reaching a peak, the agent is able to reduce the costs continuously through the half of the training. The results are stable afterwards. For α=1, the electricity cost is the lowest with €528.85 and the makespan is the longest with 1939.35 min at the end of the training. Contrarily, for α=0, the electricity cost is the largest with €609.57, while the makespan is the shortest with 1320.68 min. The intermediate α values lead to sequential results between these peak values. However, their results are closer to the results with α=0 rather than α=1. This may indicate that the makespan objective has a greater influence on the agent than the electricity cost objective for intermediate α values.

Figure 2: Evolution of the mean electricity costs and makespan during the training

Figure 3 compares the predictive schedules for the same instance data (Taillard-10) with the maximum and





minimum α values. The left schedule focuses on makespan minimization and shows that the agent is able to reduce the idle times of machines by limiting the "No-Op" action. The right schedule focuses completely on the electricity cost objective and illustrates how the agent distributes the operations over the longer time horizon by considering the electricity prices and demands of the operations. The agent completes the majority of the operations during the first 21 hours in the right schedule, similar to the left schedule. Three out of 15 jobs (Job 0, 6 and 7) are postponed to hours between 21 and 33. Completing 80% of the jobs within the same time as in the left schedule, the agent is still able to reduce the electricity costs from €609.57 to €528.85 in the right schedule (see Table 2).

Figure 3: The estimated schedules with full weights on makespan (α=0) and electricity costs objectives (α=1)

5. Summary and Outlook

In this study, we aim to present the RL-based method for energy-flexible production planning on the job-shop problem considering the timely completion of production tasks. For this purpose, we integrate the objective of electricity cost minimization into the RL environment built by [8] for makespan minimization. Our key contribution is the development of two distinct reward functions for operating a job and leaving the machine idle. Using the weight parameter for the objectives of makespan and electricity cost minimization, the algorithm provides flexibility in production planning, considering the preferences of the manufacturing company between the makespan of jobs and electricity costs. The results clearly show the trade-off situation between two objectives. Implementation on the benchmark scheduling cases show that giving full weight to the electricity cost objective can reduce electricity costs by 13% on average compared to giving full weight to makespan objective. One of the benchmark cases indicates that the agent schedules 20% of the jobs to a later time to decrease the electricity costs, while 80% are completed within the optimal time determined by the algorithm with full weight given to minimize the makespan.

Future research work may build on our findings by testing our agent for more available instance data and comparing PPO against other RL algorithms. A significant research direction would be adapting the algorithm to the more complicated form of JSS: the flexible JSS, which includes many available machines for each operation and different electricity demands for machine-operation pairs.

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References

[1] International Energy Agency (IEA). Key World Energy Statistics 2020.

[2] IEA, International Energy Agency, 2022. Global Energy Review: CO2 Emissions in 2021. https://www.iea.org/reports/global-energy-review-co2-emissions-in-2021-2.

[3] Huang, X., Hong, S.H., Yu, M., Ding, Y., Jiang, J., 2019. Demand Response Management for Industrial Facilities: A Deep Reinforcement Learning Approach. IEEE Access 7, 82194–82205.

[4] Lu, R., Li, Y.-C., Li, Y., Jiang, J., Ding, Y., 2020. Multi-agent deep reinforcement learning based demand response for discrete manufacturing systems energy management. Applied Energy 276, 115473.

[5] Wang, L., Pan, Z., Wang, J., 2021. A Review of Reinforcement Learning Based Intelligent Optimization for Manufacturing Scheduling. Complex Syst. Model. Simul. 1 (4), 257–270.

[6] Naimi, R., Nouiri, M., Cardin, O., 2021. A Q-Learning Rescheduling Approach to the Flexible Job Shop Problem Combining Energy and Productivity Objectives. Sustainability 13 (23), 13016.

[7] Chen, R., Yang, B., Li, S., Wang, S., 2020. A self-learning genetic algorithm based on reinforcement learning for flexible job-shop scheduling problem. Computers & Industrial Engineering 149, 106778.

[8] Tassel, P., Gebser, M., Schekotihin, K., 2021. A Reinforcement Learning Environment For Job-Shop Scheduling, 7 pp. http://arxiv.org/pdf/2104.03760v1.

[9] van der Veen, R.A., Hakvoort, R.A., 2016. The electricity balancing market: Exploring the design challenge. Utilities Policy 43, 186–194.

[10] Müller, T., Möst, D., 2018. Demand Response Potential: Available when Needed? Energy Policy 115, 181–198.

[11] Do, L.P.C., Lyócsa, Š., Molnár, P., 2019. Impact of wind and solar production on electricity prices: Quantile regression approach. Journal of the Operational Research Society 70 (10), 1752–1768.

[12] May, G., Stahl, B., Taisch, M., 2016. Energy management in manufacturing: Toward eco-factories of the future – A focus group study. Applied Energy 164, 628–638.

[13] McKane, A.T., Piette, M.A., Faulkner, D., Ghatikar, G., Radspieler Jr., A., Adesola, B., Murtishaw, S., Kiliccote, S., 2008. Opportunities, Barriers and Actions for Industrial Demand Response in California, 89 pp.

[14] Keller, F., Schultz, C., Braunreuther, S., Reinhart, G., 2016. Enabling Energy-Flexibility of Manufacturing Systems through New Approaches within Production Planning and Control. Procedia CIRP 57, 752–757.

[15] Dababneh, F., Li, L., Shah, R., Haefke, C., 2018. Demand Response-Driven Production and Maintenance Decision-Making for Cost-Effective Manufacturing. Journal of Manufacturing Science and Engineering 140 (6).

[16] Jia, Z., Wang, Y., Wu, C., Yang, Y., Zhang, X., Chen, H., 2019. Multi-objective energy-aware batch scheduling using ant colony optimization algorithm. Computers & Industrial Engineering 131, 41–56.

[17] Caldeira, R.H., Gnanavelbabu, A., Vaidyanathan, T., 2020. An effective backtracking search algorithm for multi-objective flexible job shop scheduling considering new job arrivals and energy consumption. Computers & Industrial Engineering 149, 106863.

[18] Wei, H., Li, S., Quan, H., Liu, D., Rao, S., Li, C., Hu, J., 2021. Unified Multi-Objective Genetic Algorithm for Energy Efficient Job Shop Scheduling. IEEE Access 9, 54542–54557.

[19] Bouazza, W., Sallez, Y., Beldjilali, B., 2017. A distributed approach solving partially flexible job-shop scheduling problem with a Q-learning effect. IFAC-PapersOnLine 50 (1), 15890–15895.

[20] Fang, K., Uhan, N., Zhao, F., Sutherland, J.W., 2011. A new approach to scheduling in manufacturing for power consumption and carbon footprint reduction. Journal of Manufacturing Systems 30 (4), 234–240.

[21] Raileanu, S., Anton, F., Iatan, A., Borangiu, T., Anton, S., Morariu, O., 2017. Resource scheduling based on energy consumption for sustainable manufacturing. J Intell Manuf 28 (7), 1519–1530.

[22] Samsonov, V., Kemmerling, M., Paegert, M., Lütticke, D., Sauermann, F., Gützlaff, A., Schuh, G., Meisen, T., 2021. Manufacturing Control in Job Shop Environments with Reinforcement Learning, in: Proceedings of the 13th International Conference on Agents and Artificial Intelligence. Science and Technology Publications, pp. 589–597.

[23] Ernst, D., Glavic, M., Capitanescu, F., Wehenkel, L., 2009. Reinforcement learning versus model predictive control: a comparison on a power system problem. IEEE transactions on systems, man, and cybernetics. Part B, Cybernetics : a publication of the IEEE Systems, Man, and Cybernetics Society 39 (2), 517–529.

[24] Sutton, R.S., Barto, A.G., 2018. Reinforcement Learning: An Introduction. Second edition. The MIT Press, Cambridge, Massachusetts, 352 pp.

[25] Konda, V. R.V., Tsitsiklis, J.N., 1999. Actor-Critic Algorithms.

[26] Schulman, J., Wolski, F., Dhariwal, P., Radford, A., Klimov, O., 2017. Proximal Policy Optimization Algorithms, 12 pp. http://arxiv.org/pdf/1707.06347v2.

[27] Taillard, E., 1993. Benchmarks for basic scheduling problems. European Journal of Operational Research 64 (2), 278–285.

[28] aWATTar. API - Preis Datenfeed. https://www.awattar.de/services/api. Accessed 1 October 2022.

Biography

Mine Felder studied Industrial Engineering (B.Sc.) at the Izmir University of Economics and Sustainable Resources Management (M.Sc.) at the Technical University of Munich. She is working as a research scientist in the research unit Intelligent Systems and Production Engineering (ISPE) at the FZI Research Center for Information Technology. Her research focuses on sustainable and smart manufacturing using machine learning methods.

Daniel Steiner is studying computer science (M.Sc.) at the Karlsruhe Institute of Technology (KIT), majoring in anthropomatics and cognitive systems as well as embedded system design and computer architecture. Since 2021, he works as a student assistant at FZI Research Center for Information Technology in Karlsruhe with a focus on machine learning in manufacturing.

Paul Busch is studying Mechanical Engineering (M.Sc.) at the Karlsruhe Institute of Technology (KIT). In his graduate thesis, he is working on the topic of the energy-flexible job shop scheduling in cooperation with the FZI Research Center for Information Technology and the KIT.

Martin Trat studied at the Karlsruhe Institute of Technology, where he majored in Industrial Engineering. He works as a research scientist at the FZI Research Center for Information Technology in Karlsruhe and focuses his research activities on the efficient and robust application of productive artificial intelligence in dynamically changing environments.

Chenwei Sun studied automotive engineering (B.Sc.) at Hefei University of Technology and mechanical engineering (M.Sc.) at Karlsruhe Institute of Technology (KIT), majoring in automotive engineering and information technology. Since 2020, he has been working as a research assistant at the FZI Research Center for Information Technology in Karlsruhe.

Janek Bender is vice department manager in the research unit Intelligent Systems and Production Engineering (ISPE) at the FZI Research Center for Information Technology in Karlsruhe. His research interests revolve around applying artificial intelligence to the manufacturing domain, especially within the context of job scheduling.

Jivka Ovtcharova is a full professor, head of the Institute for Information Management in Engineering (IMI) since October 2003 and founder of the Lifecycle Engineering Solutions Center (LESC) at the Karlsruhe Institute of Technology (KIT), established in June 2008. In addition, she is the director for Process and Data Management in Engineering (PDE) at the FZI Research Center for Information Technology in Karlsruhe since 2004.

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Laser Drying Of Graphite Anodes For The Production Of Lithium-Ion Batteries – A Process- And Material-Side Analysis For Sustainable Battery Production

Sebastian Wolf[1], Daniel Neb[1], Florian Hölting[2], Barkin Özkan[2],
Henning Clever[1], Benjamin Dorn[1], Heiner Hans Heimes[1], Achim Kampker[1]

[1]*Production Engineering of E-Mobility Components (PEM), RWTH Aachen University, Bohr 12, 52072 Aachen, Germany*
[2]*Faculty of Mechanical Engineering, RWTH Aachen University, 52072 Aachen, Germany*

Abstract

In many industries, such as the automotive industry or consumer electronics, the demand for lithium-ion batteries is increasing significantly. The state of the art in battery production is energy-consuming and cost-intensive. The drying process of the viscous active material applied to the conductor foils, together with the coating process, is responsible for more than half of the production costs of an electrode. The high energy consumption of conventional drying processes, such as convection drying, must be reduced. Therefore, lasers are used to dry the active material of the electrodes. Further advantages are the low footprint and the increased process flexibility. Moreover, the controlled energy deposition and the spatially selective heat input increase the energy efficiency of the process innovation laser drying. In this review, the results of experiments on drying anodes by laser are compared with the results of convection drying. For this purpose, different production process parameter combinations and material compositions for anodes are chosen in order to be able to derive the process and material influences on the electrode quality.

Keywords

Battery production; Lithium-ion battery; Electrode manufacturing; Production process innovation; Sustainable production; Laser drying

1. Introduction

In order to achieve the environmental policy climate targets, at both national and international level, the reduction of CO2 emissions in the transport sector is of central importance. These environmental policy climate targets are key factors in the current upheaval in the automotive industry. In recent years, automotive manufacturers have increasingly shifted their focus away from combustion engines to electromobility [1].

However, this upheaval is associated with many challenges. Two major challenges are the high cost of electric vehicles (EV) and the reduction of the carbon footprint over the total life cycle. The production costs of EVs are significantly higher due to the battery as a key component compared to conventional drives. [2, 3] One of the main influencing factors for the costs and energy consumption of battery production is the drying process with its high investing costs, high energy consumption of natural gas and resulting operating costs. [4, 5, 6] Küpper et al. showed that the coating and drying process is responsible for 54 % of the electrode production costs while these constitute about 39 % of the costs of battery cell production. Therefore, the coating and drying process makes up about 21 % of the total battery cell production costs [7].

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In recent years, research began on laser drying as a potential substitute for the conventional drying process. Lasers have already been used in industry in many areas as part of a variety of processes such as laser cutting, laser welding, laser processes for surface treatment or drilling and ablation with lasers [8]. Vedder et al. already showed that the drying of water-based anodes or cathodes containing lithium iron phosphate as active material is basically possible with almost similar quality regarding the conventional drying process [9]. The key advantages of drying electrodes by laser instead of convection drying are their high energy efficiency and small machine footprint which potentially results in lower invest and operating costs.

Nevertheless, the factors influencing the electrode quality dried by laser have hardly been researched. This publication aims to continue research in the field of laser drying of electrodes. The material and process sided factors influencing the drying quality of electrodes will be discussed. In the context of this publication, the electrodes have undergone the processes of mixing, coating, and either convection or laser drying.

2. Experimental Set-up

The battery production process is divided into three sections: Electrode manufacturing, cell assembly and cell finishing. In order to classify the subsequent experimental set-up, the process chain, showed in figure 1, of electrode production is described in detail and discussed below regarding laser drying [10].

Figure 1: Electrode manufacturing process chain

2.1 Processes in electrode manufacturing

The first manufacturing step is mixing. Here, binders such as styrene-butadiene rubber (SBR), carboxymethyl cellulose (CMC) and solvent are added to the active material (graphite). Furthermore, added conductive carbon black increases the electrical conductivity of the final cell [11]. The individual components are precisely weighed and stirred in a mixing unit. In addition to the material composition, process parameters like speed and mixing time determine the mixing process [4].

The mixing process is followed by the coating and drying of the slurry on the carrier film in a roll-to-roll process. A pump conveys the slurry evenly to the coating tool, which depends on the application method used. A distinction is made here between slot die, doctor blade or coating roller processes. [12] The carrier film is unwound from a coil at a defined web speed. The coating thickness can be varied depending on the web speed and the set pump speed with which the slurry is transported to the coating tool. In the case of the slot die application tool, the choice of shim plate and the distance between slot die and foil influence the gap width and thus the coating width and thickness. [4]

The structure and properties of the electrodes are also influenced by the subsequent drying process. The drying process has a significant influence on the quality of the cells and the production scrap rates. The task of drying is to dissolve the solvents from the applied coating and thus to dry the coating. Convection drying is the most common variant in practice, as the air flow generated is also used to remove the evaporated solvents [13]. Other drying options include infrared and laser dryers. This is followed by calendering, in which the electrode foil undergoes a rolling process. Then the coated film goes through the process steps of slitting and vacuum drying. After that, the cell is assembled, before the quality properties are finally checked for the last time in the cell finalization. [4]

2.2 Trial setup und process parameters

For the coating process in the underlying experimental setup, a one-sided coating system with a slot die is used. The web speed is adjusted by a drive located on the unwinder mandrel. In this way, different process speeds can be achieved. The slurry is conveyed to the slot die by a gear pump. The flow rate can be regulated by varying the pump speed.

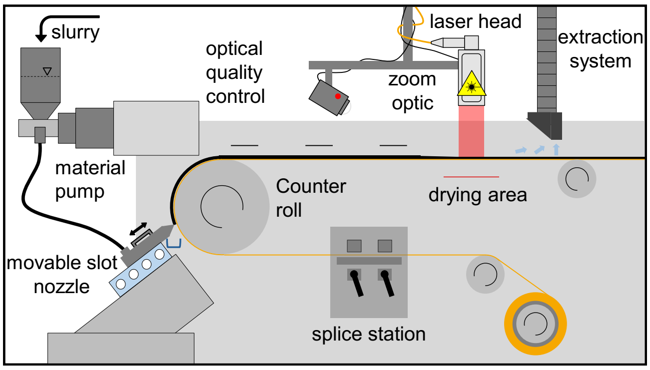

Figure 2: construction of the coating and drying process

After the coating process, the active material is dried on the 10 µm thick copper substrate foil. Two independent options are available for this in the experimental set-up used. In the first step, drying is done by a convection oven with a length of 3.5 m. Therefore, two drying chambers are present in which the solvent is evaporated by hot air. The temperatures in the two chambers can be set manually and differ. The second drying option shown in figure 2 is a diode laser. The laser used has a maximum output power of 8,000 W. In addition, a wavelength range of 900 to 1,080 nm is available. The zoom optics of the laser in the roll-to-roll process are located behind the slot die. The radiation hits the carrier foil perpendicularly on a 16 x 17 cm laser spot. A control module allows the laser power and thus intensity to be adjusted. After the drying process, the dried film is wound onto a coil with the help of a web edge control system.

Four different compositions, shown in Table, are mixed. Mixture 1 is a typical slurry recipe that is used in the industry in terms of substance concentration and used materials [14]. The other recipes are characterized by increasing the proportion of SBR (mixture 2), CMC (mixture 3) or solvent (mixture 4).

Table 1: Material composition of four tested mixtures

Mixture	1	2	3	4
Components of the mixture	Mass percentage [wt%]	Mass percentage [wt%]	Mass percentage [wt%]	Mass percentage [wt%]
Graphite	42.3	42	42.2	41.5
SBR	3.4	4.2	3.4	3.3
CMC	0.9	0.9	1.1	0.9
Conductive carbon black	0.4	0.4	0.4	0.4
Solvent	53	52.5	52.9	53.9

In addition, the process parameters of the coating and drying tests are varied. A distinction is made between the web speed, the pump speed and the heating temperatures of the two chambers or the laser intensity, whereby either convection or laser drying is used. Table 2 shows the used parameter sets of the coating process.

Table 2: Process parameter sets

Process parameter sets	1	2	3	4	5	6
Web speed [m/min]	0.8	0.8	1.3	1.3	1.8	1.8
Flow rate [cm³/min]	21	25.2	30.8	33.6	44.8	47.6
Temperature of heating chamber 1 [°C]	130	130	130	130	130	130
Temperature of heating chamber 2 [°C]	110	110	110	110	110	110
Laser intensity [W/cm²]	2.33	2.33	2.68	2.68	3.22	3.22
Total energy input per area [J/cm²]	29.71	29.71	21.03	21.03	18.25	18.25
Wet film thickness [µm]	169	203	153	167	161	171

The aim of the different compositions and process parameters is to investigate the influence on residual moisture content and the adhesion of the active material to the copper foil as the key quality parameters of the electrode drying process.

3. Process-sided evaluation

For the evaluation on the process side, the conducted analysis concentrates on the first and the fourth material compositions from Table 1 (mixture 1 and 4). A higher solvent content results in a more homogeneous mixture compared to the standard mixture. To assess the quality of the electrodes, samples of the coated foil are examined with regard to residual moisture and adhesion. The residual moisture is determined using a residual moisture meter and is measured by drying the sample and measuring the change in weight in parallel. The residual moisture content thus results from the difference in weight of the sample between the time before and after the drying process. To measure the tensile force, a punched-out sample of the coated film is stuck onto a stamp with adhesive tape. Another stamp (again equipped with adhesive tape) then moves onto the sample and presses it onto the other stamp with a previously set force. After that, the stamp is moved upwards at a constant speed. The force at which the coating is released from the carrier film is measured.

3.1 Convection drying

In order to obtain reference values for the assessment of laser drying, convection drying is discussed first. Figure 3 shows the results of the residual moisture and adhesion tests over the six sets of process parameters investigated with convection drying, which can be found in Table 2. The temperatures in the chambers of the dryer were kept constant throughout the drying process.

The residual moisture results of the mixture 4 are clearly above those of the mixture 1. This can be explained by the almost 1 % higher mass fraction of the solvent, which does not evaporate equally to the standard mixture during drying. In addition, the residual moisture increases when the flow rate ceteris paribus (c.p.) is increased. This can be seen in the transitions from parameter set 1 to 2, 3 to 4 and 5 to 6. An increased flow rate results in a higher wet film thickness, which means that more coating has to be dried in the same time. This results in a higher residual moisture content. Therefore, it can be seen that an increased wet film thickness results in an increase in residual moisture.

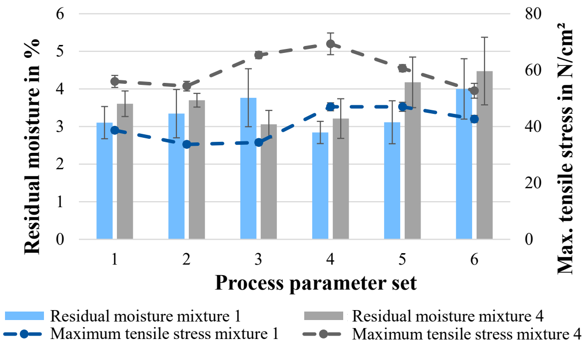

Figure 3: Residual moisture and maximum tensile stress of convection dried anodes

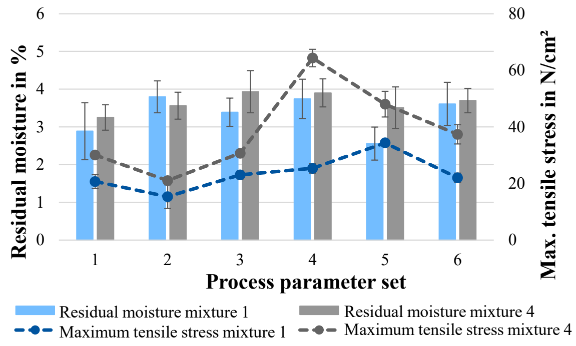

Figure 4: Residual moisture and maximum tensile stress of laser dried anodes

The analysis of the adhesion results shows a higher tensile stress of the mixture with increased solvent content compared to the standard mixture across all process parameter sets. This can be explained by an improved homogeneity of the slurry. The binder CMC has a high water absorption and can develop its potential better with an increased solvent content. This effect is explained in chapter 4.

At web speeds of 0.8 and 1.8 m/min, an increase in flow rate c.p. results in a decrease in tensile stress. A higher wet film thickness results in a lower tensile stress of the coating to the carrier film. This was not confirmed at a web speed of 1.3 m/min, an anomaly was revealed here. However, the standard mixture at process parameter set 3 also has a higher residual moisture than the mixture 4. This suggests that these samples should not be given the same importance as the other web speeds. The highest tensile stress of 69.33 N/cm² results from the solvent mixture with a web speed of 1.3 m/min and a flow rate of 33.6 cm³/min. The residual moisture is also low (3.21 %) across the process parameter sets at this web speed and the lower flow rate. Only the standard compound at a web speed of 1.3 m/min and a flow rate of 33.6 cm³/min shows a lower residual moisture. However, this results in a significantly lower tensile stress, which clearly shows that the solvent mixture is superior to the standard mixture in convection drying in terms of residual moisture and adhesion.

3.2 Laser drying

The diode laser is used to dry the electrodes. The laser spot on the electrode surface is 16 cm wide (corresponds to the coating width on the film) and 17 cm long (in the direction of movement of the film). First, a laser intensity was defined experimentally for each web speed at which the coating is dry, but the surface condition is not impaired by an excessive intensity. This results in a laser intensity of 2.33 W/cm² (total energy input per area of 29.71 J/cm²) for parameter sets 1 and 2, an intensity of 2.68 W/cm² (total energy input per area of 21.03 J/cm²) for parameter sets 3 and 4 and an intensity of 3.22 W/cm² (total energy input per area of 18.25 J/cm²) for parameter sets 5 and 6. It is noticeable here that the correlation between the increase in web speed and the increase in laser intensity is not linear in the lower tenth of the possible laser power.

In order to achieve sufficient drying results, the laser intensity does not have to be nearly doubled when the web speed increases from 0.8 m/min to 1.8 m/min (corresponds to an increase of 225 % and raise in laser intensity of 20 %). The diode laser achieves more precise focusing for higher intensities (above 10 % of the maximum capacity), so that for the low web speeds of 0.8 m/min and 1.3 m/min a higher total energy input per area is required to achieve a sufficient drying result.

3.2.1 Adhesion

Figure 4 shows the maximum tensile stress of mixture 1 and mixture 4 anodes. Here, three samples per process parameter combination were evaluated and the mean value of these three were determined. The standard deviation is shown by means of a corridor around the points.

The tensile stress of mixture 4 is higher than that of mixture 1 for all process parameter sets. This is due to the improved homogeneity of the slurry. For the web speeds of 0.8 and 1.8 m/min, increasing the flow rate c.p. results in a low tensile stress (parameter set 1 to 2 and 5 to 6). At the web speed of 1.3 m/min, the tensile stress increases when the flow rate c.p. is raised, and even significantly for mixture 4. To figure out the reason for this, Table 2 shows the wet film thicknesses of the process parameter combinations. From parameter set 1 to parameter set 2 the flow rate increases by 20 %, from 3 to 4 by 9 % and from parameter set 5 to 6 by 6 %. These percentage changes are also reflected in the wet film thicknesses. A too high wet film thickness has a negative effect on the distribution of the binders, which reduces the adhesion of the coating. Process parameter set 3 has a lower wet film thickness compared to parameter set 1, but also a lower total energy input per area, resulting in similar tensile stress results to parameter set 1. When the flow rate is increased to 33.6 cm^3/min the wet film thickness increases to 167 µm. With mixture 4 the tensile stress doubles, with the mixture 1 there is also an increase in tensile stress. This can be attributed to the fact that the laser radiation at parameter set 3 has influenced the effect of the binders due to the lower wet film thickness. The binders cannot exert their property of supporting adhesion. This is probably due to the binders were partially destroyed by the laser intensity. This effect can be compensated with an increased wet film thickness, as the laser has to dry more coating in the same time. The positive adhesion property of the binders thus remains, which is shown by the increase in tensile stress. An increase in the wet film thickness (process parameter set 6) leads to a decrease in the tensile stress, as with the web speed of 0.8 m/min. Finally, it can be stated that a too low wet film thickness has negative effects on the binders (parameter set 3). Increasing the wet film thickness can avoid this effect. However, there is a limit here. If the wet film thicknesses are above 170 µm, this results in a drop in the tensile stress. For mixture 1, a combination of a web speed of 1.8 m/min with a flow rate of 44.8 cm^3/min and a total energy input of 18.25 J/cm^2 is optimal, whereas for mixture 4, a web speed of 1.3 m/min with a flow rate of 33.6 cm^3/min and a total energy input of 21.03 J/cm^2 provides the highest stresses.

3.2.2 Residual moisture

The residual moisture values of mixture 1 and mixture 4 are listed in Figure 4. The results of the residual moisture test for all parameter sets (except parameter set 2) are higher for mixture 4 than for mixture 1. This can be explained by the increased solvent content, which cannot evaporate in the same time. When enlarging the flow rate c.p. (parameter set 1 to 2, 3 to 4 and 5 to 6) the residual moisture increases. The increased flow rate results in a higher wet film thickness, which means that more solvent has to be dried and the residual moisture increases. Only with the solvent mixture at a web speed of 1.3 m/min (parameter set 3 and 4), the residual moisture remains constant. If the standard deviations of the values are considered, this irregularity can be eliminated. The residual moisture values are in a similar range over all web speeds because the intensity has been adjusted so that the coating is visible dry. For the first process parameter set, the residual moisture is just under 3 %. If the flow rate is increased by 20 % (parameter set 2), the residual moisture increases by more than 30 % for mixture 1. With mixture 4, on the other hand, only a 10 % increase in residual moisture from parameter set 1 to parameter set 2 is discernible. From this it can be deduced that there is no direct linear relationship between flow rate and residual moisture. Furthermore, an interplay between residual moisture and adhesion can be observed. At the web speeds of 0.8 m/min and 1.8 m/min it is evident that a higher residual moisture leads to a lower adhesion (parameter sets 2 and 4). This can possibly be explained by a better utilisation of the adhesion properties of the binders at a lower moisture content of the coating [15].

In addition, process parameter set 5 provides better quality parameters for both mixture 1 and mixture 4 compared to the other five parameter sets. For mixture 1, parameter set 5 has the lowest residual moisture of the series of 2.56 % and for mixture 4 the second lowest residual moisture of 3.51 %. The total energy input per area of 18.25 J/cm² is sufficient for a dry coating result. The tensile stresses for this process parameter set are also in the upper range of the measurement series. Therefore, a suitable process window can be characterised with this process combination.

Moreover, the results of the residual moisture of the laser drying are compared with those of the convection drying. Overall, both mixture 1 and mixture 4 showed slightly better results than the residual moisture of convection drying on average for the first six sets of process parameters. The average value for the mixture 1 was approximately 0.03 % lower for laser drying than for convection drying. For mixture 4 there was a difference of approximately 0.07 %. Firstly, the results of mixture 1 are considered in detail. For process parameter set 1, the residual moisture by laser drying is below that of convection drying. If the flow rate is increased (parameter set 2), a higher laser intensity is needed to reach the residual moisture content of convection drying. The same findings can be transferred for the web speed of 1.3 m/min (parameter sets 3 and 4). At the high web speeds of 1.8 m/min, the residual moisture results of laser drying with both flow rates tested are below those of convection drying. Even with a reduced energy input per area of 15.19 J/cm² (parameter set 8), a comparable residual moisture to convection drying can be achieved. This is 0.09 % higher than that of convection drying (parameter set 5). This negligible difference can be accepted due to a significantly higher tensile stress. Besides, the residual moisture results of mixture 4 of laser drying and convection drying are compared in detail. For a web speed of 0.8 m/min, the residual moisture values of laser drying for both flow rates are below those of convection drying (parameter sets 1 and 2).

At a web speed of 1.3 m/min, the residual moisture values of convection drying cannot be achieved with the selected laser intensity of 21.03 J/cm². The reason for this is the increased solvent content. At the high web speeds of 1.8 m/min, laser drying with the selected energy input per area of 18.25 J/cm² dominates convection drying at both flow rates tested.

4. Material-side evaluation

4.1 Material-sided influences

Beside the concentration of solvent, the concentration of CMC is one of the main material-sided influencing factors on the residual moisture. As a result of the high water reactivity of CMC, there is increased water absorption [16]. This leads to a higher residual moisture content of the coating after drying. The tensile stresses after drying are positively influenced mainly by higher binder concentration, lower solvent concentration and film thickness and a higher homogeneity. [15, 17, 18]. Furthermore, the understanding of the binders CMC and SBR is important. While CMC is used as a thickening and setting agent, SBR increases the elasticity of the coating [19, 20]. Consequently, the shrinkage forces acting on the coating during drying can be absorbed favorably. If the SBR concentration is too low, cracks may occur because of the plastic absorption of these shrinkage forces [21]. Furthermore, these cracks can lead to adhesion losses [22]. Regarding the surface finish, a higher binder concentration also has a positive effect on the surface quality as a result of better filling of the cavities, especially for SBR. [6, 23]

4.2 Residual moisture

The reductions of the residual moisture contents, which were achieved by laser drying in comparison to convection drying, are shown in Figure 5. Here, the standard deviations are not to be understood as drying or measuring accuracy, but rather the range in which the measured values of the parameters sets 1, 3 and 5 lie.

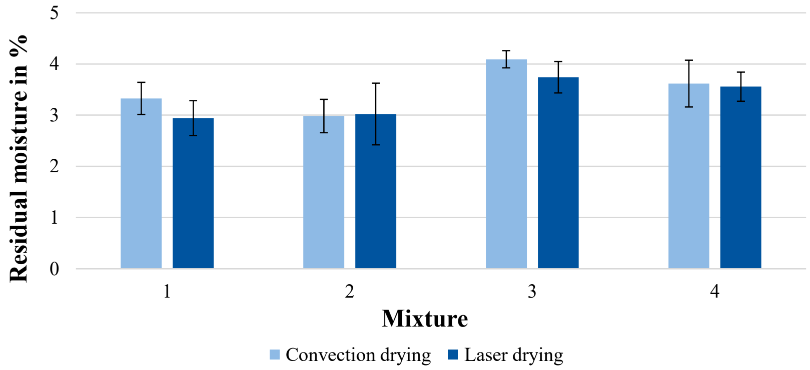

Figure 5: Residual moisture of all mixtures dried by

First, the residual moisture contents after convection drying are considered. The humidity after convection drying of mixture 2 has the lowest average measured value because of the lowest concentration of solvent. Further on, mixture 3 has the highest average residual moisture. This can be attributed to a higher water absorption due to increased CMC (see section 4.1). Mixture 1 shows the second lowest average measured humidity after convection drying. It is higher compared to mixture 2 due to an increased concentration of solvent. Apart from that, mixture 4 exhibits a higher average residual moisture than mixture 1 also as a result of the increased concentration of solvent and has a lower residual moisture than mixture 3. This is potentially due to the effect of water absorption on the humidity after drying, caused by the increased proportion of CMC, is stronger than the effect of the higher concentration of solvent regarding the mixture with a higher proportion of solvent.

In order to analyze the results after laser drying, the absorption coefficient of the coating in particular must be considered, because the absorption of laser radiation is determined by the absorption coefficient. It is essentially influenced by the graphite concentration of a material composition. [24] In Table 3, the graphite concentrations and the differences between the residual moistures of the coatings after laser drying and convection drying are shown. The results of the convection drying are used as the reference values. It is clearly seen that the highest reductions of the residual moisture contents were reached by the mixtures with the highest mass percentage of graphite, the standard mixture (total graphite concentration of 42.3 %) and the mixture with an increased proportion of CMC (total graphite concentration of 42.2 %). The mixture with an increased proportion of solvent shows a reduction of residual moisture after laser drying of 1.67 % in comparison to the residual moisture after convection drying.

Table 3: Graphite concentrations and differences of laser-dried and conventionally dried mixtures

	Standard mixture	CMC mixture	SBR mixture	Solvent mixture
Graphite concentration	42.3	42.2	42.0	41.5
Difference of residual moisture	-11.71 %	-8.56 %	+1.34 %	-1.67%

Mixture 2 shows about 1.34 % higher residual moisture after laser drying in comparison to convection drying. Regarding the graphite contents, it is unexpected that a higher reduction of the average measured humidity was achieved after laser-based drying of mixture 4 than after laser-based drying of mixture 2. Looking at the results of the residual moisture testing of each parameter, mixture 2 shows an unexpectedly high residual moisture content after laser-based drying by parameter set 2. This unexpectedly high value caused a higher average measured humidity after laser-based drying of this mixture.

To sum up the results of the residual moisture tests, it is shown that the higher concentrations of solvent and CMC lead to higher moisture contents after the drying process. Furthermore, regarding the laser-based drying the graphite concentration significantly influences the humidity due to higher absorption coefficients. Therefore, higher concentrations of graphite lead to higher absorption coefficients and these in turn lead to lower residual moisture contents.

4.3 Adhesion

The conventionally dried mixture 3 shows the highest average maximum tensile stresses due to higher binder concentration (see section 4.1). The conventionally dried mixture 4 has the second highest average maximum tensile stresses due to higher homogeneity despite an increased proportion of solvent (see section 4.1).

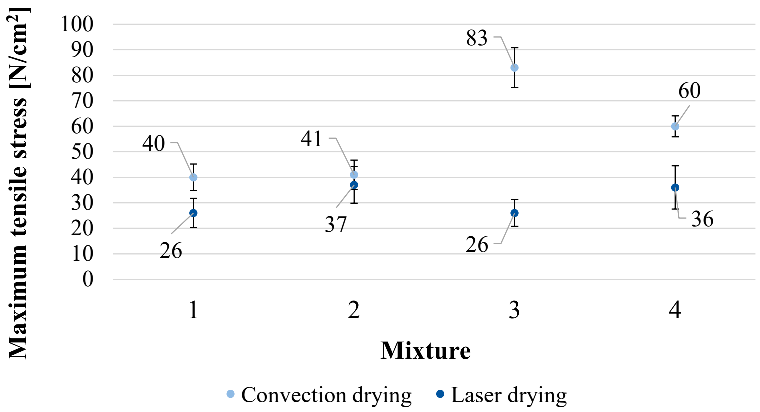

Figure 6: Maximum adhesion forces of all mixtures dried by

Furthermore, the conventionally dried mixture 1 and mixture 2 have the lowest average maximum tensile stresses. Therefore, the conventionally dried standard mixture has no significant losses regarding its adhesion. Potentially, the shrinking forces occurring during convection drying at the temperatures of 110 °C and 130 °C are comparatively low. As a result, the SBR had no significant effect regarding its improvement of elastically force absorption due to low shrinking forces. In Figure 6 the maximum tensile stresses are shown for the convection drying and laser-based drying. Here, the standard deviations are not to be understood as drying or measuring accuracy, but rather the range in which the measured values of the parameters sets 1, 3 and 5 lie. For every mixture, the maximum tensile stresses after laser-based drying are lower in comparison to convection drying. Especially the laser-dried mixture 3 shows the highest loss of tensile stresses in comparison to convective drying. Looking at the relative losses of tensile stresses after laser-based drying, the high laser intensity potentially damages the CMC. This explains the massive tensile stress losses of the laser-based drying of the mixture with an increased proportion of CMC. The loss of 40 % of tensile stresses of the laser-dried mixture 4 is higher than the loss of 35 % of tensile stresses of the laser-dried mixture 1. This potentially leads back to the relatively higher proportion of SBR in mixture 1 (3.4 %) than in mixture 4 (3.3 %). SBR can potentially cause a better absorption of the shrinking forces that occur during laser drying.

5. Conclusion

In summary, it could be shown that comparable residual moisture results and slightly lower to equivalent adhesion forces of the active material on the carrier film can be achieved with laser drying compared to convection drying. In particular, the graphite concentration has a significant influence on the residual moisture of the active material due to the high degree of absorption in the wave spectrum of the diode laser used. Furthermore, it could be shown that the solvent concentration and the amount of binders used, such as CMC and SBR, have an influence on the drying result. Regarding adhesion forces, it was shown that CMC is more sensitive to binder degradation at high laser intensities compared to SBR. This can lead to significantly high losses in the maximum tensile stresses for adhesion to the carrier film. Thus, lower laser intensities should be used to reduce the adhesion loss compared to convection drying. SBR seems to be a suitable binder for laser drying, as the shrinkage forces affecting the film and the coating during the drying process can be absorbed more elastically. For the process side evaluation, it can be stated that due to the non-linear power curve of the laser in the lower tenth of the retrievable power, there are challenges in correctly setting the laser intensity and the intensity cannot be easily scaled. Increasing the flow rate c.p. increases the wet film thickness and thus also the residual moisture. In addition, the tensile stress decreases with increasing residual moisture, as the binders can no longer fully exploit their adhesive properties at high moisture levels.

In conclusion, electrode drying by laser proves to be a promising alternative due to the low energy and space requirements. In the future, it should be investigated how laser drying can be scaled up to higher web speeds, for example by connecting several laser modules in series. Furthermore, it is necessary to compare the experimental results of other laser drying processes (e.g. VCSEL) with the experimental results of this paper. Another advantage of laser drying compared to convection drying is the faster controllability of the system, as the energy used can be adjusted without delay and long warm-up phases of the oven are avoided. Further research is needed to investigate the interdependencies of the laser drying process on the final cell quality and to further detail a process window for laser drying of anodes and cathodes for optimal electrode quality.

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References

[1] Attias, D., 2016. The Automobile Revolution. Towards a New Electro-Mobility Paradigm. Cham: Springer International Publishing.

[2] Kampker, A., Vallée, D., Schnettler, A., 2018. Elektromobilität. Berlin, Heidelberg: Springer Berlin Heidelberg.

[3] Helms, H., Kämper, C., Biemann, K., Lambrecht, U., Jöhrens, J., Meyer, K., 2019. Klimabilanz von Elektroautos. Einflussfaktoren und Verbesserungspotenzial. Agora Verkehrswende.

[4] Heimes, H., Kampker, A., Lienemann, C., Offermanns, C., Locke, M., 2018. Produktionsprozess einer Lithium-Ionen-Batteriezelle.

[5] Liu, Y., Zhang, R., Wang, J., Wang, Y., 2021. Current and future lithium-ion battery manufacturing. In: iScience 24 (4), S. 102-332.

[6] Wood, D. L., Quass, J. D., Li, J., Ahmed, S., Ventola, D., Daniel, C., 2018. Technical and economic analysis of solvent-based lithium-ion electrode drying with water and NMP. In: Drying Technology 36 (2), S. 234–244.

[7] Küpper, D., Kuhlmann, K., Wolf, S., Pieper, C., Xu, G., Ahmad, J., 2018. The Future of Battery Production for Electric Vehicles. Hg. v. The Boston Consulting Group.

[8] Bogue, R., 2015. Lasers in manufacturing: a review of technologies and applications. In: Assembly Automation 35 (2), S. 161–165.

[9] Vedder, C., Hawelka, D., Wolter, M., Leiva, D., Stollenwerk, J., Wissenbach, K., 2016. Laser-based drying of battery electrode layers. In: International Congress on Applications of Lasers & Electro-Optics. ICALEO® 2016: 35th International Congress on Applications of Lasers & Electro-Optics. San Diego, California, USA, October 16–20, 2016: Laser Institute of America, N501.

[10] Neb, D., Kim, S., Clever, H., Dorn, B., Kampker, A., 2022. Current advances on laser drying of electrodes for lithium-ion battery cells

[11] Wöhrle, T., 2013. Lithium-Ionen-Zelle. In: Reiner Korthauer (Hg.): Handbuch Lithium-Ionen-Batterien. Berlin, Heidelberg: Springer Berlin Heidelberg, S. 107–117.

[12] Kampker, A., Hohenthanner, C., Deutskens, C., Heimes, H., Sesterheim, C., 2013. Fertigungsverfahren von Lithium-Ionen-Zellen und -Batterien. In: Reiner Korthauer (Hg.): Handbuch Lithium-Ionen-Batterien. Berlin, Heidelberg: Springer Berlin Heidelberg, S. 237–247.

[13] Röth, T., Kampker, A., Deutskens, C., Kreisköther, K., Heimes, H., Schittny, B., 2018. Entwicklung von elektrofahrzeugspezifischen Systemen. In: Achim Kampker, Dirk Vallée und Armin Schnettler (Hg.): Elektromobilität. Berlin, Heidelberg: Springer Berlin Heidelberg, S. 279–386.

[14] Liu, D., Chen, L., Liu, T., Fan, T., Tsou, E., Tiu, C., 2014. An Effective Mixing for Lithium Ion Battery Slurries. In: ACES 04 (04), S. 515–528.

[15] Jaiser, S., Sanchez Salach, N., Baunach, M., Scharfer, P., Schabel, W., 2017. Impact of drying conditions and wet film properties on adhesion and film solidification of lithium-ion battery anodes. In: Drying Technology 35 (15), S. 1807–1817.

[16] Eser, J. C., Wirsching, T., Weidler, P.G., Altvater, A., Börnhorst, T., Kumberg, J., 2020. Moisture Adsorption Behavior in Anodes for Li‐Ion Batteries. In: Energy Technol. 8 (2), S. 1801162.

[17] Vuorilehto, K., 2013. Materialien und Funktion. In: Reiner Korthauer (Hg.): Handbuch Lithium-Ionen-Batterien. Berlin, Heidelberg: Springer Berlin Heidelberg.

[18] Haselrieder, W., Westphal, B., Bockholt, H., Diener, A., Höft, S., Kwade, A., 2015. Measuring the coating adhesion strength of electrodes for lithium-ion batteries. In: International Journal of Adhesion and Adhesives 60, S. 1–8.

[19] Yen, J., Chang, C., Lin, Y., Shen, S., Hong, J., 2013. Effects of Styrene-Butadiene Rubber/Carboxymethylcellulose (SBR/CMC) and Polyvinylidene Difluoride (PVDF) Binders on Low Temperature Lithium Ion Batteries. In: Journal of The Electrochemical Society, S. 1812.

[20] Liu, W.-R., Yang, M.-H., Wu, H.-C., Chiao, S. M., Wu, N.-L., 2005. Enhanced Cycle Life of Si Anode for Li-Ion Batteries by Using Modified Elastomeric Binder. In: Electrochemical and Solid-State Letters, S. 102-103.

[21] Fischer, S. B., Koos, E., 2021. Using an added liquid to suppress drying defects in hard particle coatings. In: Journal of colloid and interface science, S. 1231.

[22] Ramier, J., Da Costa, N., Plummer, C.J.G., Leterrier, Y., Månson, J.-A.E., Eckert, R., Gaudiana, R. 2008. Cohesion and adhesion of nanoporous TiO2 coatings on titanium wires for photovoltaic applications. In Thin Solid Films, S. 1908.

[23] Park, J., Ahn, K., 2021. Controlling Drying Stress and Mechanical Properties of Battery Electrodes Using a Capillary Force-Induced Suspension System. In: Ind. Eng. Chem. Res. 60 (13), S. 4873–4882.

[24] Pawlowski, L. (1999): Thick Laser Coatings: A Review. In: Journal of Thermal Spray Technology, S. 281.

Biography

Sebastian Wolf (*1997) is research associate in the group Battery Production Management at the Chair of Production Engineering of E-Mobility Components (PEM) at RWTH Aachen University, where he also studied Mechanical Engineering and Business Administration.

Daniel Neb (*1992) is research associate in the group Battery Production Management at PEM of RWTH Aachen University, where he also studied Mechanical Engineering with a specialization in Automotive Technology.

Florian Hölting (*1997) has been student assistant at PEM of RWTH Aachen University since 2021, where he also studied Mechanical Engineering and Business Administration.

Barkin Cem Özkan (*1998) studied Mechanical Engineering and Business Administration with a specialization in production technology and Operations Research and Management at RWTH Aachen University.

Henning Clever (*1992) is research associate at PEM of RWTH Aachen University since 2019 and group lead for the research group Battery Production Management since 2021. He studied Mechanical Engineering specializing in Production Engineering at RWTH Aachen University.

Benjamin Dorn (*1990) is chief engineer for Production Technology and Organization at PEM of RWTH Aachen University. He studied Mechanical Engineering and Business Administration there.

Heiner Hans Heimes (*1983) was chief engineer of the newly established Chair of PEM of RWTH Aachen University from 2015 to 2019. Since 2019, Dr.-Ing. Heimes has held the role of executive chief engineer at PEM.

Achim Kampker (*1976) is head of PEM at RWTH Aachen. He also acts as member of the executive board of the Fraunhofer FFB in Münster. Achim Kampker is involved in various expert groups of the federal and state governments.

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Specification Of 5G Networks For Agricultural Use Cases Using The Example Of Harvesters Operated By Swarm Robotics

Tim Walter[1], Kerstin Lörsch[1], Max-Ferdinand Stroh[1], Volker Stich[1]

[1]*FIR at RWTH Aachen, Aachen, Germany*

Abstract

Feeding the growing world population is a scientific and economic challenge. The target variables to be optimised are the yield that can be produced on a given area and the reduction of the resources used for this purpose. High-wage countries are faced with the problem that the use of personnel is a significant cost driver. Developing countries, on the other hand, usually operate on much smaller field sizes, so that the work in the field is still strongly characterised by manual labour. One solution to meet these challenges is the use of smaller autonomous harvesting robots. These can be networked into a swarm of machines to work even larger fields. The networking of autonomous agricultural machines is a key use case for rural 5G networks. 5G technology can offer many advantages over older mobile communications standards and therefore make use cases more efficient or enable new ones. Various use cases are also conceivable in the field of agriculture, yet it is unclear how 5G networks can and must be specified for this purpose. In this paper, using the example of 5G-connected harvesters powered by swarm robotics, we present the challenges that have arisen and the specification that has been developed.

Keywords

5G; Swarm Robotics; Smart Farming; Information Technology; Agriculture

1. Introduction

5G technology continues to grow in importance since its introduction, as can also be seen from the increasing subscription numbers of mobile radio standard. According to Ericsson's Mobility Report, the number of subscriptions increased by 70 million in the first quarter of 2022 alone [1]. Ericsson expects an increase of over 1 billion in the whole of 2022. The general tenor is that 5G technology will affect almost all industries if it not already does. The biggest changes that 5G will bring are expected in consumer goods, manufacturing, logistics and agriculture. In the B2C sector for example, higher speeds and lower latency will enable the use of augmented reality and virtual reality, so that the customer experience can be enhanced, for example, cities can use AR or VR at landmarks or museums to provide more information, so-called points of information (POI). In industry, on the other hand, improved analysis of the available real-time data can reduce downtimes on machines and set production standards. 5G technology can also lead to major changes in the logistics sector, as individual vehicles can be networked with each other [2]. Agriculture will also be increasingly influenced by 5G technology, the keyword here being so-called smart farming. The term smart farming refers to the use of information and communication technologies in agriculture. From a technological point of view, Unmanned Aerial Vehicles (UAVs), Unmanned Ground Vehicles (UGVs) and Wireless Sensor Networks play an important role in smart farming [3]. With UAVs, for example, it is possible to observe and monitor large fields from the air. In this way, various status information regarding weed growth, hidden animals,

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insect infestation and water can be automatically obtained without the need for large staff. The usage of 5G promises plenty of advantages especially in combination with (semi-)autonomous vehicles due to low latency, high connectivity, and high data throughput features. As the technology is not yet well tested in real life applications, its validation would be beneficial.

Agriculture in general is faced with various challenges. The task of feeding the expanding global population necessitates both technological and economic solutions. The yield that can be produced on a specific area and the reduction of resources needed for this goal are the target factors to be optimized [4]. Countries with high wages and developing nations confront various difficulties. Particularly in the former, the use of personnel is a major cost-driver [5]. The COVID-19 epidemic has also shown that hiring foreign harvest workers is not a dependable strategy for protecting the harvest in times of distress and can create a significant bottleneck [6]. On the other hand, developing nations struggle with the fact that their farming operations take place on much smaller fields, necessitating a lot more physical labor [7]. Because of this, it is challenging to use economies of scale and standardize production methods. Using autonomous, modular harvesting robots that are smaller is one way to address these issues. These robots can be employed in smaller groups or alone to automate the harvesting process for small fields. They can also be networked into a swarm of devices that autonomously cultivates huge yet parceled regions and avoid personnel bottlenecks. Positive side effects include greater resilience due to using multiple small machines rather than a single large one (redundancy in case of failure scenario) and the potential for cultivation under glass due to the machines' lower dimensions (water and resource savings). Thus, the usage of 5G in conjunction with swarms made up of tiny harvesters has a direct impact on greater ecological sustainability, including expanding populations of small game and more diverse plant and insect life (e.g., pheasant, partridge or admiral). Due to the use of wireless sensor technologies, cameras and autonomous systems, there is an increased data throughput that requires the use of a 5G network. Swarm algorithms for autonomous robots require that calculations do not only take place on the machine itself, but also centralized. Information as position, velocities, detected obstacles and status need to be transmitted and analyzed in short time to fulfil security standards. Thus, a performant telecommunication technology is needed.

The research presented in this paper addresses the aforementioned issues by showing the current state of an ongoing research project and providing its exemplary solutions as benchmark and basis for further work. In the beginning, we will focus on the research gap concerning this subject. Then, we will describe the use case and the elaborated requirements and specifications for the fitting 5G network. Finally, we take an outlook on developments to come.

2. Methodology

The present methodology of this research work results on the one hand from practical methods within the project and on the other hand from accompanying theoretical research. Figure 1 illustrates the procedure.

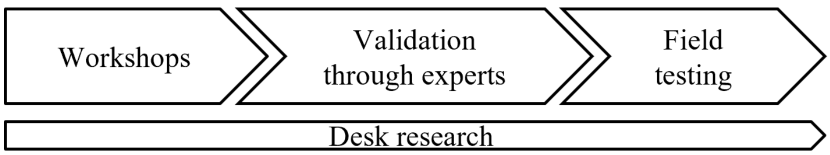

Figure 1: Illustration of the methodology

The sub-objectives of the project are to create a 5G specification and system architecture for the agricultural use case of swarm robotics harvesters, to implement the network and to test the technology in practice, with the result that the benefits and limitations of 5G technology can be demonstrated. Different methodologies were used for the various sub-objectives. The 5G specifications are based on the various use cases. These were determined during several workshops within the project team. The goal was to completely capture the various scenarios in which the 5G network becomes relevant for the harvesting robot. These use cases were validated by the robotics experts from the extended project team. Based on this, the requirements for the 5G network were defined for each defined use case. The requirements specify the latency frame, the data throughput, the need for real-time transmission and the required data rates. The specifications were discussed and validated with various 5G providers. Furthermore, a 5G short-term licence was applied for an agricultural test field to be able to test the defined use cases and the 5G specifications in a real laboratory. In the process of these field tests, the various use cases are carried out in realistic harvesting situations with the harvesting robot. Instead of getting the data directly, desk research is the act of gathering information that is already published [8]. Desk research methodology is particularly suitable for building up knowledge on new topics and substantiating existing statements or hypotheses with facts. Desk research enables a resource-saving and efficient gain of knowledge. In this case, different research papers were considered to get a holistic overview of the state of research and to identify the research gap. This is highlighted in the following chapter.

3. Research Results

In the following, we will present the results of our research.

3.1 Research Gap

As early as 1995, there was initial research into an autonomous robot that harvests fragile vegetables and fruit. In recent years, there has been a great deal of research on this, including describing the navigation and positioning of individual harvesting robots [9]. Despite the need for strong communication between machines, there has not been research on outdoor 5G communication for robots.

The existing research on 5G in agriculture covers specific topics, such as security [10,11] or it is only mentioned as an enabler for IoT applications [12,13]. Overall, there are only a few sources that deal with the design of 5G networks. One exception is Valecce et al. 2019, who specify the requirements for a 5G network for UAVs (Unmanned Air Vehicles) and UGVs (Unmanned Ground Vehicles). However, these are of a qualitative nature and are not precisely matched to the hardware used by the autonomous robots [14]. Another exception is Tomaszewski et al. 2022, where the network requirements were determined for several 5G use cases in agriculture. However, this is not based on requirements for the 5G network developed jointly with the user but based on 3GPP-defined classes of service. Further on, only the deliverability by 5G networks is discussed and no 5G network architecture is presented [15].

As can be seen in table 1, the design and functionality of the network layer is discussed with similar frequency in the agricultural sector compared to the physical layer in the field of the Internet of Things (IoT). However, it should be noted that the topic of 5G as an enabler technology is rarely supported. As described above, high importance has been attached to the technology. Consequently, several research papers have already been published on this topic, albeit being concerned with different conditions as the surroundings. Most of the work is on enclosed spaces, such as factory floors with use cases such as augmented reality and analysis of real-time data. In these areas, there are already requirements for the 5G networks and, as a result, the corresponding network specifications [16,17]. Overall, there is a deficit in research on 5G in an agricultural context [18].

Thus, we deduct a research gap for the practical specification and system architectures of 5G networks for agricultural use cases on an outdoor field especially for robotics applications.

Table 1: Surveys to physical and network layer for IoT applications in agriculture [19]

Survey	Talavera et al. [20]	Ray [21]	Tzounis et al.[22]	Elijah et al. [23]	Khanna and Kaur [24]	Shi et al. [25]	Ruan et al. [26]	Feng et al. [27]	Shafi et al [28].	Ayaz et al. [12]	Farooq et al. [29]	Radoglou-Grammatikis et al [30]	Ferrag et al. [10]	Liu et al [13]
Year	2017	2017	2017	2018	2019	2019	2019	2019	2019	2019	2019	2020	2020	2020
Physical layer	○	●	●	●	○	●	●	●	●	●	●	●	●	●
Network layer	●	●	●	●	●	●	●	●	●	●	●	○	●	●
5G considered	○	○	○	○	●	◑	◑	○	●	◑	○	○	●	◑
5G Specification	○	○	○	○	○	○	○	○	○	○	○	○	○	○

●: Supported; ◑: Partially supported; ○: Unsupported.

3.2 Results

To exemplify the utility of 5G technology for application in the agricultural space using harvesting robots linked by swarm robotics, we will first outline the use case, explain the challenges that have arisen in the first half of the still ongoing research project, and present the requirements and chosen 5G specifications and system architecture.

3.2.1 Description of use case

The use case can be divided into two sub use cases referring to the two types of agricultural machinery: a harvesting robot and a logistics unit. Physically, there will be two harvesting robots in the field and one logistics unit. The speed of both machines is approximately 2 km/h. There is also a control station at the edge of the field, which is also to be integrated into the 5G network. The control station will consist of a computer and desktop to connect the machines with the system and monitor them.

The harvesting robot is manually transported to the field. It starts in the home position; from there it must be connected to the 5G network. It connects to the platform and retrieves relevant data, such as a map in which the field to be harvested is divided into a starting point, an end point, rows of fields to be harvested and a route. It drives to the starting point and autonomously drives and harvests from there. For various reasons, e.g., because of an obstacle or a full harvest box, the harvesting robot can stop in the process. Depending on the reason for the stop, different procedures are followed. Either the problem is solved by a third party, by itself or by technology. The machine may then resume the harvesting process, or it waits for the logistics unit (see below) in case of a full harvesting box to continue harvesting after the harvesting box has been replaced. Otherwise, it drives to the home position to complete the harvesting process there or to resume harvesting after refueling.

The logistics unit is transported manually to the field. It starts in the home position; from there it must be connected to the 5G network. It connects to the platform and navigates to an empty harvest box, which is then picked up. The logistics unit now waits in a waiting position. If there is no demand, it returns to the home position and ends the process. If necessary, the logistics unit navigates to the harvesting robot. If no error occurs on the way there, the logistics unit exchanges the empty harvest box with the full harvest box in cooperation with the harvesting robot, navigates with the full harvest box to the storage location and places it there. The logistics unit then navigates back to the empty boxes, picks up one and waits in the waiting position. If an error occurs on the way of the logistics unit to the harvesting robot, it stops and, depending on whether the problem is fixed by a third party, by itself or by technology, it can either resume the process or drive to the home position and end the process.

3.2.2 Emerging challenges in the first half of the research project:

Numerous challenges arose whilst planning and testing. The most important ones are discussed below, stating a need by future end users towards the industry:

1. Lack of clarity as to which commercially existing hardware can (already) perform which 5G features and which cannot: although 5G theoretically offers many features and thus enables a wide range of specifications, not all of them can yet be offered in the currently existing, commercially available products. This severely limits the scope of action, but the overall situation is unclear.
2. Exact requirements for the 5G network are difficult to define in advance and change during the development of a use case. Agile methods can only be transferred to a limited extent, as expensive hardware is selected, purchased, and installed once in the field. The question is how to define requirements for a 5G network a priori to meet later demands.
3. Providing the necessary infrastructure in the field for a campus network proves to be difficult. This applies particularly the power supply, network coverage, and protection of all hardware from wind and weather.
4. Finding test networks is not easy. There are only a few providers and the costs for them quickly skyrocket. Especially if testing is to be done over a longer period (>1 week), the costs quickly exceed the five-digit euro range.
5. The knowledge about technical details of the design is not always easy to obtain, e.g., about the prioritization of data streams and Quality of Service (QoS).
6. The actual network coverage in the country on the exact location is unknown.
7. Required information from the 5G hardware vendor is not freely available.
8. A service catalog complementary to vendor hardware is not freely available.

3.2.3 5G-specification and system architecture

By having identified the macro and micro processes of the use cases, we were able to assess the 5G requirements that are needed to deduct the 5G network specifications. One example is the arm/fork lift alignment (micro process) of the box replacement (macro process) within the logistics unit: the latency shall not exceed 20 ms, the data rate is expected to be 17 MBps with a packet size of 0.28 MB *2, the packet loss may not exceed 10% and the process is not security critical. By combining all micro process information, the total data rate sums up to a maximum of 92 MBps for three robots in the swarm and a connected control station. The lowest latency allowed exceeds to 20ms and a package loss of <1%. Due to unclear and often insufficient network coverage and for security reasons, we chose to use a private network (campus network), instead of a public one.

Further requirements that are considered:

- Place of operation: As the hardware will be partly next to a field and only partly within a covered hut, it will be exposed to wind and weather and thus needs to work under these circumstances.
- Redundant networks: Most likely not needed.
- Set-up and dismantling: no special requirements for the hardware but needs to be dismantled after each harvesting season.

- Scaling: In this use cases for testing purposes no scaling is planned, although would need to be considered for real operation.
- Migration: Most likely not necessary between private and public networks, but not ruled out in principle.
- QoS: It is desirable that the hardware supports the QoS (Quality of Service) feature but is not a must. It is wished for a signal, that needs transmitting prioritization before other signals.
- Service: A service agreement for setting-up, implementation of the network and in operation problem support must be negotiated.

These requirements will be newly considered with the results of the field tests, for which a prototype 5G network is used. Derived therefrom, we developed the following system architecture (see Figure 2) for this agricultural outdoor use case:

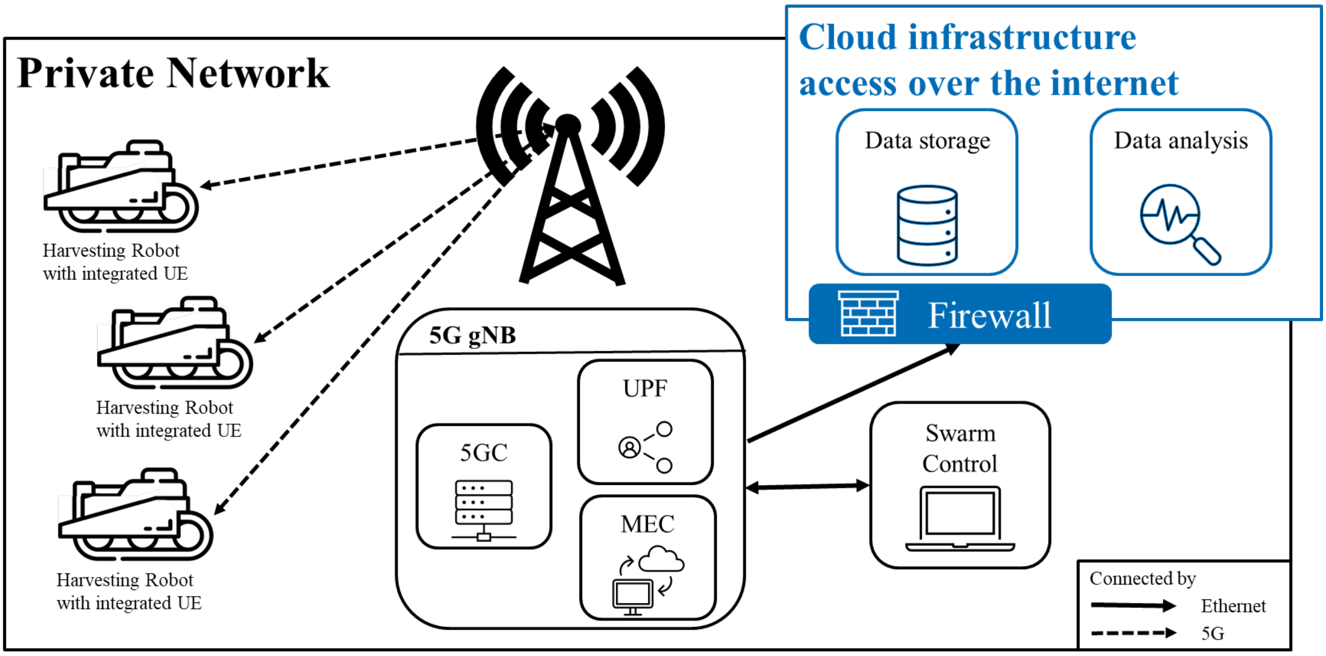

Figure 2: Proposed system architecture of the 5G network for linking harvesting machines via swarm robotics

The overall chosen structure is a private network (campus network). Within the Radio Access Network (RAN) all harvesting machines and logistic units are connected via user equipment (UE) to the base station with an antenna. The base station is a 5G next Generation Node B (5G gNB). It is connected with the Core Network containing the 5G Core (5GC), the User Plane Function (UPF) and the Mobile Edge Cloud (MEC). The Core Network is connected via ethernet to a computer on which the swarm algorithm is located and which steers and controls all processes. Furthermore, machine and video data are sent into a cloud infrastructure. There it is stored and used for analysis to improve the swarm algorithm.

4. Outlook and Conclusion

The validation of the 5G network is still ongoing. There will be several months of field testing to gain results and insights both for the swarm algorithm and the 5G specifications. After a first testing phase with a prototype 5G Network, we will go into discussions with 5G suppliers to finalize the system architecture and implement the final network on the field. By the end of 2023 we will have held several tests for the overall use case. Moreover, we plan to publish a business-case-calculator; its purpose is to give interested farmers or agricultural companies a sound calculation for which agricultural use case a 5G network delivers value in several dimensions (e.g., financial, sustainable).

Concluding we described an outdoor swarm robotics use case using 5G for connectivity. We highlighted the concrete challenges that arouse during the testing phase. Finally, we derived the requirements for the specification of the needed 5G network and proposed its system architecture.

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References

[1] Ericsson. Ericsson Mobility Report June 2022.

[2] Humayun, M., Hamid, B., Jhanjhi, N.Z., Suseendran, G., Talib, M.N., 2021. 5G Network Security Issues, Challenges, Opportunities and Future Directions: A Survey. J. Phys.: Conf. Ser. 1979 (1), 12037.

[3] Moysiadis, V., Sarigiannidis, P., Vitsas, V., Khelifi, A., 2021. Smart Farming in Europe. Computer Science Review (39).

[4] Fróna, D., Szenderák, J., Harangi-Rákos, M., 2019. The Challenge of Feeding the World. Sustainability 11 (20), 5816.

[5] Plastina, A., 2020. Estimated Costs of Crop Production in Iowa. https://www.extension.iastate.edu/agdm/crops/pdf/a1-20.pdf.

[6] Preker, A., 2020. Die Helferlücke. Landwirtschaft in der Coronakrise. https://www.spiegel.de/wirtschaft/soziales/corona-krise-in-der-landwirtschaft-das-bedeutet-der-einreisestopp-fuer-saisonarbeiter-a-b6f9b115-8591-4e83-abfe-15433f5eea6f.

[7] Lesiv, M., Bayas, J.C.L., See, L., Duerauer, M., Dahlia, D., Durando, N., Hazarika, R., Sahariah, P.K., Vakolyuk, M.'y., Blyshchyk, V., Bilous, A., Perez-Hoyos, A., Gengler, S., Prestele, R., Bilous, S., Akthtar, I.u.H., Singha, K., Choudhury, S.B., Chetri, T., Malek, Z., Bungnamei, K., Saika, A., Sahariah, D., Narzary, W., Danylo, O., Sturn, Z., Karner, M., McCallum Ian, Schepaschenko, Dimitry, Moltchanova, E., Fraisl, D., Moorthy, I., Fritz, S., 2018. Estimating the global distribution of field size using crowdsourcing. Global Change Biology, 1–13.

[8] Woolley, M., 1992. Using statistics for desk research. Aslib Proceedings 44 (5), 227–233.

[9] Rahmadian, R., Widyartono, M., 2020. Autonomous Robotic in Agriculture: A Review, in: 2020 Third International Conference on Vocational Education and Electrical Engineering (ICVEE). 2020 Third International Conference on Vocational Education and Electrical Engineering (ICVEE), Surabaya, Indonesia. 03.10.2020 - 04.10.2020. IEEE, pp. 1–6.

[10] Ferrag, M.A., Shu, L., Yang, X., Derhab, A., Maglaras, L., 2020. Security and Privacy for Green IoT-Based Agriculture: Review, Blockchain Solutions, and Challenges. IEEE Access 8, 32031–32053.

[11] Heikkilä, M., Suomalainen, J., Saukko, O., Kippola, T., Lähetkangas, K., Koskela, P., Kalliovaara, J., Haapala, H., Pirttiniemi, J., Yastrebova, A., Posti, H., 2022. Unmanned Agricultural Tractors in Private Mobile Networks. Network 2 (1), 1–20.

[12] Ayaz, M., Ammad-Uddin, M., Sharif, Z., Mansour, A., Aggoune, E.-H.M., 2019. Internet-of-Things (IoT)-Based Smart Agriculture: Toward Making the Fields Talk. IEEE Access 7, 129551–129583.

[13] Liu, Y., Ma, X., Shu, L., Hancke, G.P., Abu-Mahfouz, A.M., 2021. From Industry 4.0 to Agriculture 4.0: Current Status, Enabling Technologies, and Research Challenges. IEEE Trans. Ind. Inf. 17 (6), 4322–4334.

[14] Valecce, G., Strazzella, S., Grieco, L.A., 2019. On the Interplay Between 5G, Mobile Edge Computing and Robotics in Smart Agriculture Scenarios, in: Palattella, M.R., Scanzio, S., Coleri Ergen, S. (Eds.), Ad-Hoc, Mobile, and Wireless Networks, vol. 11803. Springer International Publishing, Cham, pp. 549–559.

[15] Tomaszewski, L., Kołakowski, R., Zagórda, M., 2022. Application of Mobile Networks (5G and Beyond) in Precision Agriculture, in: Maglogiannis, I., Iliadis, L., Macintyre, J., Cortez, P. (Eds.), Artificial Intelligence Applications and Innovations. AIAI 2022 IFIP WG 12.5 International Workshops, vol. 652. Springer International Publishing, Cham, pp. 71–86.

[16] Schulz, P., Matthe, M., Klessig, H., Simsek, M., Fettweis, G., Ansari, J., Ashraf, S.A., Almeroth, B., Voigt, J., Riedel, I., Puschmann, A., Mitschele-Thiel, A., Muller, M., Elste, T., Windisch, M., 2017. Latency Critical IoT Applications in 5G: Perspective on the Design of Radio Interface and Network Architecture. IEEE Commun. Mag. 55 (2), 70–78.

[17] Varga, P., Peto, J., Franko, A., Balla, D., Haja, D., Janky, F., Soos, G., Ficzere, D., Maliosz, M., Toka, L., 2020. 5G support for Industrial IoT Applications - Challenges, Solutions, and Research gaps. Sensors (Basel, Switzerland) 20 (3).

[18] van Hilten, M., Wolfert, S., 2022. 5G in agri-food - A review on current status, opportunities and challenges. Computers and Electronics in Agriculture 201.

[19] Friha, O., Ferrag, M.A., Shu, L., Maglaras, L., Wang, X., 2021. Internet of Things for the Future of Smart Agriculture: A Comprehensive Survey of Emerging Technologies. IEEE/CAA J. Autom. Sinica 8 (4), 718–752.

[20] Talavera, J.M., Tobón, L.E., Gómez, J.A., Culman, M.A., Aranda, J.M., Parra, D.T., Quiroz, L.A., Hoyos, A., Garreta, L.E., 2017. Review of IoT applications in agro-industrial and environmental fields. Computers and Electronics in Agriculture 142, 283–297.

[21] Ray, P.P., 2017. Internet of things for smart agriculture: Technologies, practices and future direction. AIS 9 (4), 395–420.

[22] Tzounis, A., Katsoulas, N., Bartzanas, T., Kittas, C., 2017. Internet of Things in agriculture, recent advances and future challenges. Biosystems Engineering 164, 31–48.

[23] Elijah, O., Rahman, T.A., Orikumhi, I., Leow, C.Y., Hindia, M.H.D.N., 2018. An Overview of Internet of Things (IoT) and Data Analytics in Agriculture: Benefits and Challenges. IEEE Internet Things J. 5 (5), 3758–3773.

[24] Khanna, A., Kaur, S., 2019. Evolution of Internet of Things (IoT) and its significant impact in the field of Precision Agriculture. Computers and Electronics in Agriculture 157, 218–231.

[25] Maglogiannis, I., Iliadis, L., Macintyre, J., Cortez, P. (Eds.), 2022. Artificial Intelligence Applications and Innovations. AIAI 2022 IFIP WG 12.5 International Workshops. Springer International Publishing, Cham.

[26] Ruan, J., Jiang, H., Zhu, C., Hu, X., Shi, Y., Liu, T., Rao, W., Chan, F.T.S., 2019. Agriculture IoT: Emerging Trends, Cooperation Networks, and Outlook. IEEE Wireless Commun. 26 (6), 56–63.

[27] Feng, X., Yan, F., Liu, X., 2019. Study of Wireless Communication Technologies on Internet of Things for Precision Agriculture. Wireless Pers Commun 108 (3), 1785–1802.

[28] Shafi, U., Mumtaz, R., García-Nieto, J., Hassan, S.A., Zaidi, S.A.R., Iqbal, N., 2019. Precision Agriculture Techniques and Practices: From Considerations to Applications. Sensors (Basel, Switzerland) 19 (17).

[29] Farooq, M.S., Riaz, S., Abid, A., Abid, K., Naeem, M.A., 2019. A Survey on the Role of IoT in Agriculture for the Implementation of Smart Farming. IEEE Access 7, 156237–156271.

[30] Radoglou-Grammatikis, P., Sarigiannidis, P., Lagkas, T., Moscholios, I., 2020. A compilation of UAV applications for precision agriculture. Computer Networks 172, 107148.

[31] Data Stratey Template.

[32] Lin, X., 2022. An Overview of 5G Advanced Evolution in 3GPP Release 18.

Biography

Tim B. Walter (*1993) has been a scientific researcher and project manager of the Institute for Industrial Management (FIR) at the RWTH Aachen University since 2020. In his current position as part of the Information Management Division, he specialized within the design and implementation of the information logistics of business processes and on implementing smart farming solutions.

Kerstin Lörsch (*1995) has been a scientific researcher and project manager of the Institute for Industrial management (FIR) at the RWTH Aachen University since 2022. In her work in the IT Complexity Management research group within the Department of Information Management, she is concerned with the strategic alignment of IT.

Max-Ferdinand Stroh (*1991) is a researcher at FIR at RWTH Aachen University since 2017 in the department Information Management. He is head of the department Information Management. His scientific work is focused on the practical application of AI, smart products, and IT-OT-Integration.

Prof. Dr.-Ing. Volker Stich (*1954) has been head of the Institute for Industrial Management (FIR) at the RWTH Aachen University since 1997. Prof. Dr.-Ing. Volker Stich worked for 10 years for the St. Gobain-Automotive Group and led the management of European plant logistics. His research focuses on operations management, logistics and business applications systems.

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Process for Climate Strategy Development in Industrial Companies

Stefan Seyfried[1], Astrid Weyand[1], Thomas Kohne[1], Matthias Weigold[1]
[1]Technical University of Darmstadt, Institute for Production Management, Technology and Machine Tools (PTW), Otto-Berndt Str. 2, 64287 Darmstadt, Germany

Abstract

Climate neutrality has been gaining more and more attention as a long-term goal for companies among different industries. Since this goal can hardly be achieved in the short term and requires a complex interaction of different measures, it calls for a strategic approach. This article presents a strategy process for manufacturing companies striving for climate neutrality. The strategy process consists of three macro phases: preparation phase, strategy development phase and operational implementation phase, which are iteratively carried out. The macro phases are each divided into different meso phases, which include guiding questions that must be answered by different internal stakeholders and process participants. Moreover, necessary results are described which must be available after each phase to enter the next one. The procedure is based on existing models for the description of strategy processes and approaches from the field of energy and environmental management. It combines them into a strategic approach for deriving climate strategies of industrial companies. The developed strategy process is applied to and evaluated at the ETA factory at the Technical University of Darmstadt.

Keywords

Climate Strategies; Climate Neutrality; Carbon Footprint; Transformation Paths; Transparency

1. Introduction

In order to fulfil the targets set in the Paris agreement [1], the European Union is striving to achieve climate neutrality by 2050 as the first continent and reduce its emissions by 55 percent until 2030, compared to 1990 levels [2]. These will affect industry as a large emitter of greenhouse gases [3], forcing industrial companies to systematically reduce their impact on the climate. To do so, industrial companies need to develop climate strategies which include gaining transparency about current emissions, setting targets, and identifying measures to reduce their respective emissions. After the analysis of existing strategy processes, the paper therefore proposes a process for developing and implementing a climate strategy. It is illustrated how the different steps are interlinked, what the outputs of each phase are and which persons or departments inside a company should participate in each step. Finally, the proposed process is applied to a use case examined in the ETA Factory of the Technical University of Darmstadt, a real production site for research purposes dedicated to the machining industry.

2. State of the Art

The long-term goal of climate-neutral production poses specific requirements on the corresponding strategy process. Both the term climate-neutral production and strategy processes in general are discussed in this section since these to aspects are the building blocks for the specification of the proposed process for climate strategy development.

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2.1 Climate-neutral Production

In contrast to carbon neutrality, the term climate neutrality additionally considers other climates effects which are not caused by CO2 or other greenhouse gases. It describes the state in which changes or increase in global temperatures can be avoided. Since some effects on climate change exist that are not directly measurable or directly related to company activities, the term climate neutrality is often used synonymously with greenhouse gas neutrality in the industrial sector [4,5]. Globally, the industrial sector accounts for 36 percent of the total greenhouse gas emissions (including energy consumption) [6], marking the relevance for companies to lower these emissions. Besides the ecological impact, other reasons like the importance of climate targets for investors, the demand for climate-neutral products from the customer side as well as rising energy prices strengthen companies' motivation regarding the topic of climate-neutral production [7].

Strategies to reach climate neutrality are often based on the principles of minimisation of emissions, substitution of emission-causing processes and compensation of the remaining emissions [8]. To start minimising emissions or substituting processes, transparency about the related emissions is needed as a fundamental step [9]. In a previous paper by Bardy et al. [10], success factors for the climate-neutral production were derived based on literature analysis. These success factors include the increase of energy and material efficiency, reuse of waste heat or the electrification of energy demands. Besides these measure-oriented success factors, required employee competencies for climate-neutral production can be defined. These include a certain awareness regarding the environmental impact of companies as well as the ability to see the potentials of climate friendly technologies [11].

2.2 Existing Strategy Processes

The process of developing a strategy belongs to the field of strategic management [12]. It is also referred to as strategic planning [13]. Strategic process research has existed since the early 1960s [14], originating from a purely economic perspective such as divestment or merger strategies [15]. In Bowman and Ash [16], strategy formulation is simplified and divided into the phase of identification of opportunities followed by a phase of selection. Other sources also include a target/goal definition phase [17] and/or an implementation phase [18,19]. Lynch differentiates between three aspects of strategic management: strategic analysis, strategy development and strategy implementation [12]. Mintzberg describes five different approaches to strategies (5Ps): plan, ploy, pattern, position and perspective [20]. This reflects that other factors besides planning also have an impact on the strategy. Some aspects of the strategy are usually not the result of strategic planning but rather emerge from the organisation's behaviour. This is called an emergent strategy [20]. Because of changing environmental conditions strategy processes do not only require a single phase of planning and implementation of the strategy but also a feedback loop from the implementation phase which includes monitoring the outcomes of the strategy's implementation by comparing it to the strategic targets [12].

The PDCA-cycle, first introduced in 1940 by Shewhart for the topic of Quality control [21,22], is a widely known methodology for continual improvement and implementing strategic targets. It consists of four phases. In the Plan-phase (P), goals are set and measures to reach the goals are defined. These measures are then implemented in the Do-phase (D), followed by a check-phase (C) to evaluate the effectiveness of the measures regarding the set goals. In the final Act-phase (A), required adjustments are made to eventually reach the goals defined in the Plan-phase. The PDCA cycle is defined as an iterative process, setting new goals as soon as the initial goals are reached. The PDCA cycle can be applied to a wide range of topics; it is used for example as a basis for the ISO 50001 standard [23] for energy management systems to identify and implement energy efficiency measures and in the ISO 14001 standard [24] for environmental management systems. Despite its broad applicability, it is not solely sufficient to tackle the topic of climate strategies.

Especially regarding the planning phase, more guidance is needed for companies to set effective goals regarding greenhouse gas reduction and choosing effective measures for implementation. To do so, and as already suggested 1987 by Huff and Reger [15], the strategy development process needs to be linked with the examined content – in the case of this paper, climate-neutral production.

3. Process for Climate Strategy Development

The process for the development of climate strategies is based on the literature on strategy processes and the specific requirements arising from the topic of climate-neutral production. In addition, the authors' experience from industry projects concerning the transformation of the energy system of companies towards climate neutrality is incorporated into the description model. The experience comes both from projects with individual companies and from the project ETA-Transfer [25], which systematically investigated the implementation of measures to reduce emissions for energy systems of manufacturing companies in nine case studies.

The model differentiates between three macro phases: In the *preparation phase*, the company begins to discuss climate strategy issues, gathers preliminary information, and proposes its general objective. The following *strategy development phase* is characterised by the transformation of these general objectives into a specific strategy, according to which the company proceeds with the subsequent transformation. Thus, this phase includes the *analysis of the current situation*, *target specification*, *scenario development* and *assessment* and *decision making* based on the available scenarios. Finally, implementation takes place in the *operational implementation phase*. It includes both the *organisational* and the *technical implementation* of the strategy. The three macro phases each consist of meso phases, which are described in more detail in the following sections. The steps to be completed in the meso phases are referred to as micro phases and are not included in Figure 1, which shows the overall process schematically.

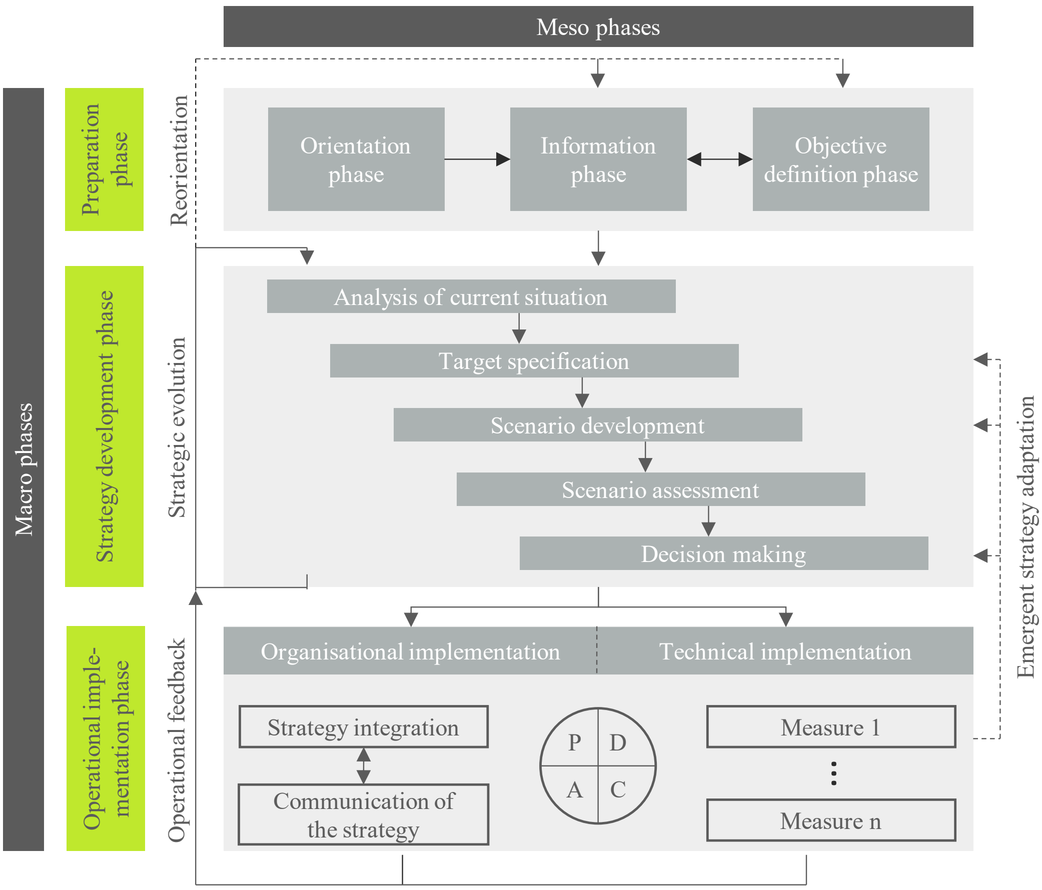

Figure 1: Process for the development of climate strategies

Since a climate strategy must be regularly adapted to changes in the company and in the technical and social framework conditions, the macro phases are not strictly traversed sequentially, but rather iteratively. After going through the *strategy development phase*, a *strategic evolution* can follow to adapt the strategy. In some cases, or at longer intervals, a *reorientation* and thus a re-entry into the *preparation phase* may become necessary. This makes sense, for example, if the strategy is to be fundamentally renewed. Experiences from the *operational implementation phase* are incorporated into subsequent *strategy development phases* through *operational feedback*.

In addition to the planned strategy development, there may also be *emergent strategic adaptations*. These originate in the operational implementation of the strategy, which may deviate from the initially planned strategy, either intentionally or unintentionally. Thus, the implementation can have effects on the *target specification*, *scenario development* and *decision making* in the *strategy development phase*. The three macro phases with their respective meso phases are described in more detail below.

3.1 Preparation Phase

The *preparation phase* initiates the process of developing a climate strategy as the first macro phase. It consists of the *orientation phase*, *information phase* and *objective definition phase*. Depending on the maturity of the company in the field of climate strategies, they are passed through one after the other or it is possible to start in the *information phase* or *objective definition phase*. During the *orientation phase*, questions are raised regarding what the company can do for climate protection, which effects climate issues have on the company and a decision is made whether to initiate the strategy process. In the subsequent *information phase*, the company obtains basic information about climate strategies in a more targeted manner and establishes initial competencies in order to shape the strategy process in an informed matter. In the *objective definition phase*, the first general goals of the climate strategy can be set, such as the scope in which climate-neutral production is to be achieved [26]. The *information phase* and the *objective definition phase* can be carried out iteratively or in parallel. Table 1 summarises the essential aspects and required participants of the *preparation phase*.

Table 1: Preparation phase

	Orientation phase	Information phase	Objective definition phase
Key question	Does our company need a climate strategy?	How do we develop a climate strategy?	What goal do we want to achieve?
Description	Individual employees or management raise the question of what the company can do in terms of climate protection and get an initial overview about the topic.	Further information on the development of climate strategies is obtained in a systematic manner via a specific department. Initial competencies are gained.	The goal of the climate strategy is roughly outlined.
Participants	Management, individual highly committed employees	Appropriate departments, individual highly committed employees	Management and appropriate departments
Outcome	Decision on whether to initiate climate strategy process	Information basis for designing the strategy process	General goal for the subsequent strategy development

3.2 Strategy development process

The core of the strategy process is the *strategy development phase*. In this phase, the climate strategy is created. The *strategy development phase* consists of five meso phases: *analysis of current situation*, *target specification*, *scenario development*, *scenario assessment* and *decision making*, as summarised in Table 2.

First, the *analysis of current situation* examines the current climate impact of the company. In particular, this means that energy and resource consumption are analysed and the carbon footprint is calculated. The *strategic evolution* covering subsequent iterations of the *strategy development phase* means the implementation progress of the climate strategy is being continuously monitored in this phase. After establishing a quantitative overview of the initial situation, the *target specification* is next. In this phase, the specific targets of the climate strategy are defined, e. g. the desired emission reduction with a timeline for reductions in specific parts of the company. This specifies the general objectives from the *preparation phase*. Subsequently, various scenarios are developed to achieve the climate targets. Scenarios are characterised by specific measures such as electrification, energy efficiency measures, integration of renewables, substitution of certain materials etc. The next phase is the *scenario assessment*, which compares the scenarios in terms of target fulfilment based on various company-specific criteria. For example, the involved costs or the availability of competencies required to implement the scenario are considered. Finally, *decision making* takes place based on the *scenario assessment*. The company's climate strategy is then defined in a first draft. It is described by the chosen scenario and characterised by specific measures. Further iterations of this process or parts of it may follow. The strategy must then be implemented operationally. This takes place in the third macro phase, the operational implementation phase. The five meso phases do not strictly need to be carried out sequentially. They can overlap in time or be handled iteratively if changes are necessary.

Table 2: Strategy development phase

	Analysis of current situation	Target specification	Scenario development	Scenario assessment	Decision making
Key question	What is the current climate impact of our company?	What targets are we aiming for and by when?	How can the goal be achieved?	How do the scenarios differ in terms of target fulfilment?	Which scenario best fits the company's goals?
Description	Analysis of the initial situation (energy and resource consumption, carbon footprint, etc.)	Definition of the strategic goal, scopes to be considered, desired emission reduction	Elaboration of different scenarios to meet the set climate target	Comparison of the scenarios based on company-specific criteria	Decision on scenario to be implemented
Participants	Appropriate departments including shop floor management	Management	Appropriate departments	Management and appropriate departments	Management
Outcome	Quantitative overview of initial situation regarding the company's climate impact	Specific climate targets for the company	Scenarios for achieving the climate targets	Assessed climate scenarios for the company	Specification of a target scenario for the climate strategy

3.3 Operational implementation phase

In the *operational implementation phase*, the chosen scenario with its characterising measures within the climate strategy is implemented. Two processes take place in parallel and are interlinked with each other: *organisational implementation* and *technical implementation*. Both processes are characterised in Table 3. In the *organisational implementation*, the strategy is integrated into existing strategies and corporate structures. In addition, communication of the strategy takes place both internally and externally. *Technical* *implementation* involves the implementation of the technical measures defined in the strategy to reduce the climate impact of the company. The technical measures can be partially processed in parallel and organised in PDCA cycles corresponding with the *organisational implementation*. This form of organisation also ensures the possibility to integrate it with existing standards such as ISO 50001 for energy management and ISO 14001 for environmental management.

Table 3: Operational implementation phase

	Organisational implementation	Technical implementation
Key question	How is the climate strategy being implemented in the organisation?	How is the climate strategy transferred into operational measures?
Description	Documentation, organisationally established and communicating the climate strategy	Implementation of measures according to the target scenario in parallel PDCA cycles
Participants	Management, appropriate departments, marketing, entire workforce	Appropriate departments including shop floor
Outcome	Organisationally established climate strategy	Coordinated implementation of technical measures

4. Application to the ETA-Factory

The developed strategy process is applied to the ETA research factory at the Technical University of Darmstadt [27] focusing on the energy system and thus on the energy related emissions (mainly scope 1 and 2 emissions of the greenhouse gas protocol [28]). The ETA research factory was built as demonstrator for energy efficiency in manufacturing systems. It operates a production line with machine tools, cleaning machines and a heat treatment furnace. Moreover, a learning factory and offices are included. The energy system of the ETA research factory consists of three thermal networks with respective heat storages and energy converters operating on electricity and gas. Moreover, compressed air, electricity and gas are supplied to the production systems. Although efficiency measures such as waste heat utilization and thermal cross-linking via heat exchanger and heat pump technology are highly integrated within the factory, the energy system still relies on fossil fuels in gas and electricity supply. The energy system as well as an exterior and interior view of the factory are depicted in Figure 2.

Since opening in 2016, the ETA research factory and its energy system were improved and expanded through different research projects. Within the research projects, measures were applied for increasing energy efficiency, implementing new energy converters, and integrating energy flexibility and digitalization to embody and demonstrate the research and gather knowledge and results within the research group. New challenges in climate goals and research on sustainable production underscores the necessity of climate-neutral operation of the ETA research factory. Thus, the presented strategy process accompanies the transformation within the ETA research factory.

Within the *preparation phase*, the dependencies, but also differentiation between energy efficiency and flexibility compared to climate neutrality were addressed. Moreover, a first qualitative analysis of the emissions, especially fossil fuel consumption within the ETA research factory were conducted. As a result of the *preparation phase*, the ETA research factory team decided that the research factory should become climate-neutral until 2025. Within the objective, climate neutrality was defined based on scope 1 and 2 emissions.

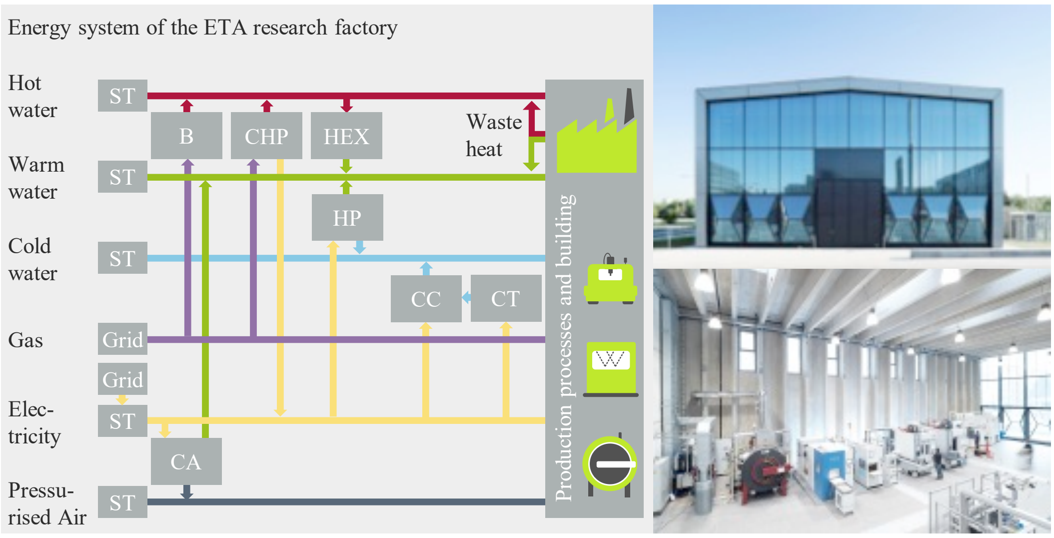

Figure 2: Left – energy system of the ETA research factory, ST: storage, B: boiler, CHP: combined heat and power, HEX: heat exchanger, HP: heat pump, CC: compression chiller, CT: cooling tower, CA: compressors for pressurised air; upper right – exterior view; lower right – view on production line, photo credits Eibe Sönnecken.

In the *strategy development phase*, the analysis of the current situation resulted in a quantitative analysis of emissions, but also in the analysis of possible measures which can be carried out by the institute's research group. Some of the measures such as energy efficiency or flexibility can be carried out directly by the research group, others are dependent on the responsible department within the university, e. g. the purchase of green electricity cannot be decided by an institute itself. Therefore, the objective of climate neutrality was adjusted and targets defined. The targets include climate neutrality in scope 1 and 2 emissions by integrating auto-production and increasing self-consumption of renewable electricity and heat without external electricity supply. Furthermore, a reduction of scope 3 emissions is set as a target. First scenarios were developed to achieve the targets. New research projects should be initiated for the specific assessment of different scenarios. With this assessment, a decision on a scenario and specific measures can be carried out.

The overall strategy process is not concluded yet, but first steps for the *operational implementation phase* have already been taken: it must be organisationally implemented that the team gains knowledge around climate neutrality and newly acquired projects are aligned with the objectives. The technical integration and implementation of new energy technologies should be carried out within new research projects linked to current research. The current results of the meso phases within the strategy process are outlined in Table 4.

Table 4: Results in the strategy process for the ETA research factory

	Results
Orientation phase	• Energy efficiency and flexibility are no longer sufficient when discussing climate change in manufacturing processes and sites
Information phase	• Climate neutrality is the main goal within different sectors to address climate change: research on definition and impact, discussion in team • Qualitative analyses of emissions within the factory: gas demand of combined heat and power units, boiler and furnace, electricity supply, materials • Information on potential technologies to be installed within the energy system of the ETA research factory
Objective definition phase	• Climate neutrality within scope 1 and 2 emissions
Analysis of current situation	• Quantitative technical energy data analysis of the overall system • Analyses of the possible measures by the research group (electricity supply contracts cannot be changed by institute)

Target specification	• Climate neutrality in scope 1 and 2 without external electricity supply until 2025 • Integration of renewable electricity and heat until 2025
Scenario development	• Electrification of processes and energy supply • Integration of hydrogen usage • Integration of photovoltaic system, geothermal heat pumps • Additionally: Increasing energy efficiency and flexibility for self-consumption of renewables
Scenario assessment	• Ongoing acquisition of new research project to further evaluate the scenarios
Decision making	• To be defined
Organisational implementation	• (New) research assistants must gain knowledge in climate neutrality; newly acquired projects must strive towards the organisational objectives
Technical implementation	• Integration and implementation of new energy technologies within new research projects

5. Conclusion and Discussion

In this paper, we present a strategy process for industrial companies striving for climate neutrality. The strategy process is divided into three macro phases: *preparation phase*, *strategy development phase* and *operational implementation phase*, which can be carried out iteratively. The process begins with the *preparation phase*, when the company initiates discussing climate strategy issues, gathers initial information, and proposes its general objective. During the *strategy development phase,* the general objective is transformed into specific targets and scenarios. At the *operational implementation phase* the strategy is implemented both organisationally and technically. The macro phases are divided into different meso phases. The meso phases include guiding questions that must be answered by different process participants. Moreover, necessary results are described which should be available after each phase.

The developed strategy process is applied to and evaluated at the ETA factory at the Technical University of Darmstadt. The team of the ETA research factory defined the objective that the research factory should become climate-neutral until 2025. The guiding questions and necessary results within the meso phases of the strategy process help structure the overall process. The following implementation of the strategy offers further opportunities to explore and re-assess the strategy process. This particularly applies to the *operational implementation phase*, which is still ongoing. The insights gained in this phase can also be used to examine the micro phases more closely within the meso phases, including the requirements for successful implementation and the steps of *operational feedback* and *emergent strategic adaptation*. In this context, it can also be analysed how measures influence each other and which chronological sequence must be followed during the implementation. As climate targets become more relevant, production targets are extended to include this aspect. This requires companies to acquire additional competencies for the development and implementation of climate strategies. The required competencies differ depending on the phase of the strategy process. Especially small and medium-sized enterprises (SMEs) without specialized departments for these tasks face new challenges. Future research should therefore examine which specific competencies are required for each phase and how these can be provided within the company or externally, for example by performing a case study in an SME. Additionally, the described meso phases are to be described in more detail separately for each phase to provide companies with a methodological toolbox for each phase. This can contribute to a more systematic preparation, development and actual operational implementation of climate strategies in manufacturing companies.

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References

[1] United Nations, 2015. Paris Agreement, Paris. http://unfccc.int/files/meetings/paris_nov_2015/application/pdf/paris_agreement_english_.pdf. Accessed 5 December 2021.

[2] European Commission, 2021. 'Fit for 55': delivering the EU's 2030 Climate Target on the way to climate neutrality, Brussels. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021DC0550. Accessed 1 December 2021.

[3] Oliver J., Peters, J., 2020. Trends in global CO2 and total greenhouse gas emissions: 2020 Report. PBL Netherlands Environmental Assessment Agency, Den Haag.

[4] Honegger, M., Schäfer, S., Poralla, P., Michaelowa, A., Perspectives Climate Research gGmbH, 2020. dena-Analyse: Klimaneutralität – ein Konzept mit weitreichenden Implikationen, Freiburg i. B. https://www.dena.de/fileadmin/dena/Publikationen/PDFs/2020/dena_BR_Analyse-Klimaneutralita__t_WEB.pdf. Accessed 1 December 2021.

[5] Millot, A., Krook-Riekkola, A., Maïzi, N., 2020. Guiding the future energy transition to net-zero emissions: Lessons from exploring the differences between France and Sweden. Energy Policy 139, 111358.

[6] Ritchie, H., Roser, M., 2020. CO_2 and Greenhouse Gas Emissions: Emissions by Sector. Our World in Data.

[7] Buettner, S.M., König, W., 2021. Looking behind decarbonisation - What pressure points trigger action?, in: eceee Summer Study Proceedings, Stockholm, pp. 345–354.

[8] Hannen, C. Transformationsstrategien zum CO2-neutralen Unternehmen. Dissertation, Kassel.

[9] Scipioni, A., Manzardo, A., Mazzi, A., Mastrobuono, M., 2012. Monitoring the carbon footprint of products: a methodological proposal. Journal of Cleaner Production 36 (18), 94–101.

[10] Bardy, S., Seyfried, S., Metternich, J., Weigold, M., 2022. Supporting the Transformation to Climate Neutral Production with Shop Floor Management. Hannover : publish-Ing.

[11] Mets, T., Holbrook, J., Läänelaid, S., 2021. Entrepreneurship Education Challenges for Green Transformation. Administrative Sciences 11 (1), 15.

[12] Lynch, R.L., 2018. Strategic management, Eighth edition ed. Pearson, Harlow, England, London, New York, Boston, San Francisco, Toronto, Sydney, Dubai, Singapore, Hong Kong, Tokyo, Seoul, Taipei, New Delhi, Cape Town, Sao Paulo, Mexiko City, Madrid, Amsterdam, Munich, Paris, Milan.

[13] Witcher, B., 2019. Absolute Essentials of Strategic Management. ROUTLEDGE, S.l.

[14] Ansoff, H.I., 1979. Strategic Management. Palgrave Macmillan Ltd, Basingstoke.

[15] Huff, A.S., Reger, R.K., 1987. A Review of Strategic Process Research. Journal of Management 13 (2), 211–236.

[16] Bowman, C., Ash, D.C., 1987. Strategic Management. Macmillan Education UK, London.

[17] Feichter, C., Grabner, I., Moers, F., 2018. Target Setting in Multi-Divisional Firms: State of the Art and Avenues for Future Research. Journal of Management Accounting Research 30 (3), 29–54.

[18] Bryson, J.M., Bromiley, P., 1993. Critical factors affecting the planning and implementation of major projects. Strat. Mgmt. J. 14 (5), 319–337.

[19] Galbraith, J.R., Nathanson, D.A., 1983. Strategy implementation: The role of structure and process, 7. repr ed. West Publ. Co, St. Paul.

[20] Mintzberg, H., Lampel, J., Quinn, J.B., 2002. The strategy process: Concepts, contexts, cases, 4th ed. ed. Prentice Hall, Upper Saddle River, NJ.

[21] Johnson, C.N., 2002. The benefits fo PDCA. https://search.proquest.com/openview/6fb24b731a9c0c8bafd90096fd751e76/1?pq-origsite=gscholar&cbl=34671.

[22] Shewhart, W.A., 1939. Statistical Method from the Viewpoint of Quality Control. Dover Publications, 1 online resource.

[23] Energy management systems - Requirements with guidance for use (ISO 50001:2018).

[24] Environmental management systems - Requirements with guidance for use (ISO 14001:2015).

[25] ETA-Transfer, 2021. https://eta-transfer.de/. Accessed 31 October 2022.

[26] Rietbergen, M.G., van Rheede, A., Blok, K., 2015. The target-setting process in the CO2 Performance Ladder: does it lead to ambitious goals for carbon dioxide emission reduction? Journal of Cleaner Production 103, 549–561.

[27] Abele, E., Schneider, J., Maier, A., 2018. ETA - die Modell-Fabrik: Energieeffizienz weiter gedacht. ETA, Darmstadt.

[28] World Resources Institute, 2015. The Greenhouse Gas Protocol: A Corporate Accounting and Reporting Standard, Washington. https://ghgprotocol.org/sites/default/files/standards/ghg-protocol-revised.pdf. Accessed 1 December 2021.

Biography

Stefan Seyfried, M. Sc. M. Sc. (*1990) has been research associate and PhD candidate at the Institute of Production Management, Technology and Machine Tools (PTW) at Technical University of Darmstadt since 2018. His research interests include energy efficiency and climate strategies of industrial enterprises and SMEs.

Astrid Weyand, M. Sc. (*1994) has been a researcher and PhD candidate since 2019 and head of research group since mid-2021 at the PTW at Technical University of Darmstadt. Her research focus is on the field of methods to improve resource efficiency in industry, including the carbon footprint calculation.

Thomas Kohne, M. Sc. M. Sc. (*1991) has been research associate and PhD candidate since 2018 and head of research group since 2021 at the PTW at Technical University of Darmstadt. His personal research fields include waste heat integration and climate strategies of industrial companies.

Prof. Dr.-Ing. Matthias Weigold (*1977) has been the head of the PTW at Technical University of Darmstadt since 2019. As director he is responsible for the research fields on Manufacturing Technology as well as Energy Technologies and Applications in Production. His personal research fields include digitization and climate-neutral production.

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Challenges Of Production Planning And Control For Powder Bed Fusion Of Metal With Laser Beam: A Perspective From The Industry

Lukas Bauch[1], Andreas Wilhelm[1], Moritz Kolter[1], Johannes Henrich Schleifenbaum[1]

[1]*Digital Additive Production / RWTH Aachen University, Aachen, Germany*

Abstract

Due to technological advance, the Additive Manufacturing (AM) technology Powder Bed Fusion of Metal with Laser Beam (PBF-LB/M) is in widespread industrial use. PBF-LB/M offers the flexibility to generate different geometries in one build job independent of tools. Therefore, exploiting tool-dependent economies of scale is not required for efficient manufacturing of various complex geometries in small quantities. However, PBF-LB/M production lines are capital intensive and include post-processing steps. Thus, high utilization and low work in process must be ensured to minimize costs, but reaching high utilization contradicts minimizing work in process and throughput time. In production planning and control (PPC), the trade-off between those production logistics key performance indicators (KPIs) is optimized. The advantage of flexibility to manufacture various geometries in one build job of PBF-LB/M comes with challenges for PPC. In this work, those challenges are analysed to derive implications for improvement, based on interviews with experts from the industry. Results show a need for PBF-LB/M specific PPC. The need is higher the greater the technological control of PBF-LB/M and the volume of a product program of a company are. Unlike for Conventional Manufacturing (CM), nesting and scheduling cannot be addressed separately in PPC for PBF-LB/M. Thus, the optimization of production logistics KPIs is more complex due to more degrees of freedom. Combined with a typically shorter planning horizon for AM, this requires automated optimization software tools for combined nesting and scheduling. Currently, PPC that considers AM characteristics does not address CM steps in the post-process adequately, even though they cause a large proportion of effort and time. Furthermore, high automatization parallel to heterogenous manual tasks require a low number of workers with training in various skills.

Keywords

Powder Bed Fusion of Metal with Laser Beam, Production Planning and Control, Nesting, Scheduling, Production Management, Production Technology, Additive Manufacturing

1. Introduction

Additive Manufacturing (AM) is defined as a process of joining materials to make parts from 3D model data [1]. There are different AM process types, that are characterized by a layer- or unit-wise generation of a workpiece [2]. With technological advance, the AM process Powder Bed Fusion of Metals with Laser Beam (PBF-LB/M) is in widespread industrial use [3]. PBF-LB/M is an AM process, in which a layer of metal powder is distributed on a powder bed. Subsequently, the powder bed is scanned selectively by a laser beam to melt and solidify the metal powder according to a digital build plan. Afterwards, another metal powder layer is applied and scanned with a laser beam. This cycle consisting of applying a powder layer and

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scanning is repeated, until the workpiece is fully generated. [1][2] This work principle offers the flexibility to generate different geometries in one build job independent of tools. Therefore, exploiting tool-dependent economies of scale is not required for efficient manufacturing of various different complex or customized geometries. [4][5]

During the implementation and use of AM, companies face different challenges in the competition. An extensive discussion of challenges for the implementation of AM can be found in [6][7][8][9]. These challenges can be assigned to the following categories [6]:

- Production technology (e.g., reliably achieving high quality [10], qualification of materials [11])
- Production management (e.g., production planning and control (PPC) [12])
- Business strategy (e.g., adaption of business models [13])
- Business administration (e.g., adaption of the product development process to AM specifics [14])

Mastering challenges of production technology and production management is considered as a directly perceptible motivator for customers. Business strategy and administration are regarded as hygiene factors, that are a basic requirement for successful implementation of AM. Unlike motivators, hygiene factors are only indirectly visible to customers. Until now, challenges regarding the motivator production technology such as stable processes, high quality, and material are focused for AM, as they address basic needs of customers. Challenges like PPC in the category of motivator production management are addressed less. [6][12]

This work focuses on PBF-LB/M because it is the most common metal AM process and in wide industrial use [3]. PBF-LB/M production lines are capital intensive [4] and include post-processing steps [15]. In contrast to tool-dependent economies of scale, machine investment-dependent economies of scale exist [4]. Thus, high utilization must be ensured to minimize costs. This contradicts minimizing work in process and throughput times. In PPC, the trade-off between production logistics performance and costs is optimized. [16][17] The advantage of PBF-LB/M to flexibly manufacture various geometries in one build job comes with challenges such as joint optimization of nesting and scheduling for PPC in production management [6][18].

With ongoing advancement in overcoming challenges in the category of production technology to address basic customer needs, the question arises, if and how companies in the industry are already facing the challenges regarding PPC as they become more important for differentiation. Furthermore, the scientific community and practitioners from industry need to know the expected future trajectory of challenges concerning PPC for PBF-LB/M for target-oriented development of solutions for PPC.

With the given considerations, this work aims to:

- Identify if and which challenges concerning PPC for PBF-LB/M the industry is currently facing
- Derive implications, which solutions are required now and in the future for successful PPC for PBF-LB/M

For this purpose, relevant state-of-the-art literature regarding PPC for AM and PBF-LB/M is analyzed and presented in section 2. Subsequently, seven interviews with experts from the industry are planned, conducted, and analyzed.

2. State-of-the art regarding PPC for PBF-LB/M

PPC aims for an allocation of orders and resources over time to realize a company's output and logistics performance according to customer demands. This includes for instance planning, initiating, and controlling of manufacturing tasks. Decisions like capacity adjustments of personnel or initiating orders from the purchasing department to the supply market are other typical tasks. Furthermore, PPC spans monitoring of orders and capacity as well as triggering of adjustments in case of deviation from the production plans. [19][20]

2.1 PBF-LB/M production planning

2.1.1 Nesting and Scheduling

Before the physical fabrication of a geometry with PBF-LB/M, nesting and further data preparation in the digital pre-process are required. Nesting includes binning, orientation, and positioning of parts. [18] One or multiple 3D models are grouped to be processed in a build job (binning) and imported into a data preparation software. Using the data preparation software, the rotation angle of the models (orientation) and their position in the build space (positioning) are defined. In the next step, support structures are designed, that fixate the part at the build plate. During the subsequent step slicing, machine code is computed according to the layer-wise work principle. [21]

The data preparation step of nesting is important for PPC. In contrast to Conventional Manufacturing (CM), nesting and scheduling problems are interrelated and thus cannot be addressed separately for optimizing the trade-off between production logistics cost and performance [18][22]. Decisions like binning parts into one build job with urgent due dates for on-time delivery or with similar z-height to increase productivity can interfere with scheduling decisions and vice-versa. [18][23]

The joint nesting and scheduling optimization problem receives high attention in the scientific community. In [18] a taxonomy for clustering publications with the topic of nesting and scheduling problems is proposed. The taxonomy includes six categories based on the part (multiple), build (single or multiple build jobs) and machine (single, multiple identical, multiple different AM machines). [18]

In [12] an architecture for a PPC system including nesting and scheduling of build jobs during data preparation for a multitude of AM plants is presented. It aims at considering requirements for an integration into operational enterprise software systems to maximize machine utilization to decrease costs. Therefore, different modules of Enterprise Resource Planning (ERP), Product Lifecycle Management (PLM), and Manufacturing Execution System (MES) are considered. An implementation of the proposed PPC is not demonstrated and validated. Furthermore, nesting and scheduling problems are arranged as separate steps in the presented process flow for creation of production orders. [12]

2.1.2 Process planning

Before nesting and scheduling, the sequence of operations and processes for manufacturing of a component are defined in process planning. The overall physical PBF-LB/M process requires different mandatory and optional CM process steps after the finished build job is removed from the machine, like stress relief treatment, separation of parts from the build plate, support and powder removal, surface treatment, or other heat treatment. [24][25]

Choosing the best suiting manufacturing steps of a process chain is the task of process planning [26]. AM process planning is very complex due to many degrees of freedom with a multitude of manufacturing technologies and design options to choose from. Besides the post-process step options, there are alternative AM options for the in-process, such as Binder Jetting (BJ) with their own mandatory and optional post-processing steps. Therefore, process planning also must consider other AM options than PBF-LB/M if they are available. Moreover, the choice of manufacturing steps interferes with adjustment of the component design. The manufacturability of a design must be considered, depending on the technologies involved in the process chain. [24][27][28][29]

2.2 PBF-LB/M production control

2.2.1 Process monitoring

In PBF-LB/M process monitoring, data is recorded during the process with different sensors and used for quality assurance, increasing machine uptime, and ensuring a reliable process. In research, novel process sensors are developed, sensing techniques are improved and their fit for specific parts and materials is assessed. [10]

In [10] and [30] literature reviews of possible process defects during the PBF-LB/M process and acoustic, optical, tomography, and thermal in-situ sensing approaches to detect those defects are presented. The obtainable information with process monitoring is valuable for PPC. For instance, if the data indicates that an error is detected during a print job that still requires several days until it is finished, the print job can be aborted. With the information from process monitoring, engineers are supported in finding what caused the error and can take measures to avoid the error from reoccurring. Taking corrective measures after a process is finished or aborted is an open-loop process control approach. [10][30][31][32].

Research also pursues the aim of real-time closed loop control of the additive generation of a part with PBF-LB/M. Observable and derived signature parameters (e.g., melt pool temperature, melt pool geometry) should be used to predict quality measures and adjust controllable process parameters (e.g., laser power and scanning speed) before an unwanted deviation of geometric, mechanical, or physical part properties occurs. [10][33][34]

2.2.2 Traceability

DIN ISO 9000 defines traceability of products as the ability to trace the origin, processing history, and distribution and location after delivery [35]. The capability of tracing parts within the production environment is essential for successful PPC in volatile circumstances like frequent changes in customer orders, incorrect planning or transition times or technical disturbances [36]. Due to the flexibility of manufacturing of different geometries independent from tools [4], various parts go through the PBF-LB/M process chain during the same time. This makes it challenging to manually identify and trace the state and location of various parts in the process chain, but this knowledge is essential for production control [36]. To enable traceability in logistics, tagging parts with detectable marks is a pursued solution [37]. In [37] requirements and different work principles of tagging of additively manufactured parts like RFID chip and embedded geometrical features like QR codes or unique pores, impurities, and other optical markers are reviewed.

3. Methodology

3.1 Planning and conducting interviews

To obtain information according to the research aim, industry experts with multiple years of AM experience who are currently involved in and/or responsible for AM operations are contacted and interviews are held. The used methodology for planning and conducting expert interviews is derived from [38]. The interviews are conducted by the authors of this work. Because the data is of qualitative and not quantitative character, an in-depth interview using a semi-structured interview guide is chosen for data retrieval. Depending on the answers to questions formulated in the interview guide, follow-up questions are possible to go more into detail. This enables a relatively free and personal conversation to get deep insights into a topic. The questions are formulated in an open way and suggestive questions are avoided. Suggestive questions could influence the answers in an unwanted way, for instance asking if a specific challenge for PPC is relevant, instead of asking if and which challenges are relevant at all, before going into detail for specific challenges.

The questions of the semi-structured interview guide are set up as follows:

1. How does your AM and PBF-LB/M production look like?
2. Which components are or will be produced?
3. How are orders planned and controlled?
4. How is quality of the components ensured?
5. Which problems do you encounter regarding planning and controlling?

Experts for PBF-LB/M of company internal AM providers (CI) and AM service providers (SP) that offer parts and services to external customers are determined as interview partners. To enable the interview partners to speak freely about sensitive topics like quality issues, names, companies, and the retrieved information are anonymized. As conversation media, an online video conference platform is used.

3.1 Preparation and interpretation of interview results

For the preparation and interpretation of the interview results, a qualitative content analysis methodology with inductive category development based on [39] is applied. First, dimensions for structuring the interview results are formulated derived from the research problem. Second, the dimensions for structuring are further refined iteratively after assessments of a partition of the documented material. Third, the whole documented material is paraphrased, and the resulting statements are ordered to the previously defined dimensions. In the fourth step, a summative check of the prepared interview results is performed. For the analysis of the prepared results, the production volume, the control of production management and the control of production technology of the different companies are ranked. A higher rank means a higher production volume, control over production or production management respectively. The built ranks have an ordinal scale and do not indicate specific distances between the ranks. Moreover, the highest rank does not imply, that the production volume or the degree of control reached a limit without further potential for improvement. Assigning the same ranks to more than one company is possible in case the interview results do not indicate a clear difference. To ensure objective ranking, the authors of this work define the ranks individually at first. If the rank of a company is ambiguous after the individual assessment, it is adjusted by a majority vote afterwards. The stated challenges regarding PPC for PBF-LB/M are analysed considering the anonymized company profile and strategic focus as well as the defined ranks (production volume, control of production technology, control of production management) to fulfil the research aim, stated in section 1.

4. Results and interpretation

The interviewed CI set their strategic focus on R&D and company internal supply of AM parts as well as services. SP1, SP3 and SP4 have a strategic focus on scaling up the production volume with series applications and SP2 to exploit the niche of high-quality and performance AM parts. Table 1 contains a summary of the paraphrased statements regarding production volume, production technology, and production management. The result of the ranking is depicted in Figure 1. The interviewed CI tend to have a smaller production volume and less PBF-LB/M system capacity than SP. Moreover, both control over production technology and production management of SP tend to be higher. The results indicate a correlation of production volume, control of production technology and control of production management. With increasing control of production technology by PBF-LB/M manufacturers, this points to a growing importance of PPC in the future. Fulfilling basic customer requirements by control of production technology seems to be a barrier for finding more positive AM business cases and investment into more PBF-LB/M system capacity.

Table 1: Paraphrased statements of the interviews with experts from the PBF-LB/M industry

Company Code	Production volume	Production technology	Production management
CI1	1 medium sized system and low production volume	Metal AM less under control compared to polymer AM. Often the first printing trial fails. Problems with support generation (where, how, what angle). Automation of post-processing would be desirable, because of currently high manual effort.	Use of company standard ERP module also for AM, but thoughts about switching to an AM specific solution exist. Short horizon for production planning of 1 -3 weeks. Production planning for post-processing is based on experience. Machine utilization is rather low, therefore no focus on increasing build space usage. Traceability is easy because of small production volume. Identification of applications for AM is hard because in other departments there is no AM knowhow.
CI2	1 medium sized system fully used and 1 large sized system in procurement	Current qualification requirements are in a known span and controlled. For new requirements, new QM concepts are required. Qualification effort is sometimes underestimated. Tensile test included in all print jobs according to industry requirements. Frequent geometrical measurements and chemical analysis.	Standard ERP and planning tool for prioritization from CM is used also for AM but does not work properly because of incompatibility of R&D and production requirements. High manual effort for nesting and scheduling. Errors in data preparation can lead to failed prints. For known parts, historic data and knowledge is used for production planning. For new parts, the printing time is calculated using the AM system software and an estimation by experience for the post-process.
CI3	2 large sized systems and 1 medium sized system of different suppliers	Metal AM with various other AM technologies in AM center. Only prototypes and jigs/fixtures, no production/series parts. Quality measures according to customers' requirements. Part identification and failed prints currently most important topics.	Use of AM specific and customized ERP/MES system led to improvement in productivity and operations but also customer satisfaction and communication. Growing pain points and learning curve during implementation of new ERP/MES and after 2 years still room for improvement. Pricing in metal too complex to use build in auto-quoting function. Short planning horizon of 1-2 weeks. Company-wide approval process is used but too slow for utilizing AM flexibility for time-sensitive parts.
SP1	8 medium sized systems and ~20000 parts per year	Use of materials in combination with parameter sets from AM system suppliers instead of third-party material suppliers. Failed prints occur. Often more parts printed than required to have backup solutions in case of quality issues. Monthly machine inspections. No use of in-situ process monitoring.	Use of a standard ERP and magnetic board for production planning. Integration of ERP and MES is perceived as a challenge. MES suppliers were screened but no fit for the individual requirements. Physical documents on the shopfloor. Intentions for paperless production exist. Horizon for production planning from a few days up to two weeks. Production planning is very complicated. Currently KPIs are not monitored in production management, but machine utilization is assessed. Powder is reused but quality requirements can interfere with powder efficiency. Big potential for saving manual effort in production planning is an MES with automated nesting and scheduling.
SP2	12 systems of 3 different suppliers and 15-60 parts per week	Statements regarding quality challenges: Claim of very high capability and focus on quality as well as quality control (feedstock, material lab, tactile and optical testing, CT and optical measurements, in-situ process monitoring). Integration of conventional technologies with a focus on CNC milling.	Use of ERP system, MES with a strategic software partner is in testing phase. AM is the most complex technology for MES integration. Planning horizon for PBF-LB/M is shorter than for CM with CNC milling. Currently no paperless production, but this is a clear goal. Overall Equipment Effectiveness and utilization are not prioritized KPIs because of focus on high performance and only result in a part of manufacturing cost. Traceability and software environment for joint production planning of AM and CM with integrated CAM functions would be beneficial.
SP3	10 systems and ~1000 parts per moth	No significant statements regarding quality problems. Many different post-processing technologies in-house. Different quality control measures for parts and feedstock according to customer requirements. Destructive tests only in fixed intervals. System calibration only in case the optic system is changed or after maintenance.	Use of self-developed MES to fit individual requirements. Use of different KPIs (scrap rate, on-time delivery, customer complaints, utilization, build space usage). Inquiries via sales and online portal. 2d nesting and scheduling complex like a puzzle problem. Nesting and scheduling impossible without software support for more than 3 machines. Estimating process step duration using experience is hard and inaccurate for post-processing. Partially paperless production. Quality control via visual inspection or with measurement methods as required by customer including powder reuse management.
SP4	12 systems and ~2000 parts per month	No significant statements regarding quality problems. Many different post-processing technologies in-house. Different quality control measures for parts including in-situ process monitoring and feedstock testing according to customer requirements. Different AM and CM post-processing technologies integrated.	Very high utilization. OEE ~70-80% achievable, goal is >60-70%. Use of other different KPIs (e.g., utilization, throughput times, on-time delivery, first time right). Inquiries via AM marketplaces, sales, other business segments, MES. Mostly manual and challenging scheduling and nesting. Partially paperless production. Use of self-developed MES to fit individual requirements with documented traceability of documents, machine planning and process monitoring. Estimation of process step duration based on experience. Different planning for series and non-series parts. Quality control via visual inspection or with measurement methods as required by customer including powder reuse management.

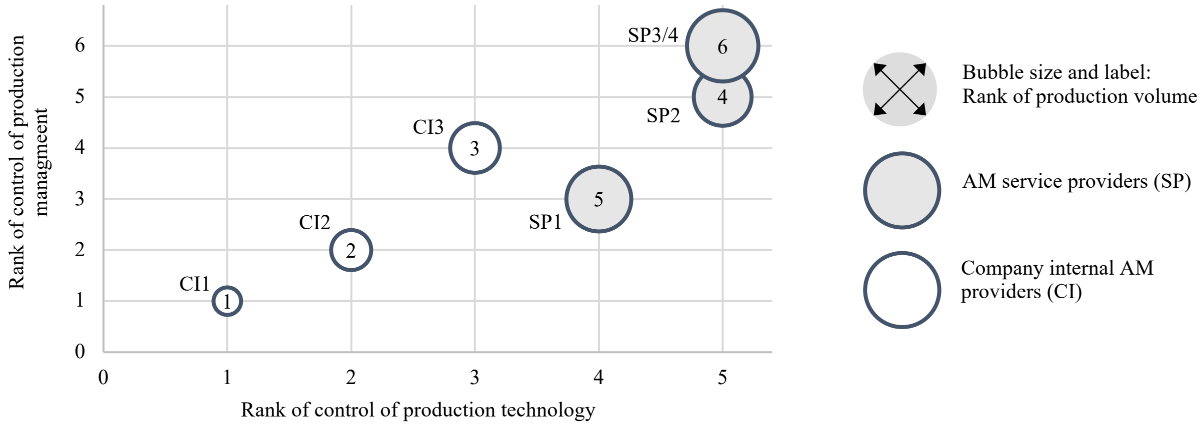

Figure 1: Ranking of the interviewed companies according to their production volume, control of production technology and control of production management

If the production technology is controlled well, scaling up the production volume is possible but requires improved PPC. With increased production volume and control over production technology, the awareness for challenges for PPC rises. SP3 and SP4 with the highest ranks regarding both production technology and production management use company-own AM specific MES. SP2 is currently testing an AM specific MES from a software supplier. In contrast, CI1, CI2 and SP1 with lower ranked control of production technology use already available but unsuitable software solutions or find workarounds like a magnetic board. Furthermore, highly ranked companies have a stronger focus on optimizing production logistics KPIs like utilization and on-time delivery in production management. To achieve good production logistics KPIs nesting and scheduling is important but due to the lack of suitable available software solutions it remains a challenge. Especially estimating of the post-processing throughput time is challenging but required to plan for on-time delivery. Currently, PPC that considers AM characteristics does not address CM steps in the post-process adequately as well, even though they cause a large proportion of effort and time.

SP1, SP3 and SP4 aim for an increased production volume by more series applications. The results indicate that the effort for e.g., identifying the application, design for AM, communication with customers, and PPC per part variant is significant. Contrary to what is often claimed for AM, this leads to lower costs if economies of scale in series production are exploited, although there is no impact of tool dependent economies of scale. Thus, the strategy of SP1, SP3 and SP4 is to solve challenges of PPC and acquire orders for series applications by exploiting AM benefits while keeping costs low and production logistics performance high. SP2 pursues the strategy of high quality and performance by integration of PBF-LB/M and subtractive manufacturing instead of focusing on cost and economies of scale.

For all companies, experience of employees is critical in PPC. For companies with high ranks, long printing durations parallel to heterogenous manual tasks in the post-process require adapted personnel planning with low number of workers but training in various skills. Pursued solutions are systems with the aim to schedule prints so they finish during work hours or flexible planning including the individual preferences and skills.

5. Summary and outlook

In this work, an analysis of challenges for PPC for PBF-LB/M based on expert interviews is presented. For companies in an early phase of technological adaption of PBF-LB/M production management has only low relevance. For companies with larger production volume and control over production technology challenges for PPC are highly relevant. With technological advance of PBF-LB/M manufacturers, this points to a growing importance of PPC in the future. ERP, MES, and data preparation solutions do not entirely fulfil the requirements from the industry. Companies jointly use CM and AM processes, but integrated software solutions for PPC for CM and AM are not in use. Thus, an automated solution for nesting and scheduling to optimize production logistics and costs for the whole AM and CM process chain is required. Furthermore, companies need software solutions for paperless traceability in production control and to reuse historic data in production planning. Further research is needed to derive a catalogue of requirements for PPC of PBF-LB/M considering the findings of this work.

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References

[1] DIN Deutsches Institut für Normung e.V., 2022. Additive Manufacturing - General principles - Fundamentals and vocabulary. Beuth, Berlin 01.040.25; 25.030.

[2] Verein Deutscher Ingenieure, 2014. Additive manufacturing processes, rapid manufacturing: Basics, definitions, processes. Beuth, Berlin 25.020.

[3] Khorasani, A., Gibson, I., Veetil, J.K., Ghasemi, A.H., 2020. A review of technological improvements in laser-based powder bed fusion of metal printers. The International Journal of Advanced Manufacturing Technology 108 (1-2), 191–209.

[4] Baumers, M., Dickens, P., Tuck, C., Hague, R., 2016. The cost of additive manufacturing: machine productivity, economies of scale and technology-push. Technological Forecasting and Social Change 102, 193–201.

[5] Hedenstierna, C.P.T., Disney, S.M., Eyers, D.R., Holmström, J., Syntetos, A.A., Wang, X., 2019. Economies of collaboration in build-to-model operations. Journal of Operations Management 65 (8), 753–773.

[6] Stittgen, T., 2021. Fundamentals of Production Logistics Positioning in the Area of Additive Manufacturing Using the Example of Laser Powder Bed Fusion.

[7] Flores Ituarte, I., Khajavi, S.H., Partanen, J., 2016. Challenges to implementing additive manufacturing in globalised production environments. International Journal of Collaborative Enterprise 5 (3-4), 232–247.

[8] Manco, P., Macchiaroli, R., Maresca, P., Fera, M., 2019. The additive manufacturing operations management maturity: A closed or an open issue? Procedia Manufacturing 41 (41), 98–105.

[9] Luft, A., Gebhardt, A., Balc, N., 2019. Challenges of additive manufacturing in production systems. MATEC Web of Conferences 299, 1003.

[10] McCann, R., Obeidi, M.A., Hughes, C., McCarthy, É., Egan, D.S., Vijayaraghavan, R.K., Joshi, A.M., Acinas Garzon, V., Dowling, D.P., McNally, P.J., Brabazon, D., 2021. In-situ sensing, process monitoring and machine control in Laser Powder Bed Fusion: A review. Additive Manufacturing 45, 102058.

[11] Ewald, S., Kies, F., Hermsen, S., Voshage, M., Haase, C., Schleifenbaum, J.H., 2019. Rapid Alloy Development of Extremely High-Alloyed Metals Using Powder Blends in Laser Powder Bed Fusion. Materials 12 (10).

[12] Baumung, W., 2020. Design of an Architecture of a Production Planning and Control System (PPC) for Additive Manufacturing (AM). Lecture Notes in Business Information Processing 389 LNBIP, 391–402.

[13] Savolainen, J., Collan, M., 2020. How Additive Manufacturing Technology Changes Business Models? – Review of Literature. Additive Manufacturing 32.

[14] Lindwall, A., Dordlofva, C., Öhrwall Rönnbäck, A., 2017. Additive Manufacturing and the Product Development Process: insights from the Space Industry, in: 21th International Conference on Engineering Design (ICED17), Vancouver, Sweden. 21-25 August 2017, pp. 345–354.

[15] Thürer, M., Huang, Y., Stevenson, M., 2021. Workload control in additive manufacturing shops where post-processing is a constraint: an assessment by simulation. International Journal of Production Research 59 (14), 4268–4286.

[16] Nyhuis, P., Schmidt, M., 2011. Logistic Operating Curves in Theory and Practice. Advances in Computer Science and Engineering, 371–390.

[17] Gutenberg, E., 1951. Grundlagen der Betriebswirtschaftslehre: Erster Band Die Produktion. Springer Berlin Heidelberg, Berlin, Heidelberg, s.l., 406 pp.

[18] Oh, Y., Witherell, P., Lu, Y., Sprock, T., 2020. Nesting and Scheduling Problems for Additive Manufacturing: A Taxonomy and Review. Additive Manufacturing 36.

[19] Wiendahl, H.-P., ElMaraghy, H.A., Nyhuis, P., Zäh, M.F., Wiendahl, H.-H., Duffie, N., Brieke, M., 2007. Changeable Manufacturing - Classification, Design and Operation. CIRP Annals 56 (2), 783–809.

[20] Wiendahl, H.H., Westkämper, E., Rempp, B., Pritschow, G., 2000. PPC in a turbulent environment: fundamentals and approaches, in: Proceedings of the 33rd CIRP International Seminar on Manufacturing Systems, pp. 320–325.

[21] Dirks, S., Schleifenbaum, J.H., 2019. Adaption of Cost Calculation Methods for Modular Laser-Powder Bed Fusion (L-PBF) Machine Concepts, in: Proceedings of the Metal Additive Manufacturing Conference. Metal Additive Manufacturing Conference, Orebro, Sweden, pp. 79–87.

[22] Kucukkoc, I., 2021. Metal Additive Manufacturing: Nesting vs. Scheduling, in: Optimization and Data Science: Trends and Applications. Springer, pp. 169-180.

[23] Chergui, A., Hadj-Hamou, K., Vignat, F., 2018. Production scheduling and nesting in additive manufacturing. Computers & Industrial Engineering 126, 292–301.

[24] Kratzer, M.J., Mayer, J., Höfler, F., Urban, N., 2021. Decision Support System for a Metal Additive Manufacturing Process Chain Design for the Automotive Industry, in: Meboldt, M., Klahn, C. (Eds.), Industrializing Additive Manufacturing. Springer International Publishing, Cham, pp. 469–482.

[25] Möhrle, M., 2018. Gestaltung von Fabrikstrukturen für die additive Fertigung. Springer Berlin Heidelberg, Berlin, Heidelberg.

[26] Swamidass, P.M., 2000. Encyclopedia of Production and Manufacturing Management. Springer US, Boston, MA.

[27] Bikas, H., Koutsoukos, S., Stavropoulos, P., 2019. A decision support method for evaluation and process selection of Additive Manufacturing. Procedia CIRP 81, 1107–1112.

[28] Denkena, B., Dittrich, M.-A., Henning, S., Lindecke, P., Denkena B., 2018. Investigations on a standardized process chain and support structure related rework procedures of SLM manufactured components. Procedia Manufacturing 2018 18, 50–57.

[29] Jacob, A., Künneke, T., Lieneke, T., Baumann, T., Stricker, N., Zimmer, D., Lanza, G., 2018. Iterative product development and production planning for additive manufacturing [Iterative produktentwicklung und produktionsplanung für die additive fertigung]. ZWF Zeitschrift fuer Wirtschaftlichen Fabrikbetrieb 113 (11), 742–745.

[30] Grasso, M., Colosimo, B.M., 2017. Process defects and in situ monitoring methods in metal powder bed fusion: a review. Measurement Science and Technology 28 (4).

[31] Wang, Z., Pannier, C.P., Barton, K., Hoelzle, D.J., 2018. Application of robust monotonically convergent spatial iterative learning control to microscale additive manufacturing. Mechatronics 56, 157–165.

[32] Scime, L., Beuth, J., 2018. Anomaly detection and classification in a laser powder bed additive manufacturing process using a trained computer vision algorithm. Additive Manufacturing 19, 114–126.

[33] Mani, M., Lane, B.M., Donmez, M.A., Feng, S.C., Moylan, S.P., 2017. A review on measurement science needs for real-time control of additive manufacturing metal powder bed fusion processes. International Journal of Production Research 55 (5), 1400–1418.

[34] Körner, C., Attar, E., Heinl, P., 2011. Mesoscopic simulation of selective beam melting processes. Journal of Materials Processing Technology 211 (6), 978–987.

[35] DIN Deutsches Institut für Normung e.V., 2015. Quality management systems: Fundamentals and vocabulary, Berlin 01.040.03; 03.120.10.

[36] Reuter, C., Brambring, F., Hempel, T., 2016. Increasing the Traceability Through Targeted Data Acquisition for Given Product Process Combinations. Procedia CIRP 52, 210–215.

[37] Sola, A., Sai, Y., Trinchi, A., Chu, C., Shen, S., Chen, S., 2021. How Can We Provide Additively Manufactured Parts with a Fingerprint? A Review of Tagging Strategies in Additive Manufacturing. Materials 15 (1).

[38] Homburg, C., 2020. Marketingmanagement: Strategie – Instrumente – Umsetzung – Unternehmensführung, 7th ed. Springer Fachmedien Wiesbaden, Wiesbaden.

[39] Mayring, P., 2000. Qualitative Content Analysis. Forum Qualitative Social Research 1 (2).

Biography

Lukas Bauch (*1995) has been research associate of the chair for Digital Additive Production DAP at RWTH Aachen University since 2021. Before that, he completed a Master of Science degree in industrial engineering. Since 2019, he has been part of various research and development projects both in industry and academia focusing on Additive Manufacturing and Digital Production.

Andreas Wilhelm (*1993) has been research assistant of the chair for Digital Additive Production DAP at RWTH Aachen University since 2019. Since 2019, he has been part of various research and development projects both in industry and academia focusing on Additive Manufacturing and Digital Production.

Moritz Kolter (*1996) is a group manager and research associate at the chair for Digital Additive Production DAP at RWTH Aachen University. He holds a Master of Science in Mechanical Engineering from Technical University of Munich. Since 2017 he has been part of various research and development projects both in industry and academia focusing on Additive Manufacturing and Digital Production.

Johannes Henrich Schleifenbaum (*1978) Univ.-Prof. Dr.-Ing. Dipl.-Wirt.-Ing. Johannes Henrich Schleifenbaum has been holding the Chair Digital Additive Production DAP at RWTH Aachen University since 2016. Furthermore, he has been managing director at Aachen Center for Additive Manufacturing since 2018.

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Characteristics For Verifying 5G Applications In Production

Abbas, Murtaza[1]; Stroh, Max[1]; Stich, Volker[1]

[1]Institute for Industrial Management (FIR) at RWTH Aachen University, Aachen, Germany

Abstract

5G offers the manufacturing industry a wireless, fast and secure transmission technology with high range, low latency and the ability to connect a large number of devices. Existing transmission technologies are reaching their limits due to the increasing number of networked devices and high demands on reliability, data volume, security and latency. 5G fulfils these requirements and combines the potential and use cases of previous transmission technologies so that unwanted isolated solutions can be merged. Use cases of transmission technologies that previously required a multitude of solutions can now be realized with a single technology. However, the general literature often refers to 5G use cases that can also be realized over cables. In this paper, a literature review presents the current state of research on the various 5G application scenarios in production. Furthermore, concrete characteristics of 5G use cases are identified and assigned to the identified application scenarios. The goal is to verify the identified 5G use cases and to work out their 5G relevance to be able to concretely differentiate them from already existing Industry 4.0 applications.

Keywords

5G-Technology, 5G use case, Industry 4.0, Networked, production

1. Introduction

Due to the challenge of digital transformation, the demands on existing transmission technologies are continuously increasing [1]. Not only the sharp increase in the number of end devices to be networked, but also the exponential growth in the volume of data transferred via data networks are pushing existing transmission technologies to their limits. [2] But also higher demands on reliability, security or even latency of the transmission pose challenges to established transmission technology [3]. In order to meet the increasing requirements, the performance of transmission technologies has also had to evolve significantly in the last few years [4]. The mobile communications technology 5G is assigned a special role in this context. This transmission technology addresses not only end users as customers, but also industrial applications for the first time. [5] In particular, the special performance parameters and characteristics of 5G make it unique compared to existing transmission technologies and provide ideal conditions for it to become a key technology of the digital transformation [6].

Numerous studies demonstrate the great economic relevance of 5G based on similar findings [7–10]. In particular, the great value creation potential of 5G in the manufacturing, energy and raw materials industries is always emphasized [9,10]. In these industries alone, 5G benefits to gross domestic product (GDP) are projected to be as high as 5% in 2030 [9]. This can be attributed not least to the realization of various future-proof 5G use cases and the associated development of new business areas and services. For example, an increase in flexibility in production can be realized by eliminating the need for fixed cabling or by making the edge control of robots wireless. Furthermore, there is the possibility of realizing anomaly detection systems or comprehensive asset tracking via the connection of large numbers of end devices [11]. In summary, machine-based decision-making, dynamic automations, or even visualizations of any kind noticeably increase the value creation of companies. But also the development of new business models with

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the help of additional amounts of data from sensors leads to an optimization in terms of time, costs or even quality [12].

The use of 5G will have a positive impact on virtually every industrial sector [7]. In this context, the joint use of infrastructure elements (infrastructure sharing) harbours great potential. Here, various sharing concepts can save costs of up to 25% even with two consortium partners [13]. Industrial parks and technology centres can benefit greatly from the joint development of 5G campus networks since the rollout phase of 5G is cost-intensive and therefore especially attractive for mergers.

This paper will lay the foundation for the evaluation of 5G use cases. In this paper, the 5G technology will be described and characterized based on relevant features. Based on this, 5G use cases shall be derived based on the previously identified characteristics and consequently assigned to the characteristics in the form of strong or weak dependency.

2. Basic terminology

Industry 4.0: Industry 4.0 (or also called the fourth industrial revolution) represents the consistent further development of three preceding industrial revolutions. It is based on historical and technological approaches of the intelligent factory and computer-integrated production. The fourth industrial revolution involves the beneficial networking of people, machines, products, systems and companies along the value chain and across the product life cycle. The aim is to produce more efficiently or more productively and to generate more customer benefits. [14]

Mobile radio: The definition of mobile radio is "radio, radiotelephony or radiotelephone traffic between mobile or between mobile and fixed stations" [15]. Mobile communications are therefore understood to mean communication between different devices, at least one of which is mobile. Challenges here are addressability when changing networks, continuation of communication after interruption, compatibility with other layer protocols, scalability and efficiency. [16]

5G: 5G is the fifth generation of mobile communications, with the associated New Radio (NR) standard. The ITU (International Telecommunication Union) has been compiling performance requirements for 5G since 2016. These include an increased down/upload rate, lower latencies, and an increased number of connected devices per km². Furthermore, both a higher tolerance for the movement speed of the end device and lower energy consumption are required. [17,11]

5G frequencies: In addition to the frequencies already in use today in the range from 0.7 to 2.4 GHz and 5 GHz, 5G can also use frequencies up to 100 GHz. However, the frequencies are initially envisaged, as well as the range between 3.4 and 3.7 GHz, which is intended exclusively for 5G. In addition, the 3.7 to 3.8 GHz frequency will not be used for public networks, but will be kept free for companies or organizations to build private 5G campus networks. [17,11,18]

5G campus network: A campus network is an internal service network of an organization or company [19]. Typically, a campus network consists of a data centre, the office network, and a connection to the Internet. These networks cover specific areas such as a corporate campus or a university campus. The important parts of a campus network according to the 3GPP are the radio network, with which terminals are connected via base stations to the user plane function and the 5G core control plane. [20] Campus networks can be implemented with different levels of integration to the public networks of the mobile network providers. For example, campus networks can be completely isolated (self-operation) or based purely on public networks with only virtual separation (network slicing). But there are also various intermediate forms (hybrid network).

3. Research method

In this study, an exploratory multiple case study was chosen as the research method, while the research design follows the phenomenological approach of qualitative research. The study relies on a non-random, purposive sample. Diversity was considered in the selection of participating companies to ensure that all conflicts of interest described above were addressed. In total, four SMEs, two large companies and two telecommunications companies were interviewed, with interviewees mostly from middle and senior management. The interviews conducted aimed to identify and validate relevant 5G characteristics as well as relevant use fields and use cases for 5G. Based on this, further evaluation of 5G campus networks will be conducted. The interviews followed a semi-structured approach with a duration of 60 minutes per interview. Due to the vast experience with video calls within the pandemic, only virtual interviews have been conducted for the time being.

A three-step approach was chosen as the basis for the interview structure, in which the 5G technology and the description of it were first discussed in an overarching manner. Subsequently, the reference to the 5G use cases in production was made and potentials were collected. Finally, the relationships between features and use cases were considered and evaluated. This research method was chosen to fully capture the specific expert knowledge of the individual subjects and to be able to determine their individual perspectives. The differentiated description of features and use scenarios makes it possible to fully capture and outline the current situation.

4. Results

For the first time, the fifth generation of mobile communications offers the possibility of setting up and operating private campus networks for industrial purposes. As a result, the unique performance parameters of 5G private campus networks make new application scenarios even conceivable. In the following, the 5G performance parameters gathered based on case study research are presented and described in more detail. In a second step, the use cases gathered based on the case-hour research are outlined and detailed. Finally, the characteristics are assigned to the use cases in the form of strong and weak dependence on each other.

4.1 5G performance parameters

In addition to the overriding performance parameters such as low latency, high data rates or high terminal density, 5G has many other performance parameters that will allow new innovative application scenarios in the future. These performance parameters will make it possible for the first time to improve existing applications as well as to run entirely new application scenarios in production. Among other things, the possibility of setting up extremely reliable private campus networks means that many existing cable connections will no longer be necessary in the future. An overview of 5G performance parameters and characteristics and the potentials for industry derived from them is summarized in Table 1.

Table 1: Overview of 5G performance parameters

Nr.	Performance parameters and characteristics of 5G	Potentials resulting from the performance parameters and characteristics of 5G
1	High Data Rates [4,21,22]	Basis for high data rate applications (example AI applications with live camera data).
2	Device Density [23–25]	Basis for applications with high numbers of devices to be connected (e.g. tracing of assembly activities by connecting the tools)
3	Low Latency [26–28]	Basis for applications with real-time requirements (e.g. robotics control/ AR/ ...)

		Basis for edge computing applications
4	Motion Support (Low handover times) [29–31]	The basis for moving application scenarios Realization of applications with speeds up to 500km/h
5	Suitable for large area network coverage (indoor and outdoor) [32–34]	Implementation of new use cases also beyond the boundaries of the factory floor/premises
6	Network Slicing (virtual splitting of the network and dedicated allocation of resources) [35–37]	Increasing the reliability of data transmission Enabling mobile applications despite safety-critical properties
7	Standalone Campus Network (in a licensed frequency band) [38–40]	Increasing the security of data transmission Increasing the reliability of data transmission Individualization of the performance parameters of the campus network to the requirements of applications to be realized
8	Summary of Technologies (Includes properties of existing technologies) [7,41,42]	Merging of different technologies like • Positioning tracking • means of communication (telephone) • Data transmission Cost reduction by lowering the maintenance effort
9	Wireless (lowering of wired applications) [9,43,44]	Increase flexibility Reduction of costs (maintenance, cable breakage, etc.)
10	Improved Energy Efficiency [45–47]	Up to 10 years battery life for low power devices (IoT)
11	Possibility of selective optimization of a private 5G campus network based on the selected use cases. [48–50]	Setting up individual campus networks Optimization of the networks to the needs of the respective company

4.2 5G Use cases

As a result of the unique performance parameters and properties of 5G and the resulting potential, various use cases in industry will be enabled or optimized. An excerpt of the application fields enabled or optimized by 5G, including exemplary applications, is compiled in Table 2

Table 2: Use cases enabled by 5G

Nr.	Use cases	Description/ Application examples
1	Remote Control [51,52,7,53,54]	Remote control of industrial equipment. **Application examples**: mobile robots, AGVs; mobile cranes, mobile pumps, stationary gantry cranes
2	Monitoring [55,28,56]	The transmission of real-time data allows for a number of different monitoring applications. **Application examples**: Monitoring of various parameters (pressure, temperature, ...), process monitoring
3	Tracing/ Positioning [57–59]	The ability to determine position means that tracking and tracing concepts can be realized via 5G in the future. **Application examples:** Traceability of orders, optimization of the flow of goods
4	Quality improvement [9,28]	In general, the use of 5G increases the quality of all processes and applications. **Application examples**: robot-assisted surgery; remote monitoring of patients

5	Vehicle-to-Vehicle Communication [58,60,61]	Communication between vehicles. **Application examples**: AGVs, Drones
6	Process Automation [62,63,48]	Control the production and handling of substances such as chemicals, food and beverages, etc. **Application examples**: mobile robots, massive wireless sensor networks, closed-loop process control, process monitoring, asset inventory management
7	Factory Automation [62,48]	Automated control, monitoring and optimization of processes and workflows. **Application examples**: Motion control, control-to-control (C2C) communication, mobile robots, massive wireless sensor networks.
8	HMIs and production IT [62,63,43]	Various devices for interaction between people and production systems/ IT-based applications such as Manufacturing Execution Systems (MES) and Enterprise Resource Planning (ERP) systems. **Application examples**: mobile control panels, AR applications
9	Logistics and warehousing [54,60]	Organization and control of the flow and storage of materials and goods within the framework of industrial production. **Application examples**: Organization and control of the flow and storage of materials and goods within the framework of industrial production.
10	Maintenance [64,58]	Monitoring of specific processes and/or equipment, but without directly intervening in the processes themselves. **Application examples**: mobile robots, massive wireless sensor networks, remote access and maintenance, AR applications

4.3 Merging 5G features into 5G use cases

For reasons of clarity, strong and weak dependencies have been considered separately. In the following, the strong dependencies are presented first, while the weak dependencies are explained in the next step.

4.3.1 Strong dependencies between use cases and features

The strong dependencies between use cases and performance parameters are summarized below. This quickly shows that the different use cases have very different effects on the respective performance parameters. As a result, it becomes clear that the potential of 5G is very diverse due to the strong performance parameters. The performance parameter "Point optimization of the 5G network" is particularly striking here, since not a single strong dependency could be detected. However, this is due to the higher-level use cases. Furthermore, it was noted that two of the three main performance parameters (device density and latency) were mentioned very frequently. This is due to the fact that these two performance parameters come together in many industry 4.0 use cases. At the same time, some performance parameters were only mentioned once. This is due to use cases that have very specific requirements. An overview of the strong dependencies between the application scenarios and the performance parameters is summarized in Figure 1.

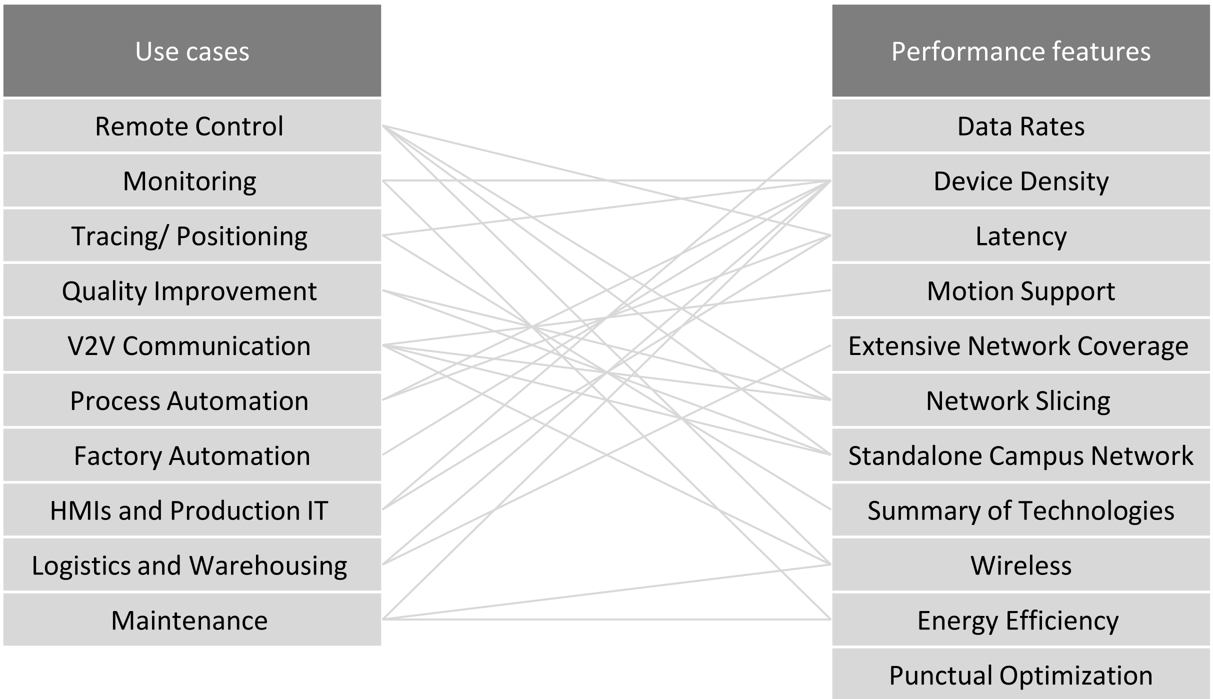

Figure 1: Strong dependencies between use cases and performance features

4.3.2 Weak dependencies between use cases and performance features

In addition to clearly strong dependencies between use case and performance parameters, there are also other, weak dependencies. A good example of this is the possibility of adapting the private 5G campus networks so that they are specifically tailored to the use scenarios. This special performance feature of a 5G network could make all the difference in specific use cases. However, the device density involved in the implemented use case also plays a major role in very many use cases (often either strong or weak dependency). It is noticeable that some performance parameters do not have a weak dependency on the performance parameters at all. The reason for this are special performance parameters, which are quite specifically directed at individual use cases. An overview of the strong dependencies between the application scenarios and the performance parameters is summarized in Figure 2.

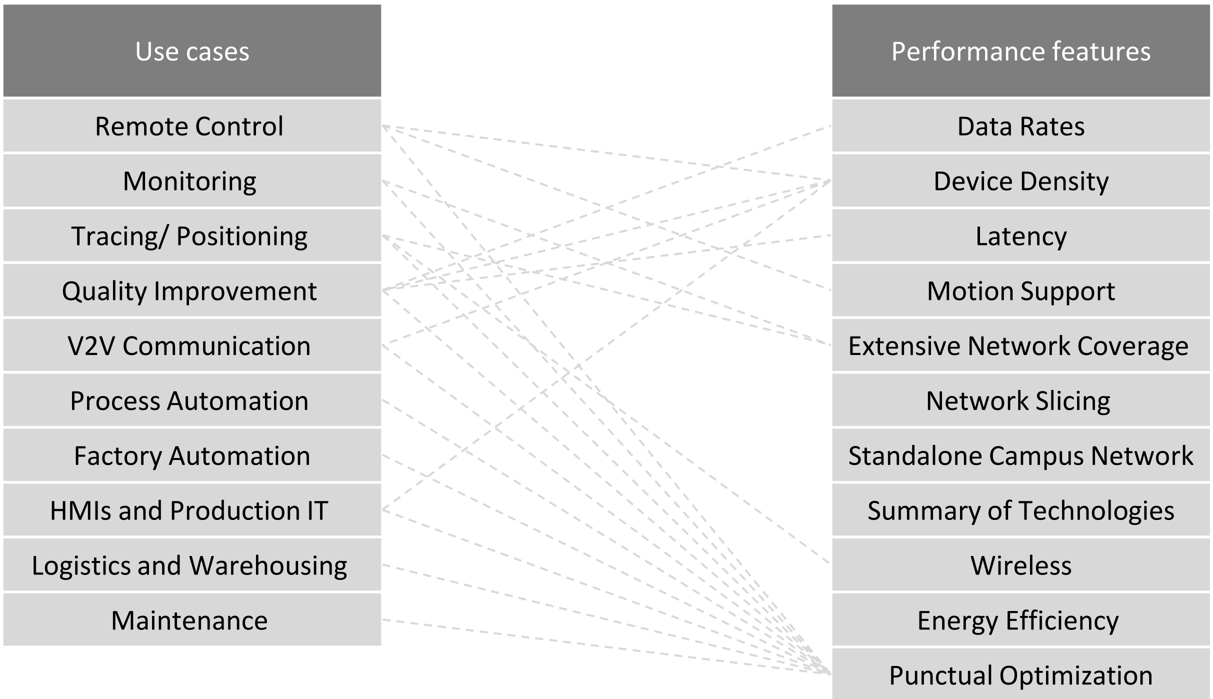

Figure 2: Weak dependencies between use cases and performance features

5. Discussion, conclusion, and outlook

The performance parameters listed here could be linked to different use cases in strong and weak dependencies. By clearly linking the performance parameters to the respective use cases, it was possible to demonstrate that 5G can realize a wide variety of application scenarios. Thus, it could be proven that especially many already existing use scenarios can be significantly improved by 5G. However, the potential of 5G cannot only be evaluated in terms of application cases, since this infrastructure not only realizes new applications and improves existing applications, but also enables higher-level links that could not have been thought of before, especially due to the high number of end devices. Furthermore, it emerged from the interviews that it is very difficult to distinguish clearly between a real 5G use case and an already existing Industry 4.0 use case. Here, sometimes very minor adjustments turn an already existing Industry 4.0 use case into a 5G use case (increasing speed, integrating people (human-machine interactions), etc.). To be able to measure the relevance of 5G in a company, use cases must not only be considered as isolated solutions, but must always be viewed in a higher-level context.

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References

[1] Hartmann, E.A., 2021. Digitalisierung souverän gestalten. Springer Berlin Heidelberg, Berlin, Heidelberg, 160 pp.

[2] Reus, O., Kriegeskotte, N., Rehfueß, U., 2015. 5G: Schlüsseltechnologie für die vernetzte Gesellschaft, 32 pp. https://plattform-digitale-netze.de/app/uploads/2016/06/151109_PF1_007_FG3_Vision_5G_lang_Ansicht.pdf. Accessed 23 March 2021.

[3] Jasperneite, J., Lohweg, V., 2020. Kommunikation und Bildverarbeitung in der Automation. Springer Berlin Heidelberg, Berlin, Heidelberg, 374 pp.

[4] Barakabitze, A.A., Ahmad, A., Mijumbi, R., Hines, A., 2020. 5G network slicing using SDN and NFV: A survey of taxonomy, architectures and future challenges. Computer Networks 167 (106984), 1–40.

[5] Bundesnetzagentur, 2020. Übersicht der Zuteilungsinhaber: Frequenzzuteilungen für lokale Frequenznutzungen im Frequenzbereich 3.700-3.800 MHz, 6 pp. https://www.bundesnetzagentur.de/SharedDocs/Downloads/DE/Sachgebiete/Telekommunikation/Unternehmen_Institutionen/Frequenzen/OffentlicheNetze/LokaleNetze/Zuteilungsinhaber.pdf?__blob=publicationFile&v=5. Accessed 23 March 2021.

[6] Simon, A., 2020. Konnektivität in neuer Dimension? https://www.computerwoche.de/a/konnektivitaet-in-neuer-dimension,3548295. Accessed 1 November 2022.

[7] Campbell, K., Diffley, J., Flanagan, B., Morelli, B., O'Neil, B., Sideco, F., 2017. The 5G economy: How 5G technology will contribute to the global economy. IHS Economics & IHS Technology, 35 pp. Accessed 1 November 2022.

[8] Demary, V., Rusche, C., 2018. Zukunftsfaktor 5G: Eine ökonomische Perspektive. IW-Report 45. Institut der deutschen Wirtschaft (IW), Köln, 23 pp. Accessed 1 November 2022.

[9] Gilbert, T., Barraclough, C., Mash, I., Easton, M., 2019. $1.4tn of Benefits in 2030: 5G's impact on industry verticals, 39 pp. Accessed 1 November 2022.

[10] Hompel, M. ten, Bauernhansl, T., Vogel-Heuser, B. (Eds.), 2020. Handbuch Industrie 4.0. Springer Berlin Heidelberg, Berlin, Heidelberg, 631 pp.

[11] Seelmann, Abbas, Henke, Stratmann, Leidinger, Knebel, 2020. 5G für die vernetzte Industrie, 4 pp. http://library.fes.de/pdf-files/wiso/16838.pdf. Accessed 1 November 2022.

[12] Ennemann, M., Holt, A., 2020. Wertschöpfung durch 5G, 10 pp. https://home.kpmg/de/de/home/themen/2020/05/wertschoepfung-durch-5g-wie-sich-weltweit-ueber-4-billionen-us-dollar-generieren-lassen.html. Accessed 1 November 2022.

[13] Schäfer, S., Elbanna, A., Neu, W., Thomas Plückebaum, 2020. Mögliche Einsparungspotentiale beim Ausbau von 5G durch Infrastructure Sharing. WIK Wissenschaftliches Institut für Infrastruktur und Kommunikationsdienste, 127 pp. https://www.econstor.eu/handle/10419/228685. Accessed 1 November 2022.

[14] Naranjo, C., Rodríguez, L., 2022. Key Variables for the Implementation of Industry 4.0 in the Colombian Service Sector, in: , Knowledge management in organisations. Springer, 2022, Cham.

[15] Bibliographisches Institut GmbH, 2020. Duden "Mobilfunk". https://www.duden.de/rechtschreibung/Mobilfunk. Accessed 1 November 2022.

[16] RWTH Aachen - Lehrstuhl für Informatik 4, 2020. Kommunikation und verteilte Systeme: Anforderungen an ein mobiles IP. Lehrstuhl für Informatik 4. Accessed 1 November 2022.

[17] Leidinger, C., Seelmann, V., Maasem, C., 2019. 5G - Evolution oder Revolution? https://5g.nrw/5g-evolution-oder-revolution/. Accessed 1 November 2022.

[18] Ud Din Arshad, Q.K., Kashif, A.U., Quershi, I.M., 2019 - 2019. A Review on the Evolution of Cellular Technologies, in: 2019 16th International Bhurban Conference on Applied Sciences and Technology (IBCAST). 2019 16th International Bhurban Conference on Applied Sciences and Technology (IBCAST - 2019), Islamabad, Pakistan. 08.01.2019 - 12.01.2019. IEEE, pp. 989–993.

[19] Huawei, 2011. Campus Network Solution V100R001C00: Deployment Guide. Accessed 1 November 2022.

[20] BMWi, 2015. Industrie 4.0 und Digitale Wirtschaft. https://www.bmwi.de/Redaktion/DE/Publikationen/Industrie/industrie-4-0-und-digitale-wirtschaft.pdf%3F__blob%3DpublicationFile%26v%3D3. Accessed 1 November 2022.

[21] Tall, A., Altman, Z., Altman, E., 2015. Multilevel beamforming for high data rate communication in 5G networks. http://arxiv.org/pdf/1504.00280v2. Accessed 1 November 2022.

[22] Wang, Y., Li, J., Huang, L., Jing, Y., Georgakopoulos, A., Demestichas, P., 2014. 5G Mobile: Spectrum Broadening to Higher-Frequency Bands to Support High Data Rates. IEEE Veh. Technol. Mag. 9 (3), 39–46.

[23] Bockelmann, C., Pratas, N.K., Wunder, G., Saur, S., Navarro, M., Gregoratti, D., Vivier, G., Carvalho, E. de, Ji, Y., Stefanovic, C., Popovski, P., Wang, Q., Schellmann, M., Kosmatos, E., Demestichas, P., Raceala-Motoc, M., Jung, P., Stanczak, S., Dekorsy, A., 2018. Towards Massive Connectivity Support for Scalable mMTC Communications in 5G Networks. IEEE Access 6 (1), 28969–28992.

[24] Cheng, J., Chen, W., Tao, F., Lin, C.-L., 2018. Industrial IoT in 5G environment towards smart manufacturing. Journal of Industrial Information Integration 10 (1), 10–19.

[25] Ratasuk, R., Mangalvedhe, N., Bhatoolaul, D., Ghosh, A., 2017. LTE-M Evolution Towards 5G Massive MTC, in: 2017 IEEE Globecom Workshops (GC Wkshps). 2017 IEEE Globecom Workshops (GC Wkshps), Singapore. 04.12.2017 - 08.12.2017. IEEE, pp. 1–6.

[26] Sachs, J., Wikstrom, G., Dudda, T., Baldemair, R., Kittichokechai, K., 2018. 5G Radio Network Design for Ultra-Reliable Low-Latency Communication. IEEE Network 32 (2), 24–31.

[27] Soldani, D., Fadini, F., Rasanen, H., Jose, D., Tuomas, N., Devaki Chandramouli, Tom Hoglund, Klaus Doppler, Teemu Himanen, Jaana Laiho and Niraj Nanavaty, 2017. 2017 IEEE 85th Vehicular Technology Conference (VTC Spring): Sydney, Australia, 4-7 June 2017 : proceedings. IEEE Access (1), 106–111.

[28] Soldani, D., Guo, Y.J., Barani, B., Mogensen, P., I, C.-L., Das, S.K., 2018. 5G for Ultra-Reliable Low-Latency Communications 2. Accessed 1 November 2022.

[29] Adib, D., Barraclough, C., Mash, I., Easton, M., 2019. 5G's impact on manufacturing: $740bn of benefits in 2030, 40 pp.

[30] Fan, P., Zhao, J., I, C.-L., 2016. 5G high mobility wireless communications: Challenges and solutions. China Commun. 13 (2), 1–13.

[31] Xiong, K., Fan, P., Zhang, Y., Letaief, K.B., 2017. Towards 5G High Mobility: A Fairness-Adjustable Time-Domain Power Allocation Approach. IEEE Access 5 (1), 11817–11831.

[32] Dahlman, E., Mildh, G., Parkvall, S., Peisa, J., Sachs, J., Selén, Y., Sköld, J., 2014. 5G wireless access: requirements and realization. IEEE Commun. Mag. 52 (12), 42–47.

[33] Liu, S., Liu, L., Yang, H., Yue, K., Guo, T., 2020. Research on 5G technology based on Internet of things, in: 2020 IEEE 5th Information Technology and Mechatronics Engineering Conference (ITOEC). 2020 IEEE 5th Information Technology and Mechatronics Engineering Conference (ITOEC), Chongqing, China. 12.06.2020 - 14.06.2020. IEEE, pp. 1821–1823.

[34] Pedersen, K., Frederiksen, F., Berardinelli, G., Mogensen, P., 2015. A Flexible Frame Structure for 5G Wide Area, in: 2015 IEEE 82nd Vehicular Technology Conference (VTC2015-Fall). 2015 IEEE 82nd Vehicular Technology Conference (VTC Fall), Boston, MA, USA. 06.09.2015 - 09.09.2015. IEEE, pp. 1–5.

[35] Campolo, C., Molinaro, A., Iera, A., Menichella, F., 2017. 5G Network Slicing for Vehicle-to-Everything Services. IEEE Wireless Commun. 24 (6), 38–45.

[36] Foukas, X., Patounas, G., Elmokashfi, A., Marina, M.K., 2017. Network Slicing in 5G: Survey and Challenges. IEEE Commun. Mag. 55 (5), 94–100.

[37] Li, X., Samaka, M., Chan, H.A., Bhamare, D., Gupta, L., Guo, C., Jain, R., 2017. Network Slicing for 5G: Challenges and Opportunities. IEEE Internet Comput. 21 (5), 20–27.

[38] Jurva, R., Matinmikko-Blue, M., Niemelä, V., Hänninen, T., 2020. Smart Campus 5G and IoT network preparations for operational mode: Specification to deploy data and network management. International Telecommunications Society (ITS)., 14 June 2020.

[39] Lambrecht, J., Steffens, E.J., Geitz, M., Vick, A., Funk, E., Steigerwald, W., 2019. Cognitive Edge for Factory: a Case Study on Campus Networks enabling Smart Intralogistics, in: 2019 24th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA). 2019 24th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), Zaragoza, Spain. 10.09.2019 - 13.09.2019. IEEE, pp. 1325–1328.

[40] Varga, P., Peto, J., Franko, A., Balla, D., Haja, D., Janky, F., Soos, G., Ficzere, D., Maliosz, M., Toka, L., 2020. 5G support for Industrial IoT Applications - Challenges, Solutions, and Research gaps. Sensors (Basel, Switzerland) 20 (3), 1–43.

[41] Fettweis, G., Alamouti, S., 2014. 5G: Personal mobile internet beyond what cellular did to telephony. IEEE Commun. Mag. 52 (2), 140–145.

[42] Malleck, H., Mecklenbräuker, C., 2018. Auf dem Weg zu 5G, der 5. Generation des Mobilfunks. Elektrotech. Inftech. 135 (7), 437–438.

[43] Neumann, A., Wisniewski, L., Ganesan, R.S., Rost, P., Jasperneite, J., 2018. Towards integration of Industrial Ethernet with 5G mobile networks, in: 2018 14th IEEE International Workshop on Factory Communication Systems (WFCS). 2018 14th IEEE International Workshop on Factory Communication Systems (WFCS), Imperia. 13.06.2018 - 15.06.2018. IEEE, pp. 1–4.

[44] Wollschlaeger, M., Sauter, T., Jasperneite, J., 2017. The Future of Industrial Communication: Automation Networks in the Era of the Internet of Things and Industry 4.0. EEE Ind. Electron. Mag. 11 (1), 17–27.

[45] Chang, K.-C., Chu, K.-C., Wang, H.-C., Lin, Y.-C., Pan, J.-S., 2020. Energy Saving Technology of 5G Base Station Based on Internet of Things Collaborative Control. IEEE Access 8 (1), 32935–32946.

[46] Ge, X., Yang, J., Gharavi, H., Sun, Y., 2017. Energy Efficiency Challenges of 5G Small Cell Networks. IEEE Commun. Mag. 55 (5), 184–191.

[47] Hu, R.Q., Qian, Y., 2014. An energy efficient and spectrum efficient wireless heterogeneous network framework for 5G systems. IEEE Commun. Mag. 52 (5), 94–101.

[48] Gundall, M., Schneider, J., Schotten, H.D., Aleksy, M., Schulz, D., Franchi, N., Schwarzenberg, N., Markwart, C., Halfmann, R., Rost, P., Wubben, D., Neumann, A., Dungen, M., Neugebauer, T., Blunk, R., Kus, M., Griebbach, J., 2019. 5G as Enabler for Industrie 4.0 Use Cases: Challenges and Concepts, in: 2019 24th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA). 2019 24th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), Zaragoza, Spain. 10.09.2019 - 13.09.2019. IEEE, pp. 1401–1408.

[49] Lema, M.A., Laya, A., Mahmoodi, T., Cuevas, M., Sachs, J., Markendahl, J., Dohler, M., 2017. Business Case and Technology Analysis for 5G Low Latency Applications. IEEE Access, 1.

[50] Pathak, R., 2020. 5G Core Network Architecture - A Beginners Guide. https://www.rajarshipathak.com/2020/01/beginners-guide-for-5g-core-network-architecture.html. Accessed 1 November 2022.

[51] Aijaz, A., 2020. Private 5G: The Future of Industrial Wireless. http://arxiv.org/pdf/2006.01820v2.

[52] Brown, G., 2019. Private 5G Mobile Networks: A Heavy Reading white paper produced for Qualcomm. Qualcomm. https://theinternetofthings.report/Resources/Whitepapers/6f44de77-8426-48b1-b858-0f8c6fa7b648_private-5g-networks-for-industrial-iot.pdf.

[53] Grotepass, J., Eichinger, J., Voigtländer, F., 2019. Mit 5G zu neuen Potentialen in Produktion und Logistik, in: Hompel, M. ten, Vogel-Heuser, B., Bauernhansl, T. (Eds.), Handbuch Industrie 4.0. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 1–35.

[54] Grotepass, J., Eichinger, J., Voigtländer, F., 2020. Mit 5G zu neuen Potentialen in Produktion und Logistik. Accessed 1 November 2022.

[55] Ordonez-Lucena, J., Folgueira Chavarria, J., Contreras, L.M., Pastor, A., 2019. The use of 5G Non-Public Networks to support Industry 4.0 scenarios, in: 2019 IEEE Conference on Standards for Communications and Networking (CSCN). 2019 IEEE Conference on Standards for Communications and Networking (CSCN) took place 28-30 October 2019 in Granada, Spain. IEEE Conference on Standards for Communications and Networking (CSCN). IEEE, Piscataway, NJ, pp. 1–7.

[56] Ullah, H., Gopalakrishnan Nair, N., Moore, A., Nugent, C., Muschamp, P., Cuevas, M., 2019. 5G Communication: An Overview of Vehicle-to-Everything, Drones, and Healthcare Use-Cases: An Overview of Vehicle-to-Everything, Drones, and Healthcare Use-Cases. IEEE Access 7 (2905347), 37251–37268.

[57] BMWi, 2020. Leitfaden 5G-Campusnetze – Orientierungshilfe für kleine und mittelständische Unternehmen. https://www.bmwi.de/Redaktion/DE/Publikationen/Digitale-Welt/leitfaden-5G-campusnetze-orientierungshilfe-fuer-kleine-und-mittelstaendische-unternehmen.html. Accessed 1 November 2022.

[58] Boban, M., Kousaridas, A., Manolakis, K., Eichinger, J., Xu, W., 2018. Use Cases, Requirements, and Design Considerations for 5G V2X, 10 pp. https://arxiv.org/abs/1712.01754. Accessed 1 November 2022.

[59] Liolis, K., Geurtz, A., Sperber, R., Schulz, D., Watts, S., Poziopoulou, G., Evans, B., Wang, N., Vidal, O., Tiomela Jou, B., Fitch, M., Diaz Sendra, S., Sayyad Khodashenas, P., Chuberre, N., 2019. Use cases and scenarios of 5G integrated satellite-terrestrial networks for enhanced mobile broadband: The SaT5G approach. Int J Satell Commun Network 37 (2), 91–112.

[60] O'Connell, E., Moore, D., Newe, T., 2020. Challenges Associated with Implementing 5G in Manufacturing. Telecom 1 (1), 48–67.

[61] Shafi, M., Molisch, A.F., Smith, P.J., Haustein, T., Zhu, P., Silva, P. de, Tufvesson, F., Benjebbour, A., Wunder, G., 2017. 5G: A Tutorial Overview of Standards, Trials, Challenges, Deployment, and Practice. IEEE J. Select. Areas Commun. 35 (6), 1201–1221.

[62] Bentkus, A., 2019. 5G for Automation in Industry: Primary use cases, functions and service requirements, 32 pp.

[63] Gangakhedkar, S., Cao, H., Ali, A.R., Ganesan, K., Gharba, M., Eichinger, J., 2018. Use Cases, Requirements and Challenges of 5G Communication for Industrial Automation, in: 2018 IEEE International Conference on Communications workshops (ICC workshops). Proceedings : Kansas City, MO, USA, 20-24 May 2018. 2018 IEEE International Conference on Communications Workshops (ICC Workshops), Kansas City, MO, USA. 20.05.2018 - 24.05.2018. IEEE, Piscataway, NJ, pp. 1–6.

[64] Angerer, H., Bahr, M., Bergmann, A., 2020. Leitfaden 5G-Campusnetze: Orientierungshilfe für kleine und mittelständische Unternehmen, 52 pp. https://www.bmwi.de/Redaktion/DE/Publikationen/Digitale-Welt/leitfaden-5G-campusnetze-orientierungshilfe-fuer-kleine-und-mittelstaendische-unternehmen.pdf?__blob=publicationFile&v=10. Accessed 1 November 2022.

Biography

Murtaza Abbas is the head of the Competence Center 5G.NRW at the Institute for Industrial Management (FIR) at RWTH Aachen University. In his work at FIR, he deals with the management of digital technologies. The topic of 5G has now accompanied him since the beginning of his work at FIR in 2019. He holds a Master's degree in Mechanical Engineering from RWTH Aachen University.

Max Ferdinand Stroh is the head of the department information management at the Institute for Industrial Management (FIR) at RWTH Aachen University. Max Ferdinand Stroh studies Mechanical Engineering at RWTH Aachen University. He led the research area for Information Technology Management at FIR since 2020.

Prof. Dr.-Ing. Volker Stich is head of the Institute for Industrial Management (FIR) at the RWTH Aachen University since 1997. Prof. Dr.-Ing. Volker Stich worked 10 years for the St. Gobain-Automotive Group and led the management of European plant logistics. His research focuses on operations management, logistics and business applications systems.

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Sociotechnical Assessment Of Risks In The Use Of Business Analytics

Jonas Müller[1], Gina Hermes[1], Gerrit Hoeborn[1], Volker Stich[1]

[1]Institute for Industrial Management (FIR) at RWTH Aachen University

Abstract

The use of Business Analytics (BA) helps to improve the quality of decisions and reduces reaction latencies, especially in uncertain and volatile market situations. This expectation leads a continuously rising number of companies to make large investments in BA. The successful use of Business Analytics is increasingly becoming a differentiator. At the same time, the use of BA is not trivial, rather, it is subject to high socio-technical requirements. If these are not addressed, high risks arise that stand in the way of successful use. In particular, it is important to consider the risks in relation to the different types of BA in a differentiated way. So far, there is a lack of suitable approaches in the literature to consider these type-specific risks with regard to the socio-technical dimensions: people, technology, and organization. This paper addresses this gap by initially identifying risks in the use of Business Analytics. For this purpose, possible risks are identified using a systematic literature review and verified with a Delphi survey with various partners experienced in dealing with BA. Subsequently, the identified and validated risks are assigned to three different types of Business Analytics (Descriptive, Predictive and Prescriptive Analytics) and assessed in order to systematically address and reduce the risks. The result of this paper is an overview of the interactions between the socio-technically assigned risks, summarized in a risk catalog, and the different types of Business Analytics.

Keywords

Sociotechnical; Risks; Risk assessment; Business Analytics; Types

1. Introduction

Continuously changing market conditions, the exponential advancement of digital technologies and the profound change in customer requirements demand high adaptability and the making of well-founded decisions with minimal reaction latencies [1-3]. To meet these developments, companies are using data-based information and decision systems with advanced statistical methods and functions (analytics), which are summarized under the name of Business Analytics (BA) [4]. The use of BA supports companies in formulating and achieving strategic, tactical, and operational goals and contributes significantly to data-driven decision-making [5]. The almost unlimited possibilities induce a paradigm shift for global competition and enable maintaining long-term competitiveness [6,7].

The expectation has been a major contributor to the continuous increase in investment for several years, with an annual average growth rate estimated at 14 percent for 2027 [8]. Despite the high expected potential, many companies face major challenges which are induced by the deployment of complex systems and technologies that have a great impact on the organization and its employees. In this context, various organizational, technical, and human risks arise, which overwhelm the companies [9]. This is reflected in a high introduction and implementation failure rate of 65 to 80 percent [3]. To address the high failure rate, it is essential to identify, assess and reduce risks in the use of BA. For this purpose, capabilities must be

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developed in the companies to address the risks and to ensure the successful use of new technologies [10,11]. To achieve this goal, this paper identifies type-specific risks in the use of BA and examines their socio-technical interactions. Thus, an overview of the interactions between the socio-technical assigned risks, summarized in a risk catalog, and the different types of BA can be given.

The remainder of the paper is organized as follows. In section 2, the relevant theoretical background is provided. The state of the art is elaborated on in section 3. The research methodology and the study design are explained in section 4. In section 5, the results of the paper, the risk catalog, and the type-specific relationship matrix are discussed. A conclusion is provided in section 6.

2. Theoretical Background

2.1 Business Analytics

As both information systems and enabling technologies have matured, the prevalence and use of these in enterprises have increased dramatically. The cause and result of this development is the ability to generate and store an exponentially increasing amount of data, which has found use under the umbrella term "Big Data" [1]. The great diversity of application and maturity is reflected in the types Descriptive, Predictive, and Prescriptive Analytics. In this paper, the conceptual understanding, description, and typification are based on [12]. They characterize BA by nine characteristics with a total of 29 features in a morphological box. On this basis, three consistent types are formed and validated [12]. In this understanding, BA as a capability can be defined as follows: "application of 'various techniques, technologies, systems, practices, methodologies, and applications that analyze critical business data' [...] to enable evidence-based problem-solving and recognition within the context of business situations [...]" [13].

2.2 MTO concept

The socio-technical systems approach was developed in the 1950s by [14]. Working in a British mine, it was found that a technological change had a significant impact on the social system [14]. A concept developed by [15] within the framework of socio-technical systems is the MTO concept. It is based on the interaction between the employees, the technical systems, and the organizational structures and processes. The central point of this concept is the work task [15]. The benefits gained by a company using BA depend in particular on the ability to use data and information effectively; the interaction between people, technology, and organization is of fundamental importance in this respect [16]. The design of the successful use of BA can thus be classified in the MTO concept [17].

2.3 Risk

Companies must take risks to seize opportunities [18]. Therefore, responsible handling of these risks must be ensured by successful risk management [19]. To this end, a uniform understanding of risk must first be created. In this paper, the risk is defined as [20] “any possible deviation from a planned state, which must be considered in terms of its cause and effect”. In this context, risk in the narrower sense, the danger of losses, and risk in the broader sense, the chance of winning, is considered [21]. In the context of the objective of this study, this means that only those risks are considered that stand in the way of the successful use of BA. Deviations that have a positive effect on the objective are thus not in focus. Risk management in companies includes all organizational processes that allow the risk management process to run [22]. Based on the risk strategy, this process consists of risk identification, risk analysis and assessment, risk control and risk monitoring, and risk communication [20-23]. Regarding operational information systems and IT security, the content of the risk management process must be adapted to the topic area [20,24]. To this end, starting from the corporate strategy, the objective of IT risk management, including the risk objects and their interactions, is first defined [20].

3. State of the Art

To summarize the state of the art, a Systematic Literature Review (SLR) is conducted. For this, the process by [25] is used. The following search strings were used in the literature review: “Business Analytics”, “Business Intelligence”, and “Big Data Analytics”. These were considered in combination with the terms “risk”, “introduction” and/or “implementation”. Additionally, related terms such as “success factors” and “utilization” were considered. IT security frameworks are considered, but are not the focus of this study, as they take less account of the socio-technical contexts in the use of BA. Based on the combinations of the different search terms, 732 publications were found using Google Scholar, IEEE Explore, and Scopus. The publications found were selected to be relevant based on the title, abstract, and a subsequent reading of the full texts. As a result, the following eleven sources were identified: [3,10,26-34].

The sources found were then analyzed based on the fulfillment of four criteria. The criteria were formed based on the objective of this work. The first two criteria represent, to what extent BA-related risks in the narrower and broader sense are considered and how they are located in the socio-technical system theory. The other criteria reflect whether the models from the literature were developed in a specific context or if they can be applied in general. The degree of fulfillment is evaluated on a 5-level scale. These five levels are “not considered”, “marginally considered”, “partially considered”, “explicitly considered”, and “focus of consideration”. None of the analyzed sources fully consider all aspects. The analysis is not an evaluation of the quality of the publications, but rather a consideration of the fulfillment of the individual criteria. The result of the analysis is shown in Figure 1.

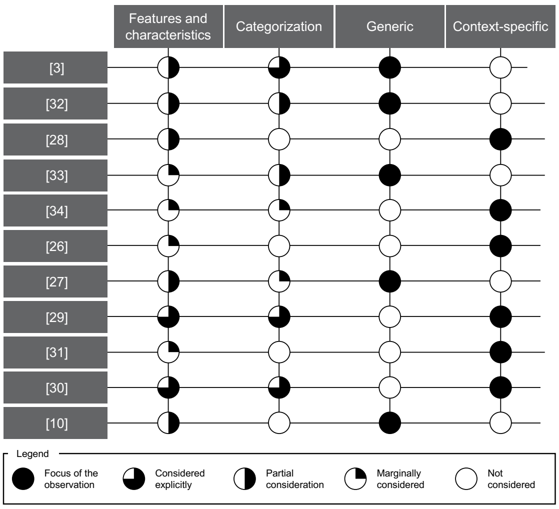

Figure 1: Overview of investigated literature

4. Research Methodology

The Delphi method is an explanatory tool for obtaining a consensus opinion on a topic using interviewing experts. The basic assumption is that the validity of the consensus is higher than that of a single opinion [35]. A central aspect of this method is the multi-stage questioning of experts to gather information on a specific topic [36,37]. The Delphi method begins with the selection of experts, followed by individual rounds of questioning, and finally the analysis of the results [37,38]. Depending on the goal of this method, four different designs can be typified, which are distinguished by seven criteria [38]. In this paper, the design of the Delphi survey is used for idea generation in a qualitative design. The special characteristic of this design is not the consensus of several opinions, but the goal to find a set of ideas for a certain problem solution [38]. In this research, the survey was modified by replacing the initial qualitative survey with a literature review (see chapter 3). The results of the literature review were then presented to the participants as the results of the first round of interviews. The experts could then reflect and contribute additional ideas in the second round of interviews. The second round of questioning was conducted using a workshop and several interviews. A standardized topic-specific dashboard was used as a tool for the survey. After the second round of questioning, the results were collected for the objective of this work and integrated into existing models. A total of seven experts were involved in a workshop and interviews from September to October. All participants were experienced in the use of BA.

5. Results

5.1 Risk catalog

Based on the literature review in chapter 3, 30 different risks related to the use of BA could be identified. With the Delphi survey, all risks could be confirmed. One risk was added during the interviews and was additionally approved in the literature. Thus, 31 socio-technical risks in the use of BA can be summarized in a risk catalog. In the following, the risks are assigned to the three socio-technical dimensions of people, technology, and organization and explained in detail. The result of this step is a risk catalog, see Figure 2.

5.1.1 People

The first dimension to be considered is people. In this dimension, a distinction is made between the risks associated with the *competence of the employees* and the risks associated with *acceptance by the employees*. The first category includes the risk of inadequate employee training and education and low IT skills [3,10,30,32]. If employees are not sufficiently familiar with BA methods or do not have the skills to analyze data correctly, the included data may be insufficient or even incorrect [30]. In addition to this, there is the risk that a user without sufficient experience cannot critically scrutinize the results obtained and does not recognize possible wrong decisions [32]. *Employee acceptance* is divided into possible employee resistance to culture change, the risk of job loss, the risk of lack of team commitment and involvement in BA methods, the risk of change in employees' previous tasks, and employee unwillingness to accept change [10,28,30,33]. The aforementioned risks of *acceptance by employees* are either induced by them or result in them. People often find it difficult to accept innovations, so they would often be against a change in an existing system [30]. In addition, for the successful implementation of BA, certain roles need to be represented by a team, which can change the responsibilities of employees [33]. The permanent risk of job loss for example prevents employees from being open to a possible change, so they may be able to prevent it [30]. In addition to these aspects, as a consequence of low *acceptance by the employee*, the risk of lack of commitment and involvement by the team must be considered. In addition to resistance to a potential culture change, the risk of negative employee attitudes towards change should also be considered in general. This can prevent the decision to use a particular tool even before it is introduced [10].

5.1.2 Technology

The second socio-technical dimension is technology. The risks in this dimension are subdivided into risks that can be assigned to *information technology (IT)* and the risks that affect the *data* as the starting point for the BA application. Concerning the risks of *information technology*, it must be taken into account that, in addition to the risks directly affecting the integration of new systems, general risks can also occur when using IT systems. Thus, it must be ensured that the systemic conditions are sufficient for the use of BA and, at the same time, security risks are taken into account [3,28,31]. This means that integration complexity and technical uncertainties must be mitigated by the infrastructure. In addition, scalability risks must be considered [10,30,34]. If a system is not sized large enough for data collection, it may not be able to collect all relevant data [30]. Finally, it must be considered that innovative methods can lead to risks if they are not sufficiently tested [26]. Therefore, the *IT* risk category consists of the risks of integration complexity, technical uncertainties, scalability risks, IT security due to data protection issues and cyber-attacks, and insufficient IT infrastructure and innovative methods [3,10,26–34]. The risk characteristics of the *data* category are the data source, data quality, and data storage [3,27–30,32–34]. These must be taken into account right from the start of the implementation process [29]. If a risk event occurs in these aspects and, for example, the data quality requirements are not met, effective decision-making may be significantly influenced [32]. The risk concerning the data source and data storage is assumed by the respective medium used. This means that successful implementation is fraught with risk if different media are used, especially media that are not easily compatible [33,29,30].

5.1.3 Organization

The last dimension considered is organization. Risks found here can be divided into the category of *financial* risks and *internal* risks. *Financial* risks can also prevent the implementation of BA, for example, due to the lack of an appropriate budget or the deterrent effect of long payback periods with uncertain returns [10,30]. Another financial aspect that adds some risk to the use of BA is the fact that there are costs that exist only during the application and cannot be estimated beforehand [10]. These hidden costs, when they occur, are an aspect that poses a risk in the use of BA. Thus, the category of financial risks includes large investments in software and hardware, long and uncertain payback periods as well as uncertainty about involved costs [10,30]. The risk characteristics of *internal* risks are insufficient resources, reassignment of employees, quality of business requirements especially the definition of BA deployment objectives, no alignment with business strategy, change management, and regulatory and security changes [3,10,27,29,30,32,33]. In addition to the resources provided by the organization, the general structures also influence the application of BA. For example, a company's change management should be transparent, accountable, and communicated accordingly to avoid concerns about the new technology [3,29]. In addition to this, the reassignment of employees must be done expeditiously, because delays in this organizational task can also be a risk for the integration of BA [30]. Another important aspect is the targeted design of the BA project about the business requirements and the strategy. These two points are important as they directly influence the BA process [3,29,32]. In addition to these two points, regulatory and security standards must also be considered. If such a norm changes, the corresponding tool must also be modified. However, this has for example the consequence, that flexible changes are no longer possible [29]. In addition to this, risks such as the lack of BA application use, insufficient top management support, and no existing knowledge management structure and organizational learning must be considered [3,27,29, 32]. If BA applications are not used sufficiently, the full business potential cannot be exploited [29]. As a result, future investments in BA will be reduced. Another important risk is the lack of top management support. If the relevance of a process is not clearly communicated and the corporate culture is not positively influenced in this direction, the project may fail [3,27,29]. The knowledge management structure and organizational learning are important success factors for the implementation of BA. They are largely responsible for the acquisition and storage of knowledge and thus have a direct impact on the internal data available to BA methods [3]. Lastly, a lack of continuous risk monitoring, static project management, and negative experience with previous IT projects must be considered as risks [3,30,32]. Continuous risk monitoring must be performed to not only be aware of the risks that might arise but also to keep track of them [3]. A lack to identify or address a risk can lead to project failure [21]. It is also important that the project management can react in an agile manner to different situations, otherwise, it hinders the adaptation [32]. Another risk is about the experience with regard to past IT projects. In particular, failed IT projects can lead to the use of a new technology being hindered [30].

socio-technical dimension	risk category	risk characteristic	Descriptive Analytics	Predictive Analytics	Prescriptive Analytics
people	competence of the employees	inadequate employee training and education [3, 30, 32]	-	+	++
		low IT skills [10, 30, 32]	-	+	++
	acceptance by the employees	employee resistande to culture change [30]	-	+	++
		change in employees' previous tasks [28, 30, 33]	-	-	+
		risk of job loss [30]	-	-	+
		lack of team commitment and involvement [30]	+	++	++
		unwillingness to accept change [10, 30]	+	+	++
technology	information technology (IT)	integration complexity [10, 28, 32, 33, 34]	+	+	++
		technical uncertainties [10, 30, 33]	+	+	++
		scalability risks [30]	+	+	+
		IT-security - data protection issues and cyber-attacks [10, 26, 28, 30, 31, 32]	+	++	++
		insufficient IT-infrastructure [3, 10, 27, 28, 29, 30, 31, 32, 33]	-	+	++
		innovative methods [26]	-	+	++
	data	data quality [3, 27, 28, 29, 30, 32, 33, 34]	+	++	++
		data source [29, 30, 33]	+	++	++
		data storage [30]	+	++	++
organization	financial	large investments for software and hardware [30]	-	+	++
		long and uncertain payback periods [10, 30]	-	-	-
		uncertainty about involved costs [10]	-	+	++
	internal	insufficient ressources [3, 29, 30, 33]	+	++	++
		reassignment of employees [10, 30, 33]	+	++	++
		quality of business requirements - definition of BA deployment objectives [29]	+	+	+
		no alignment with business strategy [3, 27, 32]	-	-	+
		change management [3, 29]	+	+	+
		regulatory and security changes [29]	-	-	-
		lack of BA application use [29]	-	+	++
		insufficient top management support [3, 27, 31, 32]	-	+	+
		no existing knowledge management structure and organizational learning [3]	+	+	++
		continuous risk monitoring [3]	-	+	+
		static project management [3, 32]	-	-	+
		negative experience with previous IT projects [33]	-	+	+

Figure 2: risk catalog including relationship matrix

5.2 Relationship matrix

The objective of this study is to identify the link between the socio-technically addressed risks and the different types of BA. For this purpose, the risks are compared with the different BA types against the background of the typification according to [12] to determine the correlation. The comparison is based on the identified risks in the literature and was confirmed by the experts of the Delphi survey. If there is no significant risk between a risk characteristic and the aspects of the BA type, it is characterized by a "-". However, if there is a medium risk, a "+" is used. High risks can be described with a "++". Based on this assessment, a total of 52 interactions could be identified. This corresponds to 55,91 percent significant interactions. As a result, the most important socio-technical risks for the individual BA types can be derived from Figure 2.

5.2.1 Descriptive Analytics

The least mature type of BA is Descriptive Analytics. This is also reflected in the characteristics of the risk assessment, in that the fewest significant risks can be assigned here. Aggregated with the risk category level, only *Information Technology* is affected by risks to a significant extent. This is induced by the risk of integration complexity, technical uncertainties, and scalability risks. The evaluation is induced by the value proposition and the analysis methodology as typification aspects. If the integration is particularly complex or the system is not sufficiently scaled, it may result in an insufficient consideration of the cause-effect relationships and thus the goal of descriptive analytics may be missed. Concerning the analysis methodology, the risk of technical uncertainties must also be taken into account. If a company does not have the technology to enable data visualization or statistical analyses, the use of BA will fail. However, at the level of risk characteristics, in addition to *information technology* risks, *internal* organizational risks can also occur in Descriptive Analytics. They include the risk of insufficient resources, the quality of business requirements, and the lack of structure for knowledge management and organizational learning. These risks relate to the direct input parameters of the BA technology, such as the type and structure of the data and, as a further aspect, the analysis methodology. If the respective risk case occurs, it becomes difficult, for example, to provide purely static and structured data. These are mandatory, as Descriptive Analytics methods cannot handle higher complexities. The analytics methodology must also be adapted to the objectives of the BA deployment to provide added value.

5.2.2 Predictive Analytics

The use of Predictive Analytics induces an increase in risks. A relationship can be found between each risk category, except for *employee acceptance*, and the BA type. In contrast to Descriptive Analytics, this BA type is more susceptible to risks due to *employee competence*. This is mainly induced by the comprehensibility of the results of the BA method and the analysis methodology. The results of this BA type are often only partially comprehensible, so employees who are not sufficiently trained have additional problems interpreting them correctly. The analysis methodology, such as data mining, also requires a certain level of IT knowledge for successful application. If an employee cannot use this knowledge, the application is in danger of failing. The increasing complexity or maturity of this BA type is reflected in many aspects of its technical system. In addition to the more complex analysis methods, a larger amount of data is also required, and semi-structured data can be used in addition to structured data. Accordingly, this type is also more susceptible to the risks from the socio-technical dimension of technology. It is noticeable that the socio-technical dimension of technology has a medium risk for the BA type in eight out of nine risks. Another peculiarity at the level of risk characteristics is the link between the risk of insufficient resources and the BA type, this was assessed as high risk and should accordingly be taken into account by the company. Analogous to the type Descriptive Analytics, the risk concerns the input parameters of the BA method. The increase in the number and strength of the risks is justified by the fact that the complexity of the methods and the requirements for the IT infrastructure are increasing. In addition to this, it should be noted that other risk characteristics of the organization may have a greater impact on this type.

5.2.3 Prescriptive Analytics

The last BA type studied is Prescriptive Analytics. It has the most and highest socio-technical risks. In total, 28 out of 31 risks are to be considered for this type. Half of the risk categories were identified as medium risk and the other half as high risk. All risks related to people need to be considered. Due to the type-specific characteristics of the BA method's task, such as automated decision-making or proactive information processing, its previous functions, and future tasks are significantly influenced. This means that the risks may increase, for example, due to the acceptance of the employees and disrupt the successful use. The characteristics of *information technology* and *data* must also be fully considered. Seven out of nine risk characteristics are classified as a high risk for the BA type. As with Predictive Analytics, this can be justified by the higher complexity of this BA type. This is not only caused by the more complex technological aspects, but also by the mature task-specific characteristics, for example, automated decision-making. The socio-technical aspect of the organization has the missing three risk characteristics, these are long and uncertain payback period, change management, as well as regulatory and security change. For these three risks, interactions with individual characteristic features can be considered, but the overall BA type is not sufficiently influenced. For a decision-maker, this means that he does not necessarily have to focus on these aspects when implementing BA. High risk is caused by the characteristics of large investment costs in software and hardware, uncertainty about involved costs, insufficient resources, lack of use of BA applications, and lack of structure for knowledge management and organizational learning. Similar to the remaining risks, these are assessed with a higher risk for Prescriptive Analytics, due to the more extensive task-specific and technological aspects.

6. Conclusion and Outlook

The categorization of risks and the investigation of their interaction can be presented as the result of this paper. Six different risk categories with a total of 31 different risk characteristics were identified in the three socio-technical dimensions. From the various interactions, it becomes apparent which socio-technical dimensions cause risks in the individual types. Best to our knowledge, this is the first overview in research of the socio-technical risks that arise from the use of BA. Overall, it can be concluded that more risks need to be considered the higher the maturity level of the Business Analytics type. In the case of Descriptive Analytics, few risks need to be taken into account; only the risk category of information technology contains a medium risk. These need to be given special consideration. In comparison, in the case of Predictive Analytics, almost all risk categories can induce a medium risk. A special focus should be placed here on the entire socio-technical dimension of technology. The third BA type, Prescriptive Analytics, has the highest risk interference. Accordingly, a comprehensive risk overview and a prior situation analysis should be performed for a successful implementation. In the future, it makes sense to develop possible risk avoidance strategies and make these available to companies.

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References

[1] Aydiner, A.S., Tatoglu, E., Bayraktar, E., Zaim, S., Delen, D., 2019. Business analytics and firm performance: The mediating role of business process performance. Journal of Business Research 96, 228–237.

[2] Duan, Y., Cao, G., Edwards, J.S., 2020. Understanding the impact of business analytics on innovation. European Journal of Operational Research 281 (3), 673–686.

[3] Müller, J., Schuh, G., Meichsner, D., Gudergan, G., 2020. Success factors for implementing Business Analytics in small and medium enterprises in the food industry, in: 2020 IEEE International Conference on Technology Management, Operations, and Decisions (ICTMOD), Marrakech, Morocco. 24.11.2020 - 27.11.2020. IEEE, pp. 1–8.

[4] Bayrak, T., 2015. A Review of Business Analytics: A Business Enabler or Another Passing Fad. Procedia - Social and Behavioral Sciences 195, 230–239.

[5] Ferraris, A., Mazzoleni, A., Devalle, A., Couturier, J., 2018. Big data analytics capabilities and knowledge management: impact on firm performance. MD 57 (8), 1923–1936.

[6] Arora, B., 2019. Big Data Analytics: The Underlying Technologies Used by Organizations for Value Generation, in: Chahal, H., Jyoti, J., Wirtz, J. (Eds.), Understanding the Role of Business Analytics. Springer Singapore, Singapore, 9-30.

[7] Seddon, P.B., Constantinidis, D., Tamm, T., Dod, H., 2017. How does business analytics contribute to business value? Info Systems J 27 (3), 237–269.

[8] Albertson, M., 2018. Software, not hardware, will catapult big data into a $103B business by 2027. https://siliconangle.com/2018/03/09/big-data-market-hit-103b-2027-services-key-say-analysts-bigdatasv/.

[9] Menzefricke, J.S., Wiederkehr, I., Koldewey, C., Dumitrescu, R., 2021. Socio-technical risk management in the age of digital transformation -identification and analysis of existing approaches. Procedia CIRP 100, 708–713.

[10] Raguseo, E., 2018. Big data technologies: An empirical investigation on their adoption, benefits, and risks for companies. International Journal of Information Management 38 (1), 187–195.

[11] Willcocks, L., Graeser, V., 2001. Delivering IT and eBusiness Value, 1. Aufl. ed. Elsevier professional, s.l., 320 pp.

[12] Müller, J., Schuh, G., Nahr, B., Hoeborn, G., Stich, V., 2023. Understanding Business Analytics: Characteristics and Archetypes. ICTMOD 2022 – in publication

[13] Ashrafi, A., Zare Ravasan, A., Trkman, P., Afshari, S., 2019. The role of business analytics capabilities in bolstering firms' agility and performance. International Journal of Information Management 47 (0), 1–15.

[14] Trist, E.L., Bamforth, K.W., 1951. Some Social and Psychological Consequences of the Longwall Method of Coal-Getting. Human Relations 4 (1), 3–38.

[15] Ulich, E., 2013. Arbeitssysteme als Soziotechnische Systeme - eine Erinnerung. Journal Psychologie des Alltagshandelns / Psychology of Everyday Activity (6).

[16] Schuh, G., Anderl, R., Dumtrescu, R., Krüger, A., Hompel, M. ten, 2020. Industrie 4.0 Maturity Index: Die digitale Transformation von Unternehmen gestalten. Update 2020, München.

[17] Mikalef, P., van de Wetering, R., Krogstie, J., 2019. From Big Data Analytics to Dynamic Capabilities: The Effect of Organizational Inertia.

[18] Königs, H.-P., 2013. IT-Risikomanagement mit System: Praxisorientiertes Management von Informationssicherheits- und IT-Risiken, 4. Aufl. ed. Springer Vieweg, Wiesbaden, 454 pp.

[19] Mahnke, A., Rohlfs, T., 2020. Betriebliches Risikomanagement und Industrieversicherung. Springer Fachmedien Wiesbaden, Wiesbaden, 745 pp.

[20] Romeike, F., Hager, P., 2020. Erfolgsfaktor Risiko-Management 4.0. Springer Fachmedien Wiesbaden, Wiesbaden, 657 pp.

[21] Seidel, M., 2011. Grundlagen und Aufbau eines Risikomanagementsystems, in: Risikomanagement und Risiko-Controlling. Organisation und Dokumentation im Unternehmen, Datenerhebung und Risikobewertung, Integration in die Führungs- und Reportingsysteme, Umsetzungsbeispiele aus der Praxis, 1. Aufl. ed. Haufe Verlag, s.l., pp. 21–50.

[22] Vanini, U. von, 2022. Risikocontrolling in der Unternehmenspraxis, in: Becker, W., Ulrich, P. (Eds.), Handbuch Controlling. Springer Fachmedien Wiesbaden, Wiesbaden, pp. 271–288.

[23] Spille, J., 2009. Typspezifisches Risikomanagemnt für die Beschaffung von Produktionsmaterialien in der Automobilzulieferindustrie, 135 pp.

[24] Adelmeyer, M., Petrick, C., Teuteberg, F., 2018. IT-Risikomanagement von Cloud-Services in kritischen Infrastrukturen: HMD Best Paper Award 2017. Springer Vieweg, Wiesbaden, Heidelberg, 38 pp.

[25] Vom Brocke, J., Simons, A., Niehaves, B., Niehaves, B., Reimer, K., Plattfaut, R., Cleven, A., 2009. Reconstructing the Giant: On the Importance of Rigour in Documenting the Literature Search Process, in: Information systems in a globalising world. ECIS 2009, 17th European Conference on Information Systems, Verona, May 08 - 10 June, 2009; proceedings, Verona.

[26] Baars, H., Kemper, H.-G., 2021. Business Intelligence & Analytics – Grundlagen und praktische Anwendungen. Springer Fachmedien Wiesbaden, Wiesbaden, 459 pp.

[27] Cruz-Jesus, F., Oliveira, T., Naranjo, M., 2018. Understanding the Adoption of Business Analytics and Intelligence, in: Rocha, Á., Adeli, H., Reis, L.P., Costanzo, S. (Eds.), Trends and advances in information systems and technologies. Volume 1. Springer International Publishing, Cham, pp. 1094–1103.

[28] Fischer, T.M., Lueg, K.-E., Steuernagel, M., Mauch-Maier, B., Hofbeck, D., Schneck, L., 2020. Business Analytics in Shared Service Organisationen, in: Fischer, T.M., Lueg, K.-E. (Eds.), Erfolgreiche Digitale Transformation von Shared Services. Springer Fachmedien Wiesbaden, Wiesbaden, pp. 147–187.

[29] Gangotra, A., Shankar, R., 2016. Strategies in managing risks in the adoption of business analytics practices. Journal of Enterprise Information Management 29 (3), 374–399.

[30] Kusi-Sarpong, S., Orji, I.J., Gupta, H., Kunc, M., 2021. Risks associated with the implementation of big data analytics in sustainable supply chains. Omega 105, 102502.

[31] Min, H., Joo, H.-Y., Choi, S.-B., 2021. Success Factors Affecting the Intention to Use Business Analytics: An Empirical Study. Journal of Business Analytics 4 (2), 77–90.

[32] Pabinger, D., Mayr, S., 2019. Controlling und Business Intelligence & Analytics, in: Feldbauer-Durstmüller, B., Mayr, S. (Eds.), Controlling - Aktuelle Entwicklungen und Herausforderungen. Digitalisierung, Nachhaltigkeit und Spezialaspekte. Springer Gabler, Wiesbaden, Heidelberg, pp. 83–106.

[33] Seiter, M., 2017. Business Analytics: Effektive Nutzung fortschrittlicher Algorithmen in der Unternehmenssteuerung, [1. Auflage] ed. Verlag Franz Vahlen, München, VIII, 233 Seiten.

[34] Woratschek, H., Borgdorf, U., Dornbusch, D., Finken, T., Große, C., Haefs, R., Knocke, H., Stopa, P., Vollmer, M., Wilhelm, J.B., Schneck, L., 2020. Implementierung digitaler Prozesse, in: Fischer, T.M., Lueg, K.-E. (Eds.), Erfolgreiche Digitale Transformation von Shared Services. Springer Fachmedien Wiesbaden, Wiesbaden, pp. 19–47.

[35] Köck-Hódi, S., Mayer, H., 2013. Die Delphi-Methode. ProCare 18 (5), 16–20.

[36] Burkhard, U., Schecker, H., 2013. Curriculare Delphi-Studien, in: Krüger, D., Parchmann, I., Schecker, H. (Eds.), Methoden in der naturwissenschaftsdidaktischen Forschung. Springer Berlin Heidelberg, Berlin, Heidelberg.

[37] Demeter, P., 2015. Near Field Communication im Handel: Expertenbefragung mittels Delphi-Methode. HMD 52 (2), 240–248.

[38] Häder, M., 2021. Delphi-Analyse, in: Zerres, C. (Ed.), Handbuch Marketing-Controlling. Grundlagen, Methoden, Umsetzung, 5., erweiterte und überarbeitete Auflage ed. Springer Gabler, Berlin, Heidelberg.

Biography

Jonas Müller, M. Sc., has been a research associate and project manager at FIR e. V. at RWTH Aachen University since 2018. There, he is working in the topic area of business transformation on the strategies, phenomena, capabilities, processes, and methods of transforming companies in the digitally networked economy. A particular focus is on the socio-technical design of the use of Business Analytics.

Gina Hermes, B. Sc, has been a student of industrial engineering specializing in mechanical engineering at RWTH Aachen University since 2016. She completed the corresponding bachelor's degree program in 2021 and is now writing her master's thesis at FIR e. V.. The focus of her work is on the investigation of Business Analytics-related risks.

Gerrit Hoeborn, M. Sc. M. Sc., is head of the business transformation department at RWTH Aachen University. He joined the department after his studies in industrial engineering at the RWTH Aachen University and Tsinghua University. His research focus is on business transformation and digital business strategies.

Prof. Dr. -Ing. Volker Stich is head of the Institute for Industrial Management (FIR) at the RWTH Aachen University since 1997. Prof. Dr. -Ing. Volker Stich worked for the St. Gobain Automotive Group for 10 years and led the management of European plant logistics. In addition, he was responsible for the worldwide coordination of vehicle development projects.

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Review and Development Of Revenue Models For A Co-Creation Platform In The Furniture Sector

Regina Schrank[1], Günther Schuh[1], Daniel Wentzel[2], Lennard Holst[1]

[1] *Institute for Industrial Management (FIR) at RWTH Aachen University, Aachen, Germany*

[2]*Chair of Marketing, RWTH Aachen University, Aachen, Germany*

Abstract

Pricing is one of the most important, but underestimated tool, to enhance a company's profitability. Especially in the furniture sector, customers place a special interest in cost-efficient products and easy processes. Individualised and sustainable furniture can help to create a unique selling point and deliver real value to the customers. Therefore, a platform to create designs together is needed and can involve several stakeholders in the design and production phase. However, in order to include several stakeholders, the pricing and revenue model need to reflect individual needs and be a benefit to all. In this paper, the initial situation and potential revenue model options will be presented. Furthermore, multiple scenarios for practical use will be discovered and an overview given.

Keywords

Revenue models, pricing; value-based pricing; co-creation; platform; do-it-together

1. Introduction

Nowadays, the furniture industry mass-produces low-cost furniture, where the products are characterized primarily by short life and low quality [1]. High competition is pushing smaller companies out of the market and aspects of product individualization to meet different living spaces and lifestyle requirements are increasingly taking a back seat. If the desire for an individualized, innovative, and sustainable piece of furniture arises, there are currently various suppliers, but they often do not meet all criteria and have long delivery times, high prices and low customer involvement [2]. Therefore, there is a need for a platform where customized, innovative, and sustainable furniture is produced and traded at a fair price. According to the "do-it-together" approach [3], a business ecosystem must be created that creates added value not only for customers, but also for designers, suppliers, and manufacturing companies. This new form of collaboration also requires rethinking potential revenue models and creating incentives for sharing the platform. The goal is to ensure the strategic fit of platform users and suitable revenue models and to optimize the use of the platform for all. Therefore, different revenue model types must be evaluated regarding their entry barriers, revenue potential, customer loyalty, and transparency. In principle, it is possible to offer different models for different stakeholders to ensure the strategic fit and enable the use of the platform.

To identify the best revenue models three steps are undertaken. First, an extensive literature research is conducted to analyse several types of revenue models. These can be categorized into freemium, subscription-based and revenue-based [4]. Subsequently matching case studies for each of the models are identified and a practical example for each of the different revenue models is examined in more detail. Furthermore, it is analysed how the respective revenue model can be implemented. Lastly, an expert workshop is conducted,

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presenting the results of the case analysis, and assessing advantages and disadvantages of the models. As a result, the best possible revenue models for general public, designers and manufacturers are identified.

2. Theoretical background

2.1 Revenue Models

The desk research has shown that there are three main revenue models for platforms, which can be further divided into different models. The main models are free/freemium, subscription-based, and revenue-based and have distinctive characteristics and sub models (Figure 1).

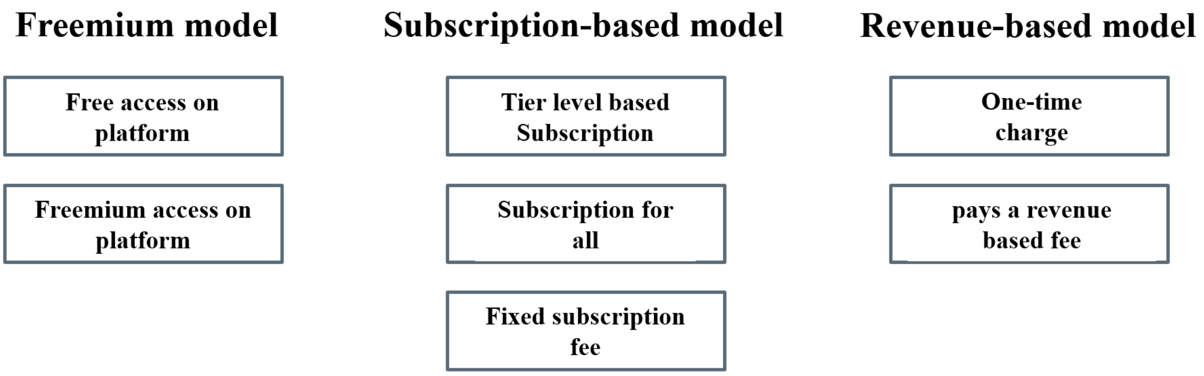

Figure 1: Main revenue models for platforms

The first revenue model is the freemium model. This model is based on free and paid access. Customers can access the basic product for free and must pay a monthly or yearly fee for the extended product. The pricing is based on availability and is usually a flat rate. In this model, the inclusion of social features is very important, as they influence the willingness to pay for premium content and thus have a strong impact on customers [5]. That means, the number of users or amount of blog entries are important attributes [6]. Furthermore, users who are more active in the community are also more willing to subscribe [7]. Therefore, there should definitely be social features or at least the possibility to integrate social media, as this leads to the product being spread and new markets being opened up [5]. However too many free offerings eliminate the incentive for users to upgrade to the paid version [7]. *Free users* should be valued highly as they provide feedback on the usability of the product and features, as well as advertise for free [8]. Research shows that freemium models fail when a low value is placed on *free users*. Other aspects that are crucial to the success of the freemium model are product bundling and cooperation with powerful and proven market players [5]. This is used to further drive awareness and distribution of the products.

Secondly, the subscription-based model is analysed with a focus on the shift towards an ad-sponsored model. In the subscription-based model, customers must commit to a paid subscription to access content on the platform, because the platform is financed by these fees [9]. The advertising-based model works slightly differently. Customers can access the platform free of charge, but other companies and brands place advertisements on the platform and pay the platform operator for this. As a customer, you pay indirectly for the platform by viewing the advertisements and possibly being encouraged to buy the products [10]. By changing between these revenue models, it is possible to influence life cycle revenues. For example, switching from a subscription-based to an ad-based model maximises life cycle revenue under certain market conditions. Shifting in the other direction is less effective. It is a challenge to convince customers who have free access to the platform in the ad-based model to switch to a subscription-based model. The right incentive must be created, as a subscription-based model has high entry barriers due to the obligation to pay. When changing the business model to maximise the life cycle revenue, direction and proactive planning are crucial, because the optimal pricing tactic differs across strategies [11].

Finally, the revenue-based model is examined. In this model, the platform operator works with independent sellers on their platform and receives a percentage of the realised revenues [12]. It is quite common that the platform operator sells high-runner items and collaborates with independent sellers on niche products due to low volumes and high fixed costs. However, this results in sellers trying to disguise high demand by minimising service to reduce early, high sales. Customer reviews can help platform owners to get to know the true level of demand. Furthermore, customer reviews counteract poor service, which is detrimental to the platform's reputation. The platform operator must set a fee, depending on the type of the manufacturer. Additionally, they try to anticipate whether a manufacturer hides its high demand when setting the level of fees. So, if there is a low probability, that the seller's sales are high then the platform operator should charge a low fee. Low fees also mean that manufacturers with all demand types can access the platform, thus increasing the platform's reach [13].

3. Research method

The case study analysis [14] identified different revenue models that are in use that serve to integrate the respective stakeholders (Table 1). In this research the focus lies on general public, designers, and manufacturers, because they are an integral part of the value creation. Platform providers are not further considered, because their role within the co-creation platform is yet to be determined.

Table 1: Overview of revenue models in-use

	General public	Designers	Manufacturers
Free/Freemium Model	eBay, Vinted Pinterest, rebuy, momox, quirky Spotify, amazon, Joyn	Behance, Faberin Freelance.de, workingnotworking, Canva, dribble	Hero, blauarbeit, wirsindhandwerk
Subscription-based Model		Peopleperhour AIGA, kimp	shopify, Handwerker-in
Revenue-based model		fiverr, DesignCrowd, Etsy, upwork	Cratejoy, MyHammer, yo!kart

For the general public, platforms with free access and freemium access are analysed. Subscription and revenue-based models are not further considered, because they require a payment, and it is intended to keep the barriers low for the general public. A very well-known platform with free access for its customers is Pinterest. Pinterest is an online pinboard where customers can share photos or graphics. The main characteristics are the free use and creation of accounts on the platforms [15]. Therefore, the entry barriers for this type of platform are low. However, for a customer there is no possibility to distinguish oneself from other customers since every customer gets the same offer. Mostly, the platform is financed through advertisements, as no direct income can be generated through the customers. The freemium model is a mixture of freely accessible content and premium content for which the general public must pay. A well-known case for this is amazon. Amazon can be used either as Basic access or Premium access [16]. With Basic access, the platform can be used free of charge, but postage costs are charged for orders. Premium access eliminates the postage costs and gives access to additional services such as films or music. However, there is an annual subscription fee. Subscription payments are made monthly or annual. Often, certain social groups, such as students, receive a reduced subscription fee. As with the free access model, the barriers to entry are low. The platform can only generate revenue from customers if there are enough incentives for them to subscribe. A positive aspect of this model is that the customer is provided with a possibility of differentiation through the subscription.

For designers, five different platform types are examined, which occur with varying frequency. The revenue-based business model is most common, such as Etsy [17]. Here, the designers pay a fee to the platform and the amount is based on the turnover generated by the respective designer. Access to the platform and the creation of accounts is usually free of charge. Only when the offered products are sold costs arise for the designers. Depending on the platform, it is sometimes possible to get premium access and thus additional services such as workshops. This results in additional monthly costs. The main advantage of the model is that payments are only made when the designers generate income and that no advance payments are necessary. In addition, the designers benefit from already established platforms and thus reach a wide range of customers. A well-known platform for designers with a freemium model is Dribbble. The platform Dribbble is both a self-promotion platform and a social network for designers, where designers can offer jobs and be recruited by clients [18]. As a basic customer, it is possible to post or accept a job offer at no additional cost. However, the possibilities for personalising the account are limited. By taking out a Pro subscription, designers can personalise their profiles and sell their own products. The payment of the subscription is either monthly or annually. Because the basic use of the platforms is free, the entry barriers for designers are low and a high network potential is created. The possibility of a premium account and the accompanying personalisation of the user profile makes it possible for designers to distinguish themselves from each other. Another business model on platforms for designers is the free access model as shown by Faberin [19]. On this platform designers collaborate with manufacturers. The concept of the Faberin platform is that designers design furniture that is produced by manufacturers. The designers receive a fee per piece of furniture sold. The platform takes care of the sale and production allowing designers to focus completely on their creative work. On the platforms with this business model, there are no additional costs for the designers. This means that designers can contact manufacturers or private customers for free, depending on the context of the platform. However, there is no possibility to customise the user profile according to one's own wishes. With this business model, production and sales are often taken over by the platform, which allows the designers to focus on the creative work. Another advantage are the low entry barriers because the use and creation of a profile are free. For the platform operators, however, this means that they do not receive any direct income from the designers. The Kimp platform is showing the contrasting revenue model of a subscription-based model [20]. Kimp is a subscription-based unlimited design service where manufacturers, start-ups and the like can work with a design team. It is mandatory for the designers to sign up for a subscription. The designers can choose between different subscription models, such as video or graphics, depending on the focus of their creative work. Subscriptions are paid either monthly or annually. In this model, the barriers to entry are higher than in the other business models, but the payments also create a lock-in effect for the designers. Thus, the exit barriers are comparatively high. The last model found in practice for designers is the tier level-based business model. On the platform peopleperhour, access and creation of a user profile on the platform is free for all designers [21]. This leads to low barriers to enter. Payments arise for designer depending on the number of orders or turnover. Here, the amount of the charges varies and depend on the platform. For example, less than 10 orders per month mean the platform is still free of charge. The next tier could be 10-20 orders and a corresponding fee is set. This goes then on.

On the platforms for manufacturers, similar business models are identified as those for the general public or designers. At the focus are three forms. These are the business models of freemium access, the mandatory subscription, and the revenue-based fees. With the freemium business model, producers can choose between free access and premium access. The platform wirsindhandwerk.de is a recommendation platform for the manufacturer sector. It is chosen as an example for freemium access for manufacturers on platforms because it connects craftsmen with customers. As with other freemium platforms, basic access and account creation is for free. Access to exclusive features, such as quality labels or certificates, is possible by taking out a subscription. Due to the free use, it creates low entry barriers, which attracts many customers. Premium access, however, is based on payments, which are made either monthly or annually. This business model stands out due to its transparency, as payments are clearly marked by a subscription and no hidden payments are made, for example, by accepting orders. In the fixed subscription business model, access to the platform and its features is only possible through a subscription for which monthly or annual payments are charged. A very well-known platform on which manufacturers pay a fixed subscription fee is Shopify. The platform provides an e-commerce software, which enables manufacturers to create an online shop to outsource their logistics [22]. Manufacturers can choose between different subscriptions, depending on the orientation of the company. Due to the reach of the platform, manufacturers do not have to engage in customer acquisition and can thus concentrate on the execution of orders. In addition, the platform provides support in creating the user profile or shop and in processing payments. Since every user of the platform also must pay subscription fees, the revenue potential from this business model is high for the platform operators. Lastly, the revenue-based business model on platforms for manufacturers is examined. myhammer is a good example of a revenue-based online marketplace for manufacturers [23]. The manufacturers can initially create a profile on the platform for free, which is checked by the platform operators. A fee is not charged until manufacturers accept an offer. The amount of the fee then depends on the order size and the trade. This is characterised by the fact that the payments to the platform are adjusted to the turnover or the number of orders of the manufacturers. The amount of the payments varies depending on the platform. Although the manufacturers must give up a share of their turnover, there are still important benefits from using the platform. For example, the platform makes it easier for customers to contact manufacturers. In addition, the manufacturers benefit from the reach of the platform and its already existing customer base.

4. Revenue models for a co-creation platform

The results of the case study are presented to experts from the industry in the form of a workshop. The aim of the expert workshops is to find the most fitting revenue model for each stakeholder group. Therefore, the experts could formulate arguments for and against each of the revenue models. With this methodology, experts and stakeholders are invited to participate to create a suitable, stimulating, and constructive discourse between the stakeholders. In the transdisciplinary workshops, experts and stakeholders are invited to engage in a rule-based and systematic discourse based on their knowledge. Through direct exchange, new knowledge is produced. [24] The workshop consisted of twenty-seven experts and stakeholders that involved three manufacturers, five designers, two potential platform providers and seventeen representatives of the general public. The participants come from eight different European countries. In the end a voting is held on which model is most suitable for the general public, designers, and manufacturers. For the voting each of the twenty-seven participants had one vote for a revenue model for the general public, designers, and manufacturers. It was not possible to vote for multiple revenue models for one stakeholder group.

4.1 General public

A free access model, like Pinterest, offers a high potential for adaptation for the co-creation platform. For example, potential customers could post their ideas for furniture on the platform and share them with designers or manufacturers. In addition, customers could also see ideas from other customers and thus be inspired. Furthermore, this type of platform also offers a high network potential. The low entry barriers and easy access to the platform speak in favour of this model. This makes it possible for potential customers to try out the platform first without being directly bound to it or having to pay money. Furthermore, this model promotes the formation of a community and thus facilitates creative exchange. As the platform is free of charge, problems may arise. For example, the operators do not generate any direct revenue for the customers in the form of a subscription and it remains open how the platform is financed. In addition, the customers have no incentive to finish their projects. The community aspect could also be a hindrance to the actual production because potential customers may be more interested in the exchange of ideas. Out of twenty-seven participants, thirteen are in favour of the business model with free access on the platform.

The other model for the general public is the freemium model. Regarding the co-creation platform, it would also be possible to offer a premium membership, in which customers would receive further support in designing furniture. Since access to the platform remains free of charge, the barriers to entry are also low in this model. Through the premium membership, however, the platform operators can generate direct revenue from the customers, which is the biggest advantage compared to the business model with free access. Furthermore, the premium membership offers an opportunity to sell additional services and thus make the platform more attractive. Also, subscribing to a premium membership signals the serious intentions of the customers, which can be helpful to create attraction for designers and manufacturers. However, implementing a subscription model in the furniture sector could be difficult because many people purchase furniture only once or only once every few years. It also remains open how customers can be incentivized to subscribe to the premium membership, since furniture can also be purchased from other designers or on other platforms. Another difficulty is the amount of the subscription fee. This must be set in such a way that the platform is financially secure, but customers do not get the impression of overpaying. In total, fourteen out of twenty-seven participants voted for this model.

4.2 Designers

For designers, five different models are identified in the case study analysis. The free model offers a good applicability in the ramp-up phase, as the entry barriers are low and thus the formation of a community is enabled. The payment of a commission benefits the platform. However, due to the free access to the platform, designers who do not have serious intentions are attracted in addition to professional designers. This could have a negative impact on the platform's reputation. One solution to this problem would be to include verification on the platform. This, in turn, would involve additional work for the platform operators. The low entry barriers could lead to an oversupply of designers, which in turn could have a negative impact on the quality of the products. Only one participant out of twenty-seven voted for this model.

A revenue model for the co-creation platform could also be freemium. For example, designers can establish contact with manufacturers or the general public for free, but personalisation of the account is only possible with a paid membership. A positive aspect of this model is the revenue is generated through the subscription fees and the low entry barriers due to the voluntary aspect of the paid membership. Since the designers' profile can be personalised through the subscription and thus the visibility is increased, this is a solution where everyone benefits for designers and the platform. Although the designers pay a small fee, they also potentially receive more orders, and the platform can finance itself through the subscription fees. It is important that the incentive to take out a subscription is great enough because the platform is only generating income through the paid members. However, designers need to have a certain customer base before they subscribe, as they need to cover their costs. Again, only one of twenty-seven participants voted for this model.

The subscription-based model can also be applied to the co-creation platform. Designers or the general public could collaborate with a design team of furniture specialists and elaborate their ideas. For the subscription models, it would be possible to distinguish between different furniture styles, such as Scandi, Industrial or Modern. A positive aspect of this model is that the platform earns direct revenue from subscription fees. For the designers, the subscription also has positive effects, as they can customise their profile and specialise additionally. This model is good if a certain customer base has already been built up, but it is difficult to implement in the initial phase due to the high entry barriers. The monthly costs put pressure on designers to design as many pieces of furniture as possible. This could have a negative impact on quality. Since the negative aspects of this model outweigh the positive ones, only one participant voted for this model.

The tier-level-based subscription is beneficial for the designers because it minimizes their risks. Since the cost do not increase proportionally to the orders, but in steps. This enables designers to participate on the platform and to populate it in the process. The lowest tier can be for free, thus creating an extremely low entry barrier. However, the different tiers are unclear now and if they should refer to number of orders or revenue generated. If it refers to orders, then designers may be incentivized to charge unreasonable prices and increase their revenue on each order, but the platform is not generating more income. Also, high competition due to low entry barriers could lead to a lack in quality. Eight out of twenty-seven experts voted for this revenue model.

Last, the revenue-based fee offers a fair and transparent payment structure for designers. Therefore, high accessibility is guaranteed, and the designers are treated as an equal partner on the platform. Moreover, there is no preferential treatment of any designer and non-serious designers may not be willing to engage on the platform. Also, the designer only has costs if s/he partakes in a project. However, the designer's turnover must be higher than the fee to make the participation worthwhile. Also, some designers may regard the fee as too high. Considering the benefits of this model, eight out of twenty-seven participants voted for this model.

4.3 Manufacturers

For manufacturers, three different models applicable to co-creation platform are identified. The first model is a freemium approach for the manufacturers. Manufacturers can receive orders and ratings from the general public and benefit from the platform's reach. The general public would be able to see the performance of the individual manufacturers through the ratings of other users and would thus have an assurance of performance. A potentially negative aspect of this model is the free access to the platform. This could mean that manufacturers who are not trustworthy are also attracted. An examination of the individual manufacturers by the platform operators could reduce this aspect. Also, the free access of the manufacturers is positive, as many manufacturers are attracted, hence the general public has a large variety to choose from. The model favours the formation of a community through the possible exchange among each other and the evaluation possibilities. Although there are arguments in favour of this model, it is considered inappropriate for the stakeholder group of manufacturers. In the vote, none of the experts supported the freemium model for manufacturers.

Another potential model is the fixed subscription fee. Manufacturers can choose between different subscriptions and view their business reports and statistics, which are provided by the platform. Due to the obligatory subscription, manufacturers must pay fees even if they have no revenues. This could lead to manufacturers leaving the platform if they receive few orders. The barriers to entry are quite high in this model and thus the experts consider it to be unfavourable for the introduction phase. Only one of the experts voted for this model.

The last model for manufacturers is the revenue-based model. This is a very fair model, because the payments depend on the turnover a manufacturer is generating. Regarding the co-creation platform, it would therefore be possible for the general public to publish production orders on the platform and be connected directly to the right manufacturer. The manufacturers then pay a fee to the platform. Since the platform assigns the order directly to the right manufacturer, the acquisition does not represent a significant effort for the manufacturer. This model is very flexible for the stakeholders and fits very well with the platform's vision of producing personal one-off furniture. Due to the positive aspects of this model, eighteen out of twenty-seven experts voted for this model. For the manufacturers, a revenue-based model should therefore be implemented. Figure 2 shows the results of the voting for each stakeholder group.

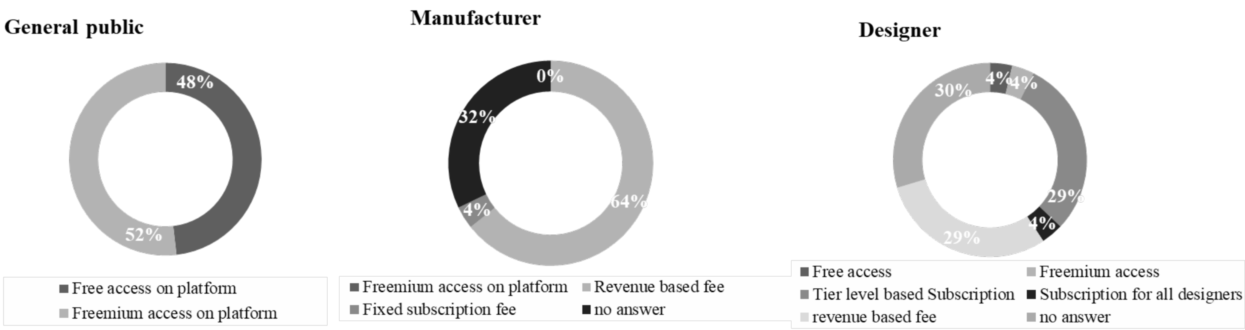

Figure 2: Outcome of the voting for the revenue models

5. Conclusion and outlook

The aim of this paper is to develop suitable revenue models, so that the stakeholder on a co-creation platform in the furniture sector have the highest possible incentives to use it. For this purpose, different revenue models are presented and further analysed by well-known practical examples. During an expert workshop, various arguments for and against the models are made.

For the general public, the free and the freemium model is considered. In the case of the former, a high network potential is quickly formed, as customers are given a simple, unproblematic entry point. In the freemium model, access also remains free, but the functions and possibilities can only be expanded by a premium membership. Since the decision between the free access and freemium access model is close in the expert workshop, it is advised to first go to market with a free offer and then offer a freemium model after the launch to further develop premium content. These two models build on each other, therefore it is possible to first build a community through the free model and then use the experience to add premium content.

The most difficult model to develop is for the designers. Three models are not further considered due to the difficult set-up phase, a previously required customer base or pressure on the designers, which means that the quality of the products suffers. The experts voted equally for either a tier-level-based subscription or a revenue based free model. Subscription minimizes the risk for designers, which makes the platform more popular. Here, the risk lies in the lack of revenue for the platform. The revenue-based free model, on the other hand, is characterized by fair payment and transparency, but puts pressure on the designers and might discourage them. Therefore, a further analysis or a focus group study with designers must be done.

In contrast, the desire for a revenue-based model is clear for the manufacturers. In this model, the manufacturer starts with a free profile and only pays a fee once an order is received. This fee depends on the size of the project and the trade. Hence, this model should be implemented.

The co-creation platform must consist of at least two different revenue models: a free/freemium and a revenue-based one to cater to the needs of the different stakeholder groups. By conducting literature analysis, case study research and an expert workshop a comprehensive and differentiated view on revenue models is achieved. Further research is necessary for the designers and the financial structure of the platform needs to be analysed to assess the profitability of the platform.

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References

[1] Cooper, T., Furmston, K., Cutts, A., Kaner, J., 2021. Furniture lifetimes in a circular economy: a state of the art review Cooper, in: Proceedings of the 4th PLATE 2021 Virtual Conference. 4th PLATE 2021, Limerick. 26-28 May.

[2] Marino, G., Zotteri, G., Montagna, F., 2018. Consumer sensitivity to delivery lead time: a furniture retail case. IJPDLM 48 (6), 610–629.

[3] Pallot, M., Fleury, S., Poussard, B., Richir, S., 2022. What are the Challenges and Enabling Technologies to Implement the Do-It-Together Approach Enhanced by Social Media, its Benefits and Drawbacks? Journal of Innovation Economics Management, I132-XLII.

[4] Dempsey, D., Kelliher, F., 2017. Revenue Models and Pricing Strategies in the B2B SaaS Market, in: Dempsey, D., Kelliher, F. (Eds.), Industry Trends in Cloud Computing. Alternative Business-To-Business Revenue Models. Palgrave Macmillan US, Cham, pp. 45–82.

[5] Holm, A.B., Günzel-Jensen, F., 2017. Succeeding with freemium: strategies for implementation. JBS 38 (2), 16–24.

[6] Reime, E.V., 2011. Exploring the Freemium Business Model.

[7] Oestreicher-Singer, G., Zalmanson, L., 2013. Content or Community? A Digital Business Strategy for Content Providers in the Social Age. MIS Quarterly 37 (2), 591–616.

[8] Maltz, J., Barney, D., 2012. Freemium Software: A Guide for Startups. https://www.ivp.com/assets/pdf/ivp_freemium_paper.pdf. Accessed 18 October 2022.

[9] Chargify, 2022. An Intro to Subscription Financial Models for SaaS Business. https://www.chargify.com/blog/an-intro-to-subscription-financial-models-for-saas-businesses/#:~:text=Subscription%20business%20models%20revolve%20around,their%20business%20month%20over%20month. Accessed 18 October 2022.

[10] Cuofano, G., 2022. What Is The Advertising Business Model? The Advertising Business Model In A Nutshell. What is The FourWeekMBA, June 25.

[11] Huotari, P., Ritala, P., 2021. When to switch between subscription-based and ad-sponsored business models: Strategic implications of decreasing content novelty. Journal of Business Research 129, 14–28.

[12] Zhao, K., Mahboobi, S.H., Bagheri, S.R., 2019. Revenue-based attribution modeling for online advertising. International Journal of Market Research 61 (2), 195–209.

[13] Jiang, B., Jerath, K., Srinivasan, K., 2011. Firm Strategies in the "Mid Tail" of Platform-Based Retailing. Marketing Science 30 (5), 757–775.

[14] Eisenhardt, K.M., 1989. Building Theories from Case Study Research. AMR 14 (4), 532–550.

[15] Mishra, S., 2019. ASSESSMENT AND EVALUATION OF INTREST-BASED SOCIAL NETWORK SERVICES.

[16] Song, M., 2021. A Comparative Study on Over-The-Tops, Netflix & Amazon Prime Video: Based on the Success Factors of Innovation. International journal of advanced smart convergence 10 (1), 62–74.

[17] Louca, R., Bhattacharya, M., Hu, D., Hong, L., 2019. Joint Optimization of Profit and Relevance for Recommendation Systems in E-commerce. RMSE@ RecSys.

[18] Casanova, R.R., 2022. The strategic challenges of under armour in 2021 with an analysis of the firm in China: The strategic challenges of under armour in 2021 with an analysis of the firm in China.

[19] Faberin, 2022. Website. www.faberin.es. Accessed 3 November 2022.

[20] Kimp, 2022. Website. www.kimp.io. Accessed 3 November 2022.

[21] Peopleperhour, 2022. Website. www.peopleperhour.com. Accessed 3 November 2022.

[22] Pais, J. P. F. d. A. Shopify equity research - staying ahead of the market: Shopify equity research - staying ahead of the market.

[23] MyHammer, 2022. Website. https://www.my-hammer.de/. Accessed 3 November 2022.

[24] Niederberger, M., 2015. Methoden der Experten- und Stakeholdereinbindung in der sozialwissenschaftlichen Forschung. Springer VS, Wiesbaden, 298 pp.

Biography

Regina Schrank (*1992) is the head of the research unit Service Sales Engineering at the Institute for Industrial Management (FIR) at RWTH Aachen University. In her research, she focuses on pricing of digital products in the manufacturing industry. Prior to that, she worked for different companies in various marketing roles in the retail sector. She holds a Master's degree in Marketing from the University of St Andrews.

Günther Schuh (*1958) has been director of the Institute for Industrial Management (FIR) at the RWTH Aachen University since 2004. Prof. Dr.-Ing. Günther Schuh is director of the chair of production engineering at RWTH Aachen University. Furthermore, he holds the Chair of Production Systems at the Laboratory for Machine Tools and Production Engineering (WZL) of RWTH Aachen University and is a member of the Board of Directors at the Fraunhofer Institute for Production Technology IPT in Aachen. He serves on supervisory and administrative boards.

Daniel Wentzel (*1978) has held the Chair of Marketing in the School of Business and Economics at RWTH Aachen University since spring 2011. Prof. Dr. oec. He studied business administration at the University of Cologne and the University of Auckland, New Zealand and received his doctoral degree from the University of St. Gallen (Switzerland) in 2008. As part of his research program, he has collaborated with many companies from the automobile, retailing, and financial services industries.

Lennard Holst (*1993) has been the head of the Service Management research department at the Institute for Industrial Management (FIR) at RWTH Aachen University since 2021. Dr.-Ing. Lennard Holst's work deals with the transformation of production companies – from providers of products to providers of integrated solutions. Lennard Holst studied industrial engineering and business administration at RWTH Aachen University. He led the research area for subscription business management at FIR before.

4th Conference on Production Systems and Logistics

Using Data-Centric Platforms To Improve Demand Forecasting And Capacity Utilization For Less Digitized Multi-Site Quarrying Businesses

John von Stamm[1], Jonas Müller[1], Gerrit Hoeborn[1], Julian Lassen[2], Volker Stich[1]

[1]FIR e. V. Institute for Industrial Management at RWTH Aachen University, Aachen, Germany

[2] Institute of Mineral Resources Engineering (MRE) RWTH Aachen University, Aachen, Germany

Abstract

The quarrying industry, which largely consists of less digitized SMEs, is an integral part of the German economy. More than 95% of the primary raw materials produced are used by the domestic construction industry. Quarrying companies operate demand-oriented with short planning horizons at several locations simultaneously. Due to the low level of digitization and the reluctance to share data, untapped efficiency potential in data-based demand forecasting and capacity planning arises. The situation is aggravated by the fact that SMEs have a heterogeneous mobile machinery so as not to become dependent on individual suppliers, and that transport distances of over 50 kilometers are uneconomical due to high transport costs and low material values. Within the research project PROmining a data-centric platform which improves demand forecast accuracy and multi-site capacity utilization is developed. One of the core functionalities of this platform is an industry-specific demand forecasting model. Against this background, this paper presents a methodology for establishing this forecasting model. To this end, expected demands of secondary industry sectors will be analyzed to improve mid-term volume-forecasting accuracy for the local quarrying industry. The data-centric platform will connect demand forecasting data with relevant key performance indicators of multi-site asset utilization. Following this methodology, operational planning horizons can be extended while significantly improving overall production efficiency. Thus, quarrying businesses are enabled to respond to fluctuating demand volumes effectively and can increase their personnel and machine utilization across multiple quarry sites.

Keywords

Demand Forecasting; Data-Centric Platform; Capacity Utilization; Quarrying Industry; Digitization of SMEs

1. Introduction

The German quarrying industry consists largely of SMEs (small and medium-sized enterprises) with fewer than 10 employees [1]. Quarrying companies operate demand-oriented with short planning horizons at several locations simultaneously. Storing quarry mass products, such as limestone, sandstone, etc., is not economically viable, as large storage areas are required and the material properties can deteriorate due to weathering. Companies that actively focus on digital transformation and automation are still the exception in the industry today [2]. In almost all SMEs within this industry, software support is currently rather rudimentary. Most equipment and process data is recorded in analog form and only analyzed when required [3]. However, the shift towards Industry 4.0 is also affecting the mining and quarrying industry. Large international corporations are already using digital technologies on a grand scale [4]. Referred to by the term

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"Mining 4.0" or "Smart Mining", this development focuses on connecting physical mining assets and external data sources within an Industrial Internet of Things (IIoT) [5]. Due to high investment costs, many SMEs shy away from setting up a comprehensive IIoT infrastructure. Yet there is great efficiency potential for quarrying companies if multi-site operations can be controlled remotely [6]. A data-centric platform, which consolidates and evaluates site-specific data to optimize overall capacity utilization can lead to significant cost savings in the long term [7]. However, capacity utilization is subject to fluctuations caused by regional, seasonal and conjunctural demand dynamics [8]. Demand forecasting therefore relies heavily on extensive external datasets. Due to SME's heterogeneous machinery with incompatible sensor technology, platform solutions from major equipment suppliers are unsuitable [3]. Therefore, multi-site SMEs need a customized digital platform solution to monitor site-specific KPIs and adjust capacity planning to demand development. This platform can help SMEs leverage large efficiency potentials through improved forecasting capabilities and capacity planning [3].

While a data-centric platform design and a corresponding operator model have been detailed in previous publications a demand forecasting model that fits the requirements for SMEs of the German quarrying industry is yet to be published [3]. Therefore, this paper aims at establishing a methodology to create a regional demand forecasting model. In conjunction with recording current utilization metrics on the platform, demand-driven capacity planning can be improved. The forecasting model follows the methodology of Kosow and Gaßner [9] and is based on trend extrapolation of downstream industry demands. It breaks down Germany-wide demand volumes into regional and site-specific production outputs. Matched with site-specific capacity data, the forecasting model provides a decision-making basis for demand-oriented production planning. It can support SMEs with increasing production efficiency, reducing energy consumption and optimizing equipment maintenance schedules [10].

2. Theoretical background

2.1 Data-centric platforms and their application in the quarrying industry

Data sets generated, collected, structured, and stored by machines, form the basis of data-centric (B2B) platforms [11]. Data-centric platforms therefore represent a combination of interoperable, scalable, and modular technologies, that work together to meet an organization's entire data needs [12]. To this end, the connections between machines, sensors and software applications are critical to ensure effective data collection and transmission [13]. In a manufacturing environment, they form the Industrial Internet of Things (IIoT), which encompasses the integration and connection of machines, products, and processes in data-centric platforms [6]. The IIoT creates an automized interaction between machines and operating processes which can be used to increase efficiency throughout the value chain. This improves productions logistics as well as inventory management or the business processes in general [14].

The importance of developing data-centric platforms is increasing across the economy [15]. Data-centric platforms offer companies the opportunity to create new markets or tap into new customer segments. Companies also benefit from automated information exchange and services between two or more parties and gain insights from production data [16].

Data-centric platforms are already applied in the quarrying industry by large mining corporations. These platform solutions are offered by major equipment manufacturers as fleet management system for the manufacturer's own machinery [2]. Platforms that are utilizable for SMEs are not yet marketable as their heterogeneous fleets are not compatible with the software solutions and sensors [3]. Although existing platforms can provide real-time data on capacity utilization, forecasting functionalities have not yet been included. Quarrying companies incur high operating and maintenance costs. At the same time the storage of most quarry products is uneconomical. Therefore, it is important to forecast the development of demand to plan capacity utilization accordingly [17].

2.2 Demand forecasting in the quarrying industry

The German quarrying industry is characterized by a high regionality of sales markets. The material value of quarry products is very low compared to the transport costs. Thus, transport distances of more than 50 kilometers are usually uneconomical. The production volumes of the quarrying companies are therefore directly dependent on local demand [18]. Relevant external data that enables a company to forecast demand include information about consumers and market dynamics [19]. The construction sector is the largest consumer of quarry products, accounting for up to 95% of the downstream sector [1]. Seasonal effects are prevalent in the construction sector, with weather-related production declines of up to 70% during the winter months. This has a direct impact on companies in the quarrying sector, which are demand-driven and therefore have to adjust their production volumes accordingly [20].

The greatest potential of demand forecasting lies in the increase in operating efficiency and the reduction of production and maintenance costs [21]. Maintenance intervals of the machines can be calculated predictively, and personnel can be deployed in a targeted manner to ultimately reduce costs and improve production efficiency [14]. Realizing the highest possible capacity utilization with the given operating resources is essential to achieve a high economic added value [22]. Demand forecasts help with production planning and can thus contribute significantly to this.

2.3 Capacity utilization in the quarrying industry

Capacity planning is an important tool in business management, where operating resources are allocated according to the order situation and demand [17]. Modern quarrying assets are equipped with IoT sensors. They can collect a wide range of data, which is stored on the manufacturer's platform [23]. The data is then analyzed to gain information on capacity utilization. Important Key Performance Indicators (KPI's) for measuring capacity utilization comprise operating hours, fuel consumption, idle time, and production output [23].

Optimizing capacity utilization of multi-site quarry operations holds significant economic potential. Due to the regional dependency of the industry, it is important for companies to orchestrate production volumes across all sites. However, due to the low level of digitalization, the exchange of information functions only inadequately, and site data is not shared effectively. Further, there is hardly any data exchange with other operators in the industry [3]. These factors lead to over- or under-utilization of production with consequences for response time, capacity, budget, efficiency, strategy, staffing levels and maintenance. [24,25].

3. Related research and innovation contribution

Within the PROmining research project a data-centric platform concept has been developed previously [3]. The platform aims to visualize both current capacity utilization and estimate future demands to enable quarrying SMEs to monitor and plan their capacity utilization in an efficient and digitized way. Capacity planning is based on two key functionalities offered by the platform:

1) A KPI-dashboard, visualizing cross-cite capacity utilization by analyzing site-specific internal data regarding mobile assets, working hours of personnel, utility consumption and production volume.
2) A regional demand forecasting model based on trend extrapolation of downstream industry demands, which breaks down Germany-wide demand volumes into regional and site-specific production volumes.

The interplay of internal data on capacity utilization and external data feeding the demand forecasting model on the platform is shown schematically in Figure 1.

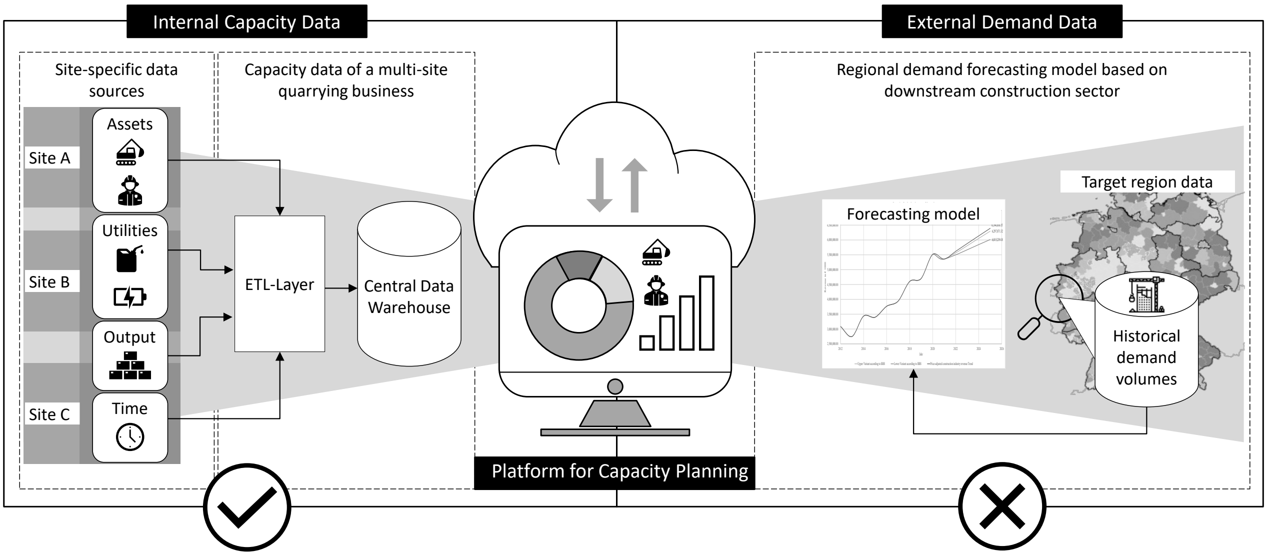

Figure 1: The data-centric platform merges internal capacity data with external demand forecast

The KPI-dashboard has been previously developed and integrated into the platform (see Figure 2).

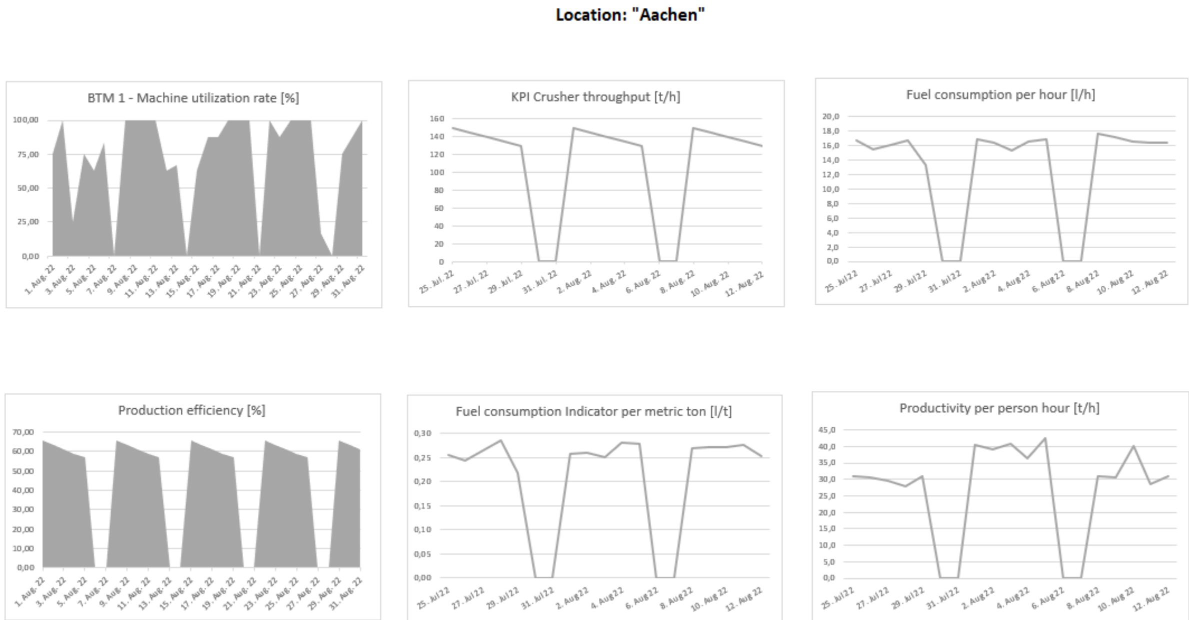

Figure 2: Cross-site KPI-dashboard of the platform

It visualizes production data of quarrying sites in the region “Aachen” as well as different KPIs, e. g. “Throughput crusher [t/h]”, “Fuel consumption [l/h]”, “Productivity per person-hour [t/ph]” or “Capacity of mobile operating equipment [t/h]”. These indicators are used to calculate and visualize relevant KPIs, such as the production efficiency of each site, the machine utilization rate of individual production assets and machine availability. These can be used to identify unused capacities, such as conveying equipment that is not being optimally utilized.

The second key component, the regional demand forecasting model has not been implemented yet. This paper presents a methodology to create a regional demand forecasting model. Combined with current capacity utilization KPIs on the platform, this can improve future demand-oriented capacity planning for SMEs in the German quarrying industry.

4. Methodology and Study Design

To create a regional demand forecasting model to improve overall capacity utilization of German SMEs in the quarrying industry, a scenario-based analysis is conducted. This is built on a quantitative trend analysis (TIA) [9]. A scenario is defined as a presentation of possible situations in the future while trends are defined as certain developments in a specific period of time [9]. The basis of the analysis is trend monitoring, which requires extensive data collection. Identified trends and their predicted developments are being calculated with statistical methods to estimate possible future outcomes. It must be noted that a trend analysis, based solely on quantitative trend extrapolation might lack the reference to realistic future states described by qualitative factors [26]. Nonetheless, a quantitative TIA provides a practical methodology for predicting the most likely scenarios with quantifiable probabilities of occurrence [9]. Trend extrapolation requires mapping a general trend or a reference scenario [26]. Therefore, data on a series of possible future events is gathered via expert surveys or market analyses. The identified events are then projected onto the base trend in terms of their occurring probability and impact strength. Thus, individual key factors can be varied and combined with constant factors. This results in alternative progressions of the trends [9]. Figure 3 illustrates the application of a TIA based on a trend extrapolation and maps different trend developments. Up to time t0, historical data is considered for the construction of the extrapolation. Between t0 and the time of the scenario analysis, a continuation of the determined base trend (trend a) is generated. Furthermore, during this period, the TIA data is projected onto the base trendline, resulting in different trend developments (trend development b, c).

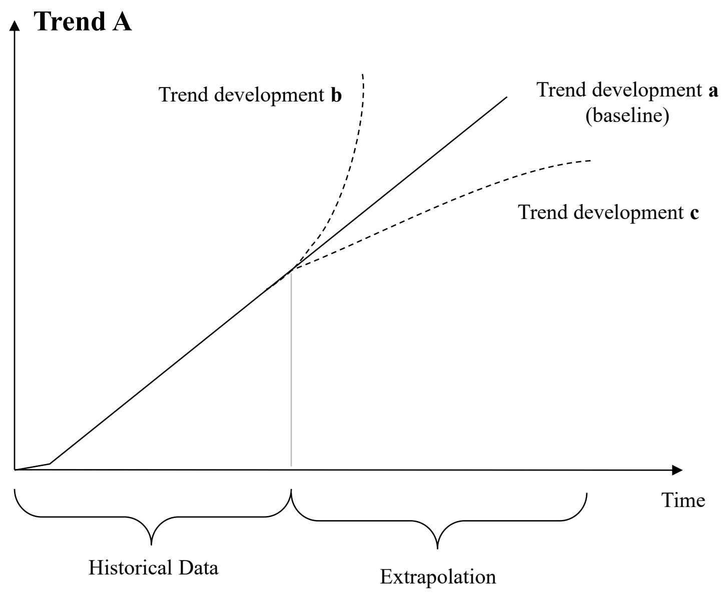

Figure 3: Schematic representation of a trend impact analysis [9]

5. Results

5.1 Methodology for establishing a regional demand forecasting model

In the light of the increasing uncertainty of societal and natural circumstances, future-oriented decisions and capacity planning are becoming more and more important [9]. As database for the demand forecasting model, external data of the downstream construction industry was used. The development of the regional demand forecasting model follows the methodology of Kosow and Gaßner and can be divided into five steps which are shown in Figure 4.

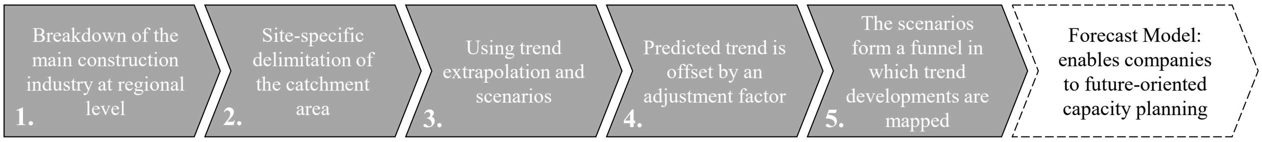

Figure 4. Methodology for establishing the forecasting model

The downstream construction industry is the most important customer segment of the quarry industry, accounting for 95% of the purchase volume. The working hypothesis is, that fluctuations in demand in the construction sector lead directly to comparable changes in production volumes in the quarrying industry. Further it is assumed that construction sector sales figures act as an indicator of quarrying industry production volumes. Thus, it is possible to draw conclusions about the regional demand for quarry products based on the turnover of regional construction companies.

The following step is the delimitation of the site-specific catchment area of a company. Due to high transport costs, the relevant radius of deliveries is limited to a maximum of 50 kilometers. Aachen, Germany was studied as an example region. 10 municipalities border the Aachen region that meet this requirement.

After that, the turnover of the construction industry in the above-mentioned area was examined and a trend extrapolation was carried out. The total sales revenues of the regional construction sector were examined on a monthly and yearly basis and projected onto the regional quarrying industry. A regular drop in demand of up to 70% during the winter months is noticeable. This is due to the difficult weather conditions that the construction industry faces during this period [20]. In a year-on-year comparison, however, this temporary decline was negligible due to its regularity. The possible development trends in the construction industry were analyzed separately by the BBS-Study [27]. The analysis distinguishes four main areas of activity in the construction industry (see Table 1), which can be mapped separately for the scenarios:

Table 1: Scenarios for the four areas in the construction industry

Calculation of the two scenarios according to BBS (change compared to 2020)	**Upper variant 2025**	**Lower variant 2025**
Construction volume in new residential construction	9.10%	5.70%
Volume of new non-residential construction	13.90%	5.80%
Construction volume in existing buildings	18.30%	13.00%
Construction volume in civil engineering	15.50%	11.80%
Mean value of the percentage change in the construction volume	**14.20%**	**9.08%**

Economic developments in the four fields of activity mentioned above are estimated using leading indicators for overall economic and demographic development [27]. In line with the different underlying data, a distinction is made between a lower and an upper variant which is shown in Table 1. These variants are applied to the overall revenue of 2020 to represent an upper and lower boundary in 2025. The various scenarios form a funnel in which a range of possible trend developments is mapped so that companies can adjust their capacity planning to the probable change in demand.

In the fourth step the predicted trend is offset by an adjustment factor which is based on a study by the German "Bundesverband Baustoffe – Steine und Erden e.V.": *"In order to take into account, the described changes in the demand for raw materials in the construction industry and the relevant economic sectors, an adjustment factor of -1.75 percentage points per year is applied when estimating the future demand for quarry products in Germany. This includes the difference in the change in the real production value or the production quantity (tonnage). "* [27]

In the following, the trend extrapolation result is shown for the region Aachen resulting from the steps described above. The turnover of the construction industry from 2012 to 2021 was analyzed for the ten different municipalities in the transport radius of Aachen. Based on the data, a trend extrapolation was carried out up to the year 2025, whereby the sum of the turnover of the 10 locations was extrapolated. The resulting value of 6,507,904.47 TEUR was reassessed with an adjustment factor of -1.75 percentage points. The predicted price-adjusted construction-related turnover for a quarrying company in Aachen 2025 amounted to 6.297.871,32 TEUR. To consider additional scenarios the upper and lower variants of the expected change for 2025 in the four areas of the construction industry (see Table 1) were offset against the overall construction turnover in 2020. The result of the upper variant is 6.394.016,15 TEUR and of the lower variant is 6.015.239,18 TEUR. All three scenarios are shown below in Figure 5.

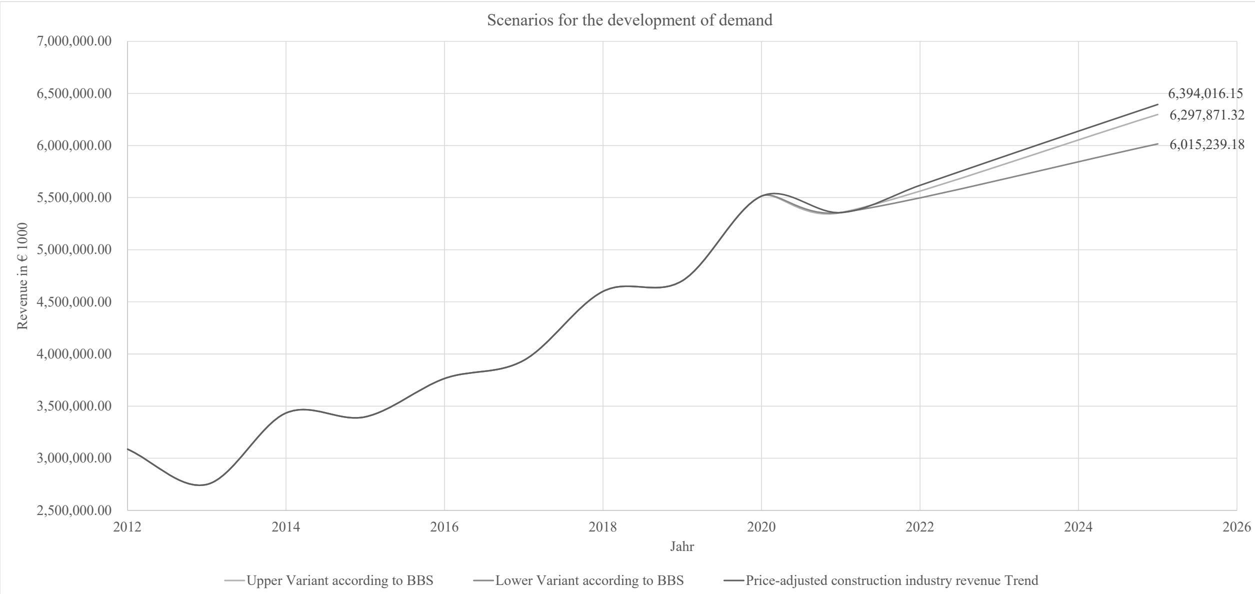

Figure 5: Trend extrapolation and scenarios for the development of demand in the quarrying industry

The different scenarios form a result funnel encompassing a range of possible trend developments. These regional scenarios, in combination with the recording of internal capacity utilization, offer quarrying companies in Aachen the possibility of carrying out improved future-oriented capacity planning.

6. Conclusion

A methodology for developing a regional demand forecasting model was explained using the example of the quarrying industry in Aachen. The approach of developing a regional demand forecasting model provides a five-step process for SMEs in the quarrying industry. As one of the main functionalities of the presented data-centric platform the regional demand forecasting model can help SME improve their decision-making on capacity utilization.

Studies show that the industry is subject to strong fluctuations due to regional, seasonal and conjunctural demand dynamics and still has some efficiency potential open due to the low level of digitalization. While the methodology for building a regional forecasting model can provide guidance, concrete input data is essential for improving the accuracy of the resulting model. With this in mind, it is necessary to understand what factors the four construction industry sectors studied are directly dependent on and how. In addition, it would be interesting to analyze how regional demand differs with respect to specific categories of quarry products, as price differences and production volumes can vary significantly. With additional data sources, more accurate multivariate forecasting methods can certainly be applied. However, since demand forecasting is hardly used within this industry, even a linear regression method considering only the most important influencing factors, could offer great practical benefit.

It can be assumed that this methodology can be transferred to structurally comparable industries with a low level of digitization as well. However, the underlying hypotheses for demand forecasting rely on the heavy dependency of the regional quarrying industry and construction sector. Therefore, the forecasting methodology needs to be validated and tested within the quarrying industry first before being adopted in other industry sectors.

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References

[1] Basten, M., 2021. bbs-Zahlenspiegel 2021: Daten und Fakten zur Baustoff-Steine-Erden-Industrie, Berlin.

[2] Deloitte, 2018. Tracking the trends 2018: The top 10 issues shaping mining in the year ahead.

[3] Müller, J., Lassen, J., Hoeborn, G., Conrad, R., Stich, V., Lober, N., 2022. Improving Forecasting Capability and Capacity Utilization in Less Digitized Industries Through Participation in the Platform Economy, in: Camarinha-Matos, L.M., Ortiz, A., Boucher, X., Osório, A.L. (Eds.), Collaborative Networks in Digitalization and Society 5.0. 23rd IFIP WG 5.5 Working Conference on Virtual Enterprises, PRO-VE 2022, Lisbon, Portugal, September 19–21, 2022, Proceedings, vol. 662, 1st ed. 2022 ed. Springer International Publishing; Imprint Springer, Cham, pp. 141–150.

[4] Bratsch, F., 2018. Digitalisierung und Anlagenmanagement im Steinbruch. GICON –Großmann Ingenieur Consult GmbH. ForumMIRO, 29 November 2018, Berlin.

[5] Bertayeva, K., Panaedova, G., Natocheeva, N., Kulagovskaya, T., Belyanchikova, T., 2019. Industry 4.0 in the mining industry: global trends and innovative development. E3S Web Conf. 135, 4026.

[6] Clausen, E., Sörensen, A., Uth, F., Mitra, R., Lehnen, F., Schwarze, B., 2020. Assessment of the Effects of Global Digitalization Trends on Sustainability in Mining.

[7] Elisabeth Clausen, Aarti Sörensen, Fabian Uth, Rudrajit Mitra, Felix Lehnen, Berit Schwarze, 2020. Assessment of the Effects of Global Digitalization Trends on Sustainability in Mining.

[8] Andruleit, H., Elsner, H., Graupner, T., Homberg-Heumann, D., Huy, D., 2018. Rostoffsituationsbericht 2017.

[9] Kosow, H., Gaßner, R., 2008. Methoden der Zukunfts- und Szenarioanalyse: Überblick, Bewertung und Auswahlkriterien. IZT, Berlin, 88 pp.

[10] Piller, C., Wölfel, D.W., 2014. Production Planning for SMEs – Implementation of Production Planning with Subject-Oriented Business Process Management (S-BPM), in: Junqueira Barbosa, S.D., Chen, P., Cuzzocrea, A., Du, X., Filipe, J., Kara, O., Kotenko, I., Sivalingam, K.M., Ślęzak, D., Washio, T., Yang, X., Zehbold, C. (Eds.), S-BPM ONE - application studies and work in progress. 6th international conference, S-BPM ONE 2014, Eichstätt, Germany, April 22-23, 2014 ; proceedings, vol. 422. Springer, Cham, pp. 164–173.

[11] BDI – Federation of German Industries, 2020. German-Digital-B2B-Platforms. HANDBOOK | DIGITALISATION | BEST PRACTICES (0103).

[12] Catanzano, S., 2022. The modern data platform drives data-centric organizations. TechTarget, August 15.

[13] Xu, X., Han, M., Nagarajan, S.M., Anandhan, P., 2020. Industrial Internet of Things for smart manufacturing applications using hierarchical trustful resource assignment. Computer Communications 160, 423–430.

[14] Haucap, J., Kehder, C., Loebert, I., 2020. B2B-Plattformen in Nordrhein-Westfalen: Potenziale, Hemmnisse und Handlungsoptionen.

[15] Röhl, K.-H., Bolwin, L., Hüttl, P., 2021. Datenwirtschaft in Deutschland.

[16] Gull, Isabel und Lundborg, Martin, 2019. Digitale Plattformen als Chance für den Mittelstand.

[17] Eickemeyer, S.C., Witte, T., Mische, V., Busch, J., 2013. Modell zur bedarfsgerechten Kapazitätsplanung. Zeitschrift für wirtschaftlichen Fabrikbetrieb 108 (9), 634–638.

[18] Skrypzak, T., 2016. Untersuchungen zur Optimierung der Prozessabläufe und der Energieeffizienz bei der Gewinnung von Natursteinen in Festgesteinstagebauen. Dissertation, Aachen.

[19] Schlüchtermann, J., Siebert, J., 2015. Industrie 4.0 und Controlling: Erste Konturen zeichnen sich ab. CON 27 (8-9), 461–465.

[20] Otto, J., Ditzen, M., 2019. Baugewerbe, in: , Konjunkturprogramme in der Bauindustrie. Springer Fachmedien Wiesbaden, Wiesbaden, pp. 29–38.

[21] Agostino, I.R.S., Silva, W.V., Da Pereira Veiga, C., Souza, A.M., 2020. Forecasting models in the manufacturing processes and operations management: Systematic literature review. Journal of Forecasting 39 (7), 1043–1056.

[22] Hackstein, R., Dienstdorf, B., 1973. Grundfragen der Kapazitätsplanung. Zeitschrift für wirtschaftlichen Fabrikbetrieb 68 (1), 18–25.

[23] Suciu, M., Kowitz, S., 2019. Digitizing Raw Material Mining – End-to-End Integration into an IIoT Platform for the Analysis of Machine Data. Mining Report Glückauf 155 (4).

[24] Kowitz, S.-F., 2016. Discover Patterns in Exceptions - Entdecke das Muster im Sonderfall: Bergbau 4.0 und Big Data: Erfahrungen eines Start-ups. GeoResources 2016 (3), 46–48.

[25] Rauth, H., 2012. Anlagenmanagement: Reorganisation der Instandhaltung eines Steinbruchs unter technischwirtschaftlicher Reflexion. Fakultät für Wirtschaftswissenschaften. Hochschule Mittweida. https://monami.hs-mittweida.de/frontdoor/deliver/index/docId/2301/file/DA_RAUTH_Anlagenmanagement.pdf. Accessed 7 December 2021.

[26] Amer, M., Daim, T.U., Jetter, A., 2013. A review of scenario planning. Futures 46, 23–40.

[27] Bundesverband Baustoffe – Steine und Erden e.V., 2022. Die Nachfrage nach Primär- und Sekundärrohstoffen der Steine-und-Erden-Industrie bis 2040 in Deutschland.

Biographies

John von Stamm holds a master's degree in industrial engineering and materials science and is a project manager and doctoral candidate at the Institute of Industrial Management (FIR) at RWTH Aachen University. As a member of the Department of Business Transformation and the Digital Leadership Research Group since 2021, he leads research and consulting projects focusing on digital business models, corporate sustainability, and organizational resilience.

Jonas Müller holds a master's degree in industrial and mechanical engineering and is the Deputy Head of Department Business Transformation and the Head of the Digital Leadership Research Group at the Institute of Industrial Management (FIR) at RWTH Aachen University. He is a doctoral candidate and has led numerous research and consulting projects in the field of digitalization and corporate transformation strategies since he started working at the FIR in 2018.

Gerrit Hoeborn holds two master's degrees in industrial engineering and mechanical engineering and is the Head of Department Business Transformation at the Institute of Industrial Management (FIR) at RWTH Aachen University. Before working as the Head of Department he has led the Research Group Business Ecosystem Design. He is a doctoral candidate and has led numerous research and consulting projects in the context of digitalization, Ecosystems, and platform design as well as corporate transformation strategies since he started working at the FIR in 2019.

Julian Lassen holds a master's degree in mining engineering and is a doctoral candidate at the Institute of Mineral Resources Engineering (MRE) at RWTH Aachen University. As member of the Department Mining Engineering his research focuses on technical and economic factors along the entire value chain of a mining operation with the aim of a safe, efficient, and economical supply of mineral raw materials.

Prof. Dr.-Ing. Volker Stich has been Managing Director of the Research Institute for Rationalization (FIR) at RWTH Aachen University since 1997. He has been working on innovative issues of business organization and IT systems, especially in the areas of logistics, intra- and inter-company production management, the development of technical services in the business-to-business sector, and issues of information management. In 2010, he was appointed "Extraordinary Professor" in recognition of his intensive commitment to both the FIR and the RWTH Aachen Campus.

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Classification of Product Data for a Digital Product Passport in the Manufacturing Industry

Lukas Stratmann[1], Gerrit Hoeborn[1], Christoph Pahl[1], Günther Schuh[1]
[1]FIR at RWTH Aachen University, Aachen, Germany

Abstract

The European Commission set out the goal of carbon neutrality by 2050, which shall be achieved by fostering the twin transition – sustainability through digitalization. A keystone in this transition is the implementation of a prospering Circular Economy (CE). However, product information required to establish a flourishing CE is hardly available or even accessible. The Digital Product Passport (DPP) offers a solution to that problem but in the current discussion, two separate topics are focused on: its architecture and its application on batteries. The content of the DPP has not been an essential part of the discussion, although access to high-quality data about a product's state, composition and ecological footprint is required to enable sustainable decision-making. Therefore, this paper presents a classification of product data for circularity in the manufacturing industry to emphasize the discussion about the DPP's content. Developed through a systematic literature review combined with a case-study-research based on common operational information systems, the classification comprises three levels with 62 data points in four main categories: (1) Product information, (2) Utilization information, (3) Value chain information and (4) Sustainability information. In this paper, the potential content structure of a DPP is demonstrated for a use case in the machinery sector. The contribution to the science and operations community is twofold: Building a guideline for DPP developers that require scientific input from available real-world data points as well as motivating manufacturers to share the presented data points enabling a circular product information management.

Keywords

Circular Economy; Circular Ecosystems; Digital Product Passport; Information modeling; Circular product management; Information systems

1. Introduction

Europe is considered to be a frontrunner in the Circular Economy (CE) with a dedicated Circular Economy Action Plan [1]. However, the development of CE is still in its infancy. Only about 13% of the materials used in the EU are secondary materials [2]. This comes at a time when the economy is faced with the challenge of handling disrupted supply chains while managing further import and export restrictions. Organizations are in the process of transforming their traditionally linear-oriented business models into closed resource cycles to secure the prosperity of our society in the long term. In that approach, the use of digital technologies will be central in enabling a fully developed CE [3]. They will provide crucial support in building a CE by disclosing relevant information about materials, substances and product components in a product's life cycle to relevant stakeholders [5,4]. However, this end-to-end transparency on product data is not sufficiently fulfilled today [7,6,5]. In the Circular Economy Action Plan, EU policy mentions digital solutions without being able to provide detailed information on their content and scope [1]. The success of a functioning CE, especially for complex and digitized machinery and equipment, depends on the joint optimization of a cross-company provision of data and the establishment of circular strategies. A potential

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solution is presented by the Digital Product Passport (DPP) [8]. The DPP is a configurable, digital record of an individual product with the objective to enable a circular product lifecycle [9]. Ensuring the implementation of a DPP, several conceptual steps are still required [8]. The first step on this journey is the presented classification of product data which helps in conceptualizing a comprehensive DPP.

2. Theoretical background

2.1 Circular Economy

The CE is a concept keeping products in a value-adding life cycle as long as possible [10,11]. It can be traced back to the approach of Industrial Ecology in the 1990s before modern definitions broadened its scope [13,12]. Modern concepts of the CE have expanded the scope to the complete product life cycle [15,14]. Although no universally accepted definition is known to the author, in practice, a common understanding has been established. According to KIRCHHERR ET AL., CE replaces the existing end-of-life concept by reducing, reusing, recycling and recovering materials in production and consumption processes [15]. Its objective is to preserve and recover as much of the economic and ecological value as possible to reduce the use of naturally limited resources [4,17,16]. Projections estimate that the CE has the potential to save 80-90 percent of raw materials and energy consumption leading to a 25-30 percent reduction in product prices [18].

2.2 Digital Product Passport

The idea of the DPP as a central, product-specific information tool has already been discussed for several years and integrated into the discussion of various instruments such as the digital twin, material passport or life cycle record file [8,9,19]. GÖTZ ET AL. define the DPP as an instrument that provides product information on energy consumption, emissions, production, repair or handling at the end of the utilization cycle [9]. For this purpose, all stakeholders are served in order to facilitate reporting obligations for companies, to enable customers to make sustainable consumption decisions, and to provide repair companies with the necessary instructions [9]. In contrary to GÖTZ ET AL., the DPP aims at supplying information at the end of a utilization cycle but also during its utilization. Nevertheless, the high degree of data transparency and openness required is seen controversial in the scientific community [20]. At the current point in time, the political measures strongly encourage the use of a DPP while the industrial digital capabilities enable an economically viable introduction of the DPP. Especially in the machining industry, connectivity and data processing of industrial equipment have reached a maturity level that supports the implementation of a DPP.

However, despite a lively scientific and political debate, the DPP is not beyond a pre-conceptual phase yet [8,21]. To develop the required input for its content and implementation, a large portion of the challenge remains within the research community. So far, political and industrial players have only defined requirements for the DPP on a basic level [9]. However, there are several digital technologies and industrial standards such as blockchain, the reference architecture model 4.0 (RAMI 4.0) or the Asset Administration Shell (AAS) that are available but have not prevailed yet. Complementing these requirements to ensure the DPP's usability and database summarizes the motivation for this paper. Especially, the manufacturing sector has been chosen due to its unique characteristics of high-value, complex and long-lasting products.

3. Research approach and method

This paper aims at providing a classification for users that are in the process of developing a specific DPP for its industrial equipment. Therefore, the applied methods are practice-oriented to ensure the applicability of this paper's results. The final classification is derived by defining general characteristics in a requirement analysis through a systematic literature review and matching these with existing information attributes that have been derived from a Data Analysis (see figure 1). Apart from a classification, the approach presents a Gap analysis of information that are theoretically existent and that are still not available.

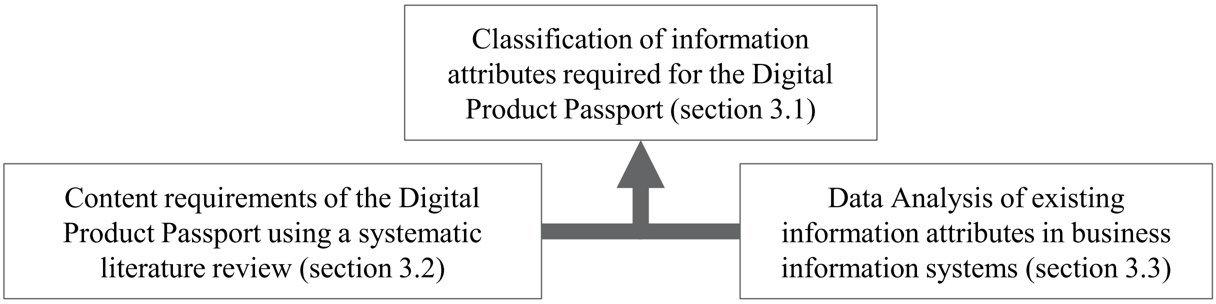

Figure 1 Research method applied in this paper

3.1 Classification

In computational science, classification systems are used as common method to share knowledge and develop a common terminology [22]. Presenting a common starting point for the content of a DPP, the classification method is chosen to reduce complexity and systematically research relevant circular information attributes. In general, classifications are describe by BAILEY as one of the most central conceptualization techniques to reduce complexity and characterize elements [23]. They are defined as *the ordering of entities into groups or class on the basis of their similarity* [23,24]. Therefore, a classification must be exhaustive and mutually exclusive, meaning that there must be a class for each element and no element can fit into two classes [23]. According to VESSEY ET AL., the classification process in computer science requires a *purpose of the classification, criteria for classification* and a *method for classification* [22]. Regarding the purpose, the authors developed a specific classification that primarily classifies relevant information of a DPP. The criteria of the classification are derived using a requirement analysis which is detailed in the next section. Regarding the method, this paper focuses on a qualitative classification with discrete and exhaustive categories.

3.2 Content requirements and systematic literature review

Identifying the content requirements of DPPs, the authors use the requirement approach outlined by the IEEE Computer Society [25]. The authors propose a four-step method containing of *elicitation, analysis, specification* and *validation* to perform a thorough requirement process [25]. Within this part of research, a specification and validation iterations have not been in the scope.

3.2.1 Elicitation

The *requirements elicitation is concerned with the origins of software requirements and how the software engineer can collect them* [25]. In this paper, the authors apply a systematic literature review to identify the passport's requirements scientifically accurately. The research discipline of literature review has established itself and is considered an essential step in the implementation of research projects [26]. It discloses existing research knowledge and established processes in order to gain new insights [26]. The literature search faces the challenge of accurately representing the field of inquiry that the researcher is trying to cover [26]. For this research paper, the PRISMA method (Pre-ferred reporting items for systematic reviews and meta-analyses) is chosen for the literature review process [27,28]. It consists of the four phases *identification*, *pre-selection*, *suitability*, and *final selection* [27]. Structuring the literature search through the appropriate selection of keywords in selected databases and using forward and backward search, relevant articles are efficiently identified [26]. After removing duplicates, the pre-selection is performed by evaluating title and abstract regarding the underlying topic [27]. Subsequently, the suitability of the articles is verified by an analysis of the full text and included in the final selection of the literature review [27].

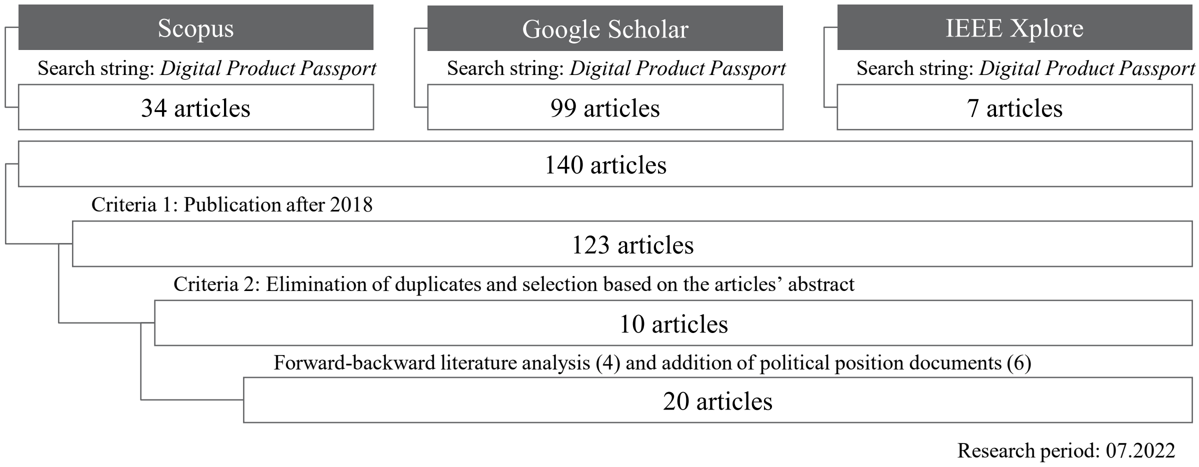

Figure 2 Systematic literature review for the content requirements (own visualization)

Figure 2 shows the literature review process used to identify the relevant literature. Eliminating publications before 2018 and duplicates, 10 articles were initially selected for an in-depth analysis. During this analysis, the forward-backward analysis disclosed additional four papers and it became apparent that the political environment expressed further demands. Therefore, a total of 20 articles were included into the requirement analysis.

3.2.2 Analysis

The requirement analysis traditionally concerns the classification of requirements into a structure that can be implemented [25]. Scanning the identified articles for political and practical expectations regarding the DPP, the requirements have been classified and listed. In total, 19 requirements were identified in table 1.

Table 1: Content requirements for the DPP in the machinery sector

Requirement	Description of requirement	Source
Production method	Ensure availability of components and parts by disclosing production method and technique	[9,29]
Product design	Enable repair and (de-)assembly by making design information public	[8,21,30,9,31,29]
Material composition	Enable recycling by delivering detail information about a product's material composition	[33,9,31,32,29,20]
Product identification	Ensure unique identification of products by integrating individual recognition features	[8,34,29]
Standardization	Disclose information on applied standards and norms	[9,35]
General information	Make available universal product information	[31,35,20]
Storage and transport	Ensure a product's mobility by releasing storage and transport information	[29]
Utilization characteristics	Enable product-specific R-strategies by analyzing utilization data	[29,35,19]
Status assessment	Enable transparency of a product's status and "health" by gathering relevant status information	[7,21,34,9,32,29,19,20]
Performance history	Measure the product performance to derive a product's performance history	[21,29]
Value analysis	Enable information basis to analyze a product's value	[29,20]
Trustworthiness	Ensure reliability of information by including security measures	[7,20]
Compliance	Ensure compliance of Europe-wide and national regulations by including value-chain information	[20]

Location	Map the current and historical locations of a product	[19,20]
Traceability	Ensure tracking and tracing of products and components through different lifecycles	[8,34,30,35,19,20]
End-of-Life	Make available important information on the End-of-Life options	[8,33,30,32,29]
Ecological impact	Make transparent the ecological impact of a product through data transparency	[21,9,31,20]
Social impact	Make transparent the social impact of a product by gathering the relevant information	[20]

3.3 Data Analysis selecting existing information attributes

Within the requirement analysis, it was highlighted that the DPP should be built upon existing information that is easily accessible in organizations. Therefore, a Data Analysis has been applied to identify the content and information baseline of current organizational information systems. Applying a case study research approach, a selection of information systems to scan for data points was made based on the list created by BOOS AND ZANCUL [36,37]. The selection of the information systems is featured in figure 3. Subsequently, a longlist of data points that can be tracked by these systems was derived and summed up to 1.128 data points. Focussing the longlist on a data analysis, two criteria for the selection were established: the abstraction level of *information* must be met and the data point must be product-related. In total, 51 information attributes were selected (see figure 3).

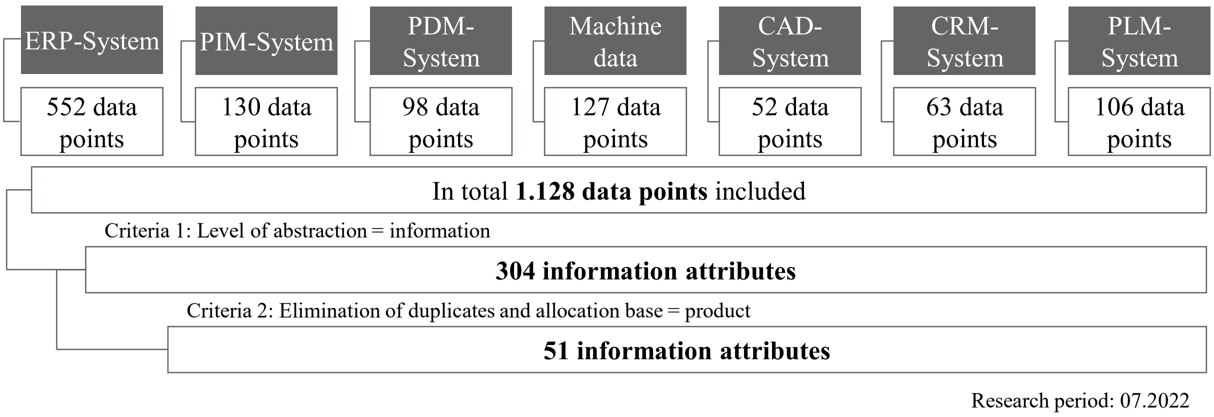

Figure 3 Qualitative data analysis of information systems (own visualization)

4. Classification of Product Data for a Digital Product Passport

Having detailed the research methodology, the classification of Product Data for a DPP of industrial equipment is presented. In total, the classification contains 62 information attributes in 21 sub-categories and 4 main categories. 51 information attributes can be met by current information systems while 11 still need to be developed to meet the DPP's demand. In total, the classification consists of 3 category-levels that are presented in the following. With this classification, software developers have a starting point to build the content architecture of the DPP.

4.1 Categories of the classification

Especially the four main categories and its 21 sub-categories give an indication of the scope of the DPP. This classification allows any user to obtain an overview of relevant content areas when implementing its specific DPP. The four main categories are adapted from BERGER ET AL. and contain *Product information, Utilization information, Value chain information* and *Sustainability information* [21]. The *Product Information* describe master information about the product itself that is mostly non-changeable and known after designing or manufacturing. In contrast, the *Utilization Information* are configurable data that can dynamically be adjusted during its lifecycle and largely consist of usage and service data. The *Value chain Information* contain adjustable data of a product's supply chain to increase transparency along its stakeholders. This especially focuses on its supply chain actors. The *Sustainability Information* contain data to generate a digital twin of ecological, social, and circular information. Figure 4 presents the main and sub-category.

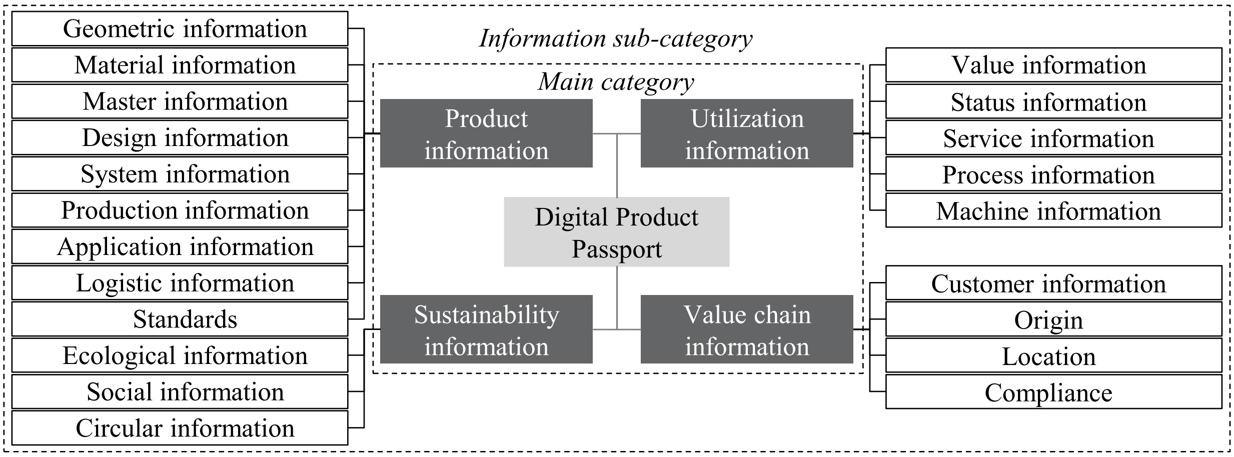

Figure 4 Main categories and sub-categories for the content of a DPP in the manufacturing industry

4.2 Information attributes of the classification of Product Data for a Digital Product Passport in the manufacturing industry

In the following, each sub-category and their information attributes are presented in detail.

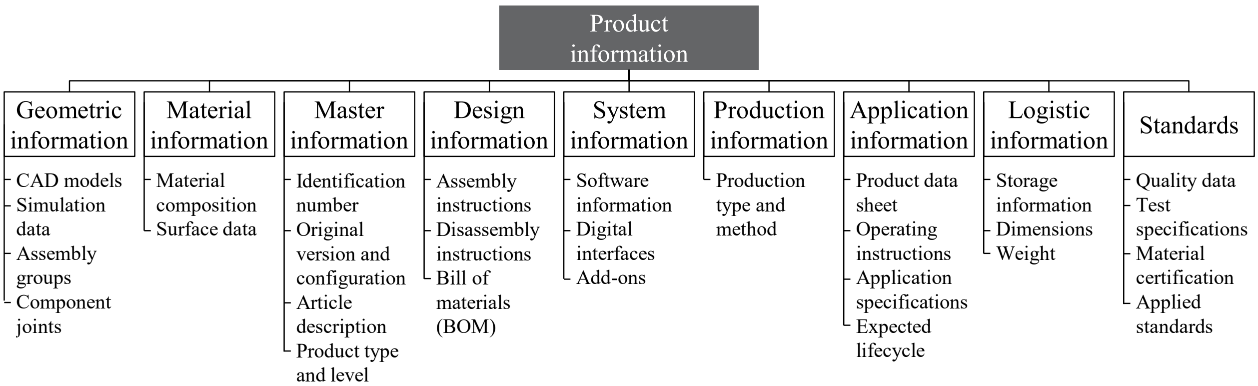

Figure 5 Information attributes of the main category "Product information"

The main category of *Product information* holds 9 sub-categories. The sub-category of *Geometric information* focuses on digital three-dimensional models of a product's components and their grouping. The sub-category *Material information* contains data about the material composition and surface structure of a component. *Master information* consists of identifying and additional data about a product's characteristics. *Design information* provides data about the (de-)assembly and components of a product and industrial equipment. *System information* characterizes a product's digital and software capabilities. *Production information* presents further data about manufacturing processes and applied methods. *Application information* is the category providing further information on how to use and operate the machinery efficiently. *Logistic information* contains all data required to store and transport a product or its components. *Standards* comprises data to achieve test specifications and standards that have been used for the product.

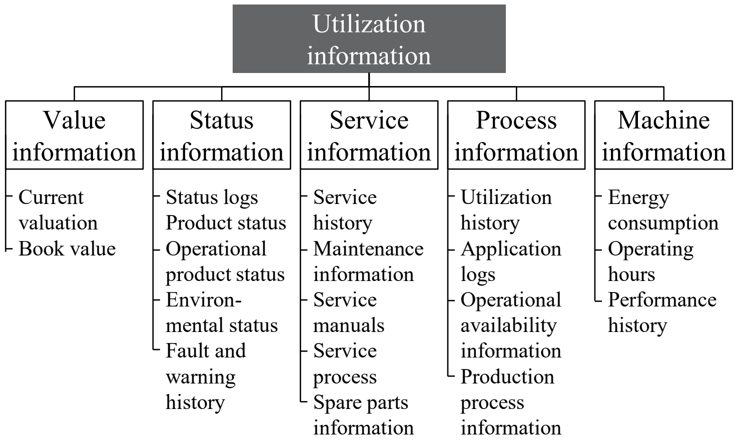

Figure 6 Information attributes of the main categories “Utilization information”

The main category of *Utilization information* has 5 sub-categories. *Value information* is a dynamic figure that stores the current valuation and book value of the industrial equipment. *Status information* describes data of the current and historical condition of the machine storing logs and the warning history. *Service information* stores data about maintenance and service from manuals to service history. *Process information* includes information about the production processes that can be utilized to analyze a machine’s physical condition and performance. *Machine information* contains information about the historical performance and energy consumption that can support in a machine’s condition monitoring.

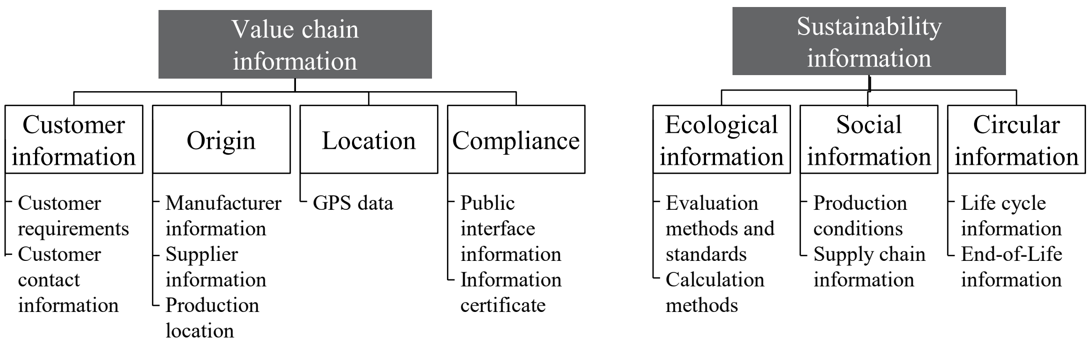

Figure 7 Information attributes of the main categories “Value chain information” and “Sustainability information”

The main category of *Value chain information* comprises 4 sub-categories. *Customer information* includes information about previous users and customers including their specific requirements and usage history. *Origin* stores information about the machine’s origin including location of manufacturing. *Location* contains information about the GPS data and the current location of the machine. *Compliance* describes a class that stores information about interfaces and security measures to comply with public regulations.

The main category of Sustainability information comprises the 3 sub-categories of *ecological, social* and *circular information.* These sub-categories contain all information that is required to generate a comprehensive sustainable picture of the machine.

5. Conclusion and future research

The developed content classification of a DPP in the manufacturing industry is a significant step forward in order to enable organizations to benefit from the potentials of a digital CE. This paper should be seen as opportunity starting a scientific discussion about what information is necessarily required and what is optional. The four categories of *Product Information, Utilization Information, Value chain Information* and *Sustainability Information* give an indication of the information types and areas that are required. The 21 sub-categories enable a comprehensive scope of required information types, that still offer a configurable space depending on the specific use case. In contrast, the 62 information attributes should be seen as initial proposition of relevant material to enable the objective of a digitally enabled CE. It is beneficial that 51 attributes are, in theory, already existing and accessible. However, there is still the challenge to specify 11 attributes that are demanded but not existent in current information systems.

Still undefined is the question of detailing the level of a product-based or component-based DPP. Ideally, component-based DPPs consolidate into a product-based DPP but further research is required to detail the approach. In addition, the classification still requires a validation to review if further information is missing. A validation with software and industry experts should be aimed for to ensure full applicability and integrity. The high abstraction level of the presented classification also necessitates a more detailed data model before implementation. Therefore, future research should focus on connecting the presented information attributes to explicit information software systems and derive a strategy of how to implement common interfaces. This also applies to the information accessibility between different stakeholders in the lifecycle of a machine. This element will be addressed in further research by the authors enabling a digital ecosystem. From an industrial perspective, the industrial players should start building trusted ecosystems in which they can deploy a basic version of the DPP using the identified main categories and gather firsthand experience. Fundamental questions such as a centralized or decentralized architecture can be tested under real-world conditions.

References

[1] European Commission, 2020. A new Circular Economy Action Plan For a cleaner and more competitive Europe, Brüssel. https://eur-lex.europa.eu/resource.html?uri=cellar:9903b325-6388-11ea-b735-01aa75ed71a1.0017.02/DOC_1&format=PDF.

[2] eurostat, 2022. Circular material use rate. European Commission. https://ec.europa.eu/eurostat/databrowser/view/cei_srm030/default/table?lang=en. Accessed 12 October 2022.

[3] Berg, H., Bendix, P., Jansen, M., Le Blévennec, K., Bottermann, P., Pohjalainen, E., Wahlström, M., 2021. Unlocking the potential of Industry 4.0 to reduce the environmental impact of production. Eionet Report.

[4] 2013. Economic and business rationale for an accelerated transition: Towards the Circular Economy. Towards the Circular Economy Vol. 1. https://ellenmacarthurfoundation.org/towards-the-circular-economy-vol-1-an-economic-and-business-rationale-for-an. Accessed 28 February 2022.

[5] Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit (BMU), 2021. Umweltpolitische Digitalagenda: Digitaler Produktpass. https://www.bmu.de/faqs/umweltpolitische-digitalagenda-digitaler-produktpass/. Accessed 11 July 2021.

[6] Berg, H., Le Blévennec, K., Kristoffersen, E., Strée, B., Witomski, A., Stein, N., Bastein, T., Ramesohl, S., Vrancken, K., 2020. Digital circular economy - a cornerstone of a sustainable European industry transformation. https://ss-usa.s3.amazonaws.com/c/308476495/media/19365f987b483ce0e33946231383231/201023%20ECERA%20White%20Paper%20on%20Digital%20circular%20economy.pdf.

[7] Berg, H., Kulinna, R., Guth-Orlowski, S., Stöcker C., Thiermann, R., Porepp, N., 2022. Overcoming Information Asymmetry in the Plastics Value Chain with Digital Product Passports. Wuppertal Paper, Wuppertal. https://epub.wupperinst.org/frontdoor/deliver/index/docId/7940/file/WP197.pdf. Accessed 12 July 2022.

[8] Adisorn, T., Tholen, L., Götz, T., 2021. Towards a Digital Product Passport Fit for Contributing to a Circular Economy. Energies 14 (8).

[9] Götz, T., Adisorn, T., Tholen, L., 2021. Der Digitale Produktpass als Politik-Konzept: Kurzstudie im Rahmen der Umwelpolitischen Digitalagenda des Bundesministeriums für Umwelt, Naturschutz und nukleare Sicherheit

(BMU). 20_Wuppertal Report, Wuppertal. https://epub.wupperinst.org/frontdoor/deliver/index/docId/7694/file/WR20.pdf.

[10] Bourguignon, D., 2016. Closing the loop: New circular economy package, Brüssel.

[11] Ellen MacArthur Foundation, 2015. Towards a Circular Economy: Business Rationale for an Accelerated Transition. https://www.ellenmacarthurfoundation.org/publications/towards-a-circular-economy-business-rationale-for-an-accelerated-transition. Accessed 25 May 2021.

[12] Pearce, D.W., Turner, R.K., 1994. Economics of natural resources and the environment, 3. Dr ed. The Johns Hopkins Univ. Press, Baltimore, 378 pp.

[13] Andersen, M.S., 2007. An introductory note on the environmental economics of the circular economy. Sustain Sci 2 (1), 133–140.

[14] Potting, J., Hekkert, M., Worrell, E., Hanemaaijer, A., 2017. Circular Economy: Measuring Innovation in the Product Chain: Policy Report. PBL Netherlands Environmental Assessment Agency, The Hague. https://www.pbl.nl/sites/default/files/downloads/pbl-2016-circular-economy-measuring-innovation-in-product-chains-2544.pdf. Accessed 7 March 2022.

[15] Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the circular economy: An analysis of 114 definitions. Resources, Conservation and Recycling 127, 221–232.

[16] Thierry, M., Salomon, M., van Nunen, J., van Wassenhove, L., 1995. Strategic Issues in Product Recovery Management. California Management Review 37 (2), 114–136.

[17] Klenk, F., Gleich, K., Meister, F., Häfner, B., Lanza, G., 2020. Approach for developing implementation strategies for circular economy in global production networks. Procedia CIRP 90, 127–132.

[18] Tolio, T., Bernard, A., Colledani, M., Kara, S., Seliger, G., Duflou, J., Battaia, O., Takata, S., 2017. Design, management and control of demanufacturing and remanufacturing systems. CIRP Annals 66 (2), 585–609.

[19] Portillo-Barco, C., Charnley, F., 2015. Data requirements and assessment of technologies enabling a product passport within products exposed to harsh environments: A case study of a high pressure nozzle guide vane. International Journal of Product Lifecycle Management 8 (3), 253–282.

[20] Walden, J., Steinbrecher, A., Marinkovic, M., 2021. Digital Product Passports as Enabler of the Circular Economy. Chemie Ingenieur Technik 93 (11), 1717–1727.

[21] Berger, K., Schöggl, J.-P., Baumgartner, R.J., 2022. Digital battery passports to enable circular and sustainable value chains: Conceptualization and use cases. Journal of Cleaner Production 353.

[22] Vessey, I., Ramesh, V., Glass, R.L., 2005. A unified classification system for research in the computing disciplines. Information and Software Technology 47 (4), 245–255.

[23] Bailey, K.D., 1994. Typologies and taxonomies: An introduction to classification techniques. SAGE, Thousand Oaks, Calif., 90 pp.

[24] Bailey, K.D., 2005. Typology Construction, Methods and Issues, in: , Encyclopedia of Social Measurement. Elsevier, pp. 889–898.

[25] Bourque, P., Fairley, R.E., 2014. SWEBOK v3.0: Guide to the Software Engineering Body of Knowledge. IEEE, Piscataway, 346 pp.

[26] vom Brocke, J., Simons, A., Niehaves, B., Riemer, K., Plattfaut, R., Cleven, A., 2009. Reconstructing the Giant: On the Importance of Rigour in Documenting the Literature Search Process, in: Newell, S., Whitley, E.A., Pouloudi, N., Wareham, J., Mathiassen, L. (Eds.), Information systems in a globalising world. ECIS 2009, 17th European Conference on Information Systems, Verona, May 08 - 10 June, 2009 ; proceedings, Verona, pp. 2206–2217.

[27] Moher, D., Liberati, A., Tetzlaff, J., Altman, D.G., 2009. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. BMJ (Clinical research ed.) 339, b2535.

[28] Page, M.J., McKenzie, J.E., Bossuyt, P.M., Boutron, I., Hoffmann, T.C., Mulrow, C.D., Shamseer, L., Tetzlaff, J.M., Akl, E.A., Brennan, S.E., Chou, R., Glanville, J., Grimshaw, J.M., Hróbjartsson, A., Lalu, M.M., Li, T., Loder, E.W., Mayo-Wilson, E., McDonald, S., McGuinness, L.A., Stewart, L.A., Thomas, J., Tricco, A.C., Welch, V.A., Whiting, P., Moher, D., 2021. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ (Clinical research ed.) 372, n71.

[29] Nippraschk, M., Goldmann, D., 2020. Recycling 4.0 - System Dynamics as a Control Tool for Raw Material and Information Flows in the Circular Economy, in: Holm, O., Thomé-Kozmiensky, E., Goldmann, D., Friedrich, B. (Eds.), Recycling und Rohstoffe. Thomé-Kozmiensky Verlag GmbH, Neuruppin, pp. 610–623.

[30] Europäische Kommission, 2019. Der europäische Grüne Deal: Mitteilung der Kommission an das Europäische Parlaement, den Europäischen Rat, den Rat, den Europäischen Wirtschafts- und Sozialausschuss und den Ausschuss der Regionen, Brüssel.

[31] Luscuere, L.M., 2017. Materials Passports: Optimising value recovery from materials. Proceedings of Institution of Civil Engineers: Waste and Resource Management 170 (1), 25–28.

[32] Müller, F., Kohlmeyer, R., Krüger, F., Kosmol, J., Krause, S., Dorer, C., Röhreich, M., 2020. Leitsätze einer Kreislaufwirtschaft, Dessau-Roßlau. https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2020_04_27_leitlinie_kreislaufwirtschaft_bf.pdf. Accessed 11 July 2022.

[33] 2020. Umweltpolitische Digitalagenda, Berlin. https://www.bmu.de/fileadmin/Daten_BMU/Pools/Broschueren/broschuere_digitalagenda_bf.pdf.

[34] Donetskaya, J., Gatchin, Y., 2020. A generalization of approaches to creating a digital passport supporting the stages of the electronic product life cycle and the features of the formation of design decisions based on it, in: Scientific Technical Union of Mechanical Engineering "Industry 4.0" (Ed.), Industry 4.0. International Scientific Journal, vol. 5, Sofia, pp. 101–104.

[35] Plociennik, C., Pourjafarian, M., Nazeri, A., Windholz, W., Knetsch, S., Rickert, J., Ciroth, A., Precci Lopes, A.d.C., Hagedorn, T., Vogelgesang, M., Benner, W., Gassmann, A., Bergweiler, S., Ruskowski, M., Schebek, L., Weidenkaff, A., 2022. Towards a Digital Lifecycle Passport for the Circular Economy. Procedia CIRP 105, 122–127.

[36] Boos, W., Zancul, E., 2012. PPS-Systeme als Bestandteil des Product Lifecycle Management, in: Schuh, G., Stich, V. (Eds.), Produktionsplanung und -steuerung 2. Evolution der PPS, 4., überarbeitete Auflage ed. Springer Berlin / Heidelberg, Berlin, Heidelberg, pp. 336–364.

[37] Eisenhardt, K.M., 1989. Building Theories from Case Study Research. The Academy of Management Review 14 (4), 532.

Biography

Lukas Stratmann holds an M.Sc. RWTH degree in Mechanical Engineering and Business Administration from the RWTH Aachen University. He is currently doctoral candidate at the FIR Institute for Industrial Management and team leader for Ecosystem Design. His specific focus is research in circular ecosystems and how stakeholders can be incentivized to implement a Circular Economy.

M.Sc. M.Sc. **Gerrit Hoeborn** is head of the Business Transformation department at RWTH Aachen University. He joined the department after his studies in industrial engineering at the RWTH Aachen University and Tsinghua University. His research focus is business transformation and digital business strategies.

Christoph Pahl completed his bachelor's and master's degree industrial engineering at the RWTH Aachen University. As part of his master's thesis, Mr. Pahl worked on the classification of product information for the conceptualization of a digital circular economy. In particular, he focused on circular product properties and relevant product information which are necessary for a digital information system in a circular economy.

Prof. Dr.-Ing. Dipl.-Wirt.-Ing. Günther Schuh is the director of the Institute for Industrial Management (FIR) at RWTH Aachen University, holds the Chair for Production Systems at the WZL, and is a member of the board of directors of the Fraunhofer Institute for Production Technology IPT in Aachen. Professor Schuh is a member of several supervisory boards and boards of directors.

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Data Enabled Failure Management Process (DEFMP) across the Product Value Chain

Robin Günther[1], Martin Wende[2], Sebastian Baumann[3], Felix Bartels[4], Sebastian Beckschulte[1], Goy Hinrich Korn[4], Robert H. Schmitt[1,2]

[1] Laboratory for Machine Tools and Production Engineering WZL of RWTH Aachen University, Aachen, Germany
[2]Fraunhofer Institute for Production Technology IPT, Aachen, Germany
[3]DATAbility GmbH, Darmstadt,Germany
[4]KRONE Business Center GmbH & Co. KG, Spelle, Germany

Abstract

The continuously increasing amount of production data and the advancing development of digitization solutions promote advanced data analytics as a promising approach for failure management. Beyond the consideration of single units, examining the end-to-end value chain, including development, production, and usage, offers potential for failure in management-related investigations. Nonetheless, challenges regarding data integration from different entities along the value creation process, data volume and formats handling, effective analytics, and decision support arise. The CRISP-DM approach has become a widely established reference as a conceptual framework for data-driven solutions. However, the linkage between existing failure management procedures and the subsequent development of data-driven solutions needs to be specified. Accordingly, this paper presents a cross-value chain Data Enabled Failure Management Process (DEFMP). The central element is a process model to implement a cross-value chain data-enabled failure management, considering established quality management and data analytics approaches. Based on available failure, product, and process knowledge along the value chain, a path towards developing a comprehensive decision support system is shown. DEFMP combines a reactive failure process with a data-driven approach to incorporate data analytics for proactive improvements. Using DEFMP, the failure management process of a commercial vehicle manufacturer is adapted. With this, partial automation of failure management is made possible. In addition, the potential for improvements is identified and prioritized.

Keywords

Data Analytics; Data Management; Decision Support; Data Enabled Failure Management Process; Production; Value Chain

1. Introduction

Failure management deals with the systematic detection, analysis and correction of failures while pursuing proactive measures to obtain quality knowledge and prevent failures before occurrence [1, 2]. Currently, data utilization across the entire value chain is limited and complex structures and interrelations within the value chain cannot be uncovered [3, 4]. Applied to use cases of the commercial vehicle industry, which is characterized by complex production and distribution networks, the potentials of data-enabled failure management across the value chain are explored. A prerequisite for fully exploiting the potential of failure management is the horizontal integration of value-creation networks [5]. Integrating data sources and collaborative data use along the value chain enables the uncovering of far-reaching interrelations between involved partners and divisions [6].

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Deploying data-based methods, particularly their embedding into existing failure management procedures, is still a significant challenge for companies. This can be explained by the need for a precise analysis strategy or a deficit of methodological knowledge [7]. Several reference models already intend to standardize the data analytics approach. Particularly worth highlighting is the Cross-industry Standard Process for Data Mining (CRISP-DM), which has become quite established for industrial applications [8]. Even though this process already guides data analysis projects, transferability to challenges of failure management is not trivial since specific requirements of the discipline are not considered. Furthermore, integrating data-based solutions into existing improvement procedures is not further specified. Expanding the focus beyond the company's boundaries further enhances the complexity of data-driven approaches. In addition to increasing data preparation and processing requirements, systematic mechanisms for integrating various data sources are necessary. It becomes apparent that the procedure requires further development to create a suitable framework for use cases of cross-value chain failure management.

Accordingly, this paper aims to outline and specify a methodology concept for cross-value chain failure analysis in the use case of the commercial vehicle industry. The standard procedure of the CRISP-DM is extended according to the specific requirements of the target area. Furthermore, a direct connection to existing failure management procedures is shown. Challenges and potentials of cross-site data exploitation enable comprehensive decision support for reactive and proactive handling of failures. The paper is structured as follows: Chapter 2 shows relevant reference models of adjacent fields. Subsequently, the requirements and objectives of cross-value chain failure management are discussed (chapter 3). Chapter 4 describes the structure of the DEFMP in detail. The evaluation of the methodology is carried out in chapter 5. Finally, the reflection on the results and the following work are presented in chapter 6.

2. Foundations

2.1 Failure Management Processes for Production Environments

To improve the company's overall performance, the efficient identification and elimination of failures is a primary objective [9]. A holistic failure management approach is essential to elaborate adequate measures for achieving quality goals, for example, preventing failures before their occurrence. [10]. The tasks of failure management include the recording, evaluation, and elimination of failures as well as failure prevention in following products through a corresponding analysis of the failure causes. The central aspect is the purposeful provision and processing of relevant information. This is crucial for building a knowledge base of previously solved failures [11]. In the literature, various reference processes are dedicated to failure identification, processing, and avoidance.

The earliest relevant approach that deals comprehensively with failure elimination in production is the phase model, according to HOFMANN. Starting with failure detection, the model shows five phases for failure elimination [12]. The SAFE model offers a comprehensive concept for the design of failure management in manufacturing environments. The process model consists of eight steps that derive preventive and reactive measures for failure avoidance or elimination. The importance of systematic archiving of failure knowledge is emphasized. In addition to prioritizing failure cases, selecting suitable measures is facilitated to continuously improve the decision process in the event of failures [13]. The Complaint and Failure Management Model (CFM) describes a data-oriented reference process. The CFM is a sub-process of the Aachen Quality Management Model, which represents the company's interaction of quality-creating processes, management, and support services. In this regulatory framework, CFM can map process-based and data-supported quality control loops and report failure knowledge to companies in a targeted manner. The CFM thus forms a regulatory framework but remains at a high level of abstraction despite the precise design of the individual elements [14]. Therefore, recent research is expanding the CFM model by considering data quality aspects. Focusing on manual assembly, mechanisms for standardizing the failure type and object description are discussed. A consistent description of the failure information improves the data quality and simplifies the failure analysis [15].

The approaches considered present a distinct development in the failure management process. In many cases, generic reference processes are derived and described, which must be run through for a successful failure correction. The contents of the individual process steps show some similarities. It can be determined that the topic of data organization receives special attention in most approaches. For example, ORENDI and CFM provide the first possible solutions without going into more detail about possible data analytics methodologies. In particular, the interaction across the product value chain is not considered.

2.2 Data Analytics Methodologies

Standard processes to enable data-driven decisions are already well established. Common process models are CRISP-DM (Cross Industry Standard Process for Data Mining), KDD (Knowledge Discovery in Databases), and SEMMA (Sample, Explore, Modify, Model, Assess) [15]. Many of the individual sub-steps are comparable or identical between the three approaches. Especially the CRISP-DM methodology has established itself as a standard methodology as it provides a structured approach for data mining projects. The phases of business understanding, data understanding, data preparation, modelling, evaluation and deployment are distinguished [16]. The steps are carried out sequentially. However, different iterations between the steps are recommended. In recent years, different adaptions have been suggested to address case-specific requirements [17]. Especially with a strong focus on machine learning applications, multiple extensions of CRISP-DM regarding data preparation and modelling have been developed [18].

Regarding quality management, approaches to harmonize existing quality management standards with data analytics methods already exist. SCHÄFER ET AL. combine quality management methods of the DMAIC cycle with corresponding steps of the CRISP-DM. The result forms the integrated QM-CRISP-DM cycle [19]. HUBER ET AL. pursue a similar approach and consider specific engineering requirements [20]. In particular, the increased complexity in engineering assessment and implementation plays a leading role. The resulting data mining methodology for engineering (DMME) adds the phase of technical understanding before data understanding. The addition of the process step allows for evaluating the technical problem and implementing necessary technical adjustments to extract relevant data. Additionally, they add a phase for technical implementation prior to the implementation phase, as the solution deployment likely requires technology changes.

2.3 Reflection

CFM and CRISP-DM are widely accepted approaches. However, these are unsuitable for implementing a cross-value chain failure management approach due to the absence of essential process steps and, in particular, a need for more linkage between the two areas of failure management and data analytics. The reference models in failure management provide different frameworks for standardized (reactive and prospective) failure investigation and strategies for continuous improvement. Knowledge transfer as structured documentation is already discussed, and, in some cases, analysis methods are implied. However, the approaches merely address internal improvement processes. Furthermore, appropriate data analytics methodologies and practical strategies for their deployment are not provided.

Data analytics approaches enable a structured deployment of data-based solutions. Nevertheless, the CRISP-DM and related extensions show deficits for immediate application in commercial vehicle production networks. Even if quality orientation becomes more important in data analytics, the specific failure management requirements still need to be addressed, for example, by defining a link between existing failure management initiatives and the deployment of advanced analytics. Additional challenges arise from broadening the investigation focus to additional data from various stakeholders. This challenge requires introducing an extra step of data integration to enable the use of quality knowledge and process and product data from different phases along the value chain. This reveals a need for a structured methodology that meets the challenges of cross-value chain data exploration and seamlessly connects to existing failure management procedures – building on existing quality knowledge.

3. Objective and requirements for a cross-value chain failure management

According to chapter 2.3, there is a need for further development of existing data analytics and failure management approaches. Through additional design workshops at companies in the commercial vehicle industry, relevant gaps and potentials for failure management were identified. The main aspects being addressed in this regard are the following:

Failure identification and handling need to incorporate both internal failures during production and external failures and associated data beyond a company's boundaries. This requires the development of rule-based failure identification methods and advanced analytics to identify trends and provide forecasts. Mechanisms are required that allow efficient handling of failure events and foster knowledge management for continuous improvement.

Data integration and valorization are essential components of cross-value chain failure management. Collecting and interconnecting process data from relevant product lifecycle phases (deployment, production, usage, recycling) is needed to generate meaningful data-driven insights and optimizations. Technical challenges, e.g., providing sufficiently detailed data, are to consider. Existing expert knowledge on processes, failure patterns, process and product characteristics must also be made available because many characteristics are not, or only insufficiently, contained in measured data points. Furthermore, information security is of central importance. Requirements towards confidentiality (restrict access appropriately), integrity (data validity), and availability (service functionality) are to apply.

Data-enabled services provide d*ecision support* to stakeholders across the value chain. These need to complement existing failure management mechanisms and allow advanced insight generation. The failure management-related deployment objectives, process optimizations, availability optimizations, and performance optimizations are considered [21]. Process optimizations aim to identify failure sources, implement predictive quality control in the manufacturing process, and evaluate associated failure costs, risks, and proactive measures. Availability and performance optimization provides extensive condition information and maintenance and usage recommendations for customers. The benefits provided to manufacturers are advanced failure knowledge regarding costs, time in service, and quality decline, including failure forecasting. To address different stakeholders from development, production, quality management, and usage, different areas of improvement are considered:

- **Process optimization**
  Field level: Employees receive advanced information on the production order, including failure risks for the product and measures for failure avoidance and resolution.
  Control and operation level: For daily and intraday reviews, advanced failure information is aggregated in terms of cost, time, and patterns. This serves an early identification of trends and anomalies, derivation of actions at an early stage and the support of failure control working and planning groups.
- **Availability & performance optimization**
  Customer level: Product users receive information on current system states (e.g., for health monitoring) and optimized recommendations for maintenance (regarding minimal costs and downtime) to prevent malfunctions and failures.
  Operation level: In addition to the advanced failure information mentioned above, indications of possible failure causes are relevant for the availability extension. The availability of spare parts or maintenance initiatives can be initiated on time.

4. Data-Enabled Failure Management Process (DEFMP)

Fig. 1 shows the approach of the Data-Enabled Failure Management Process (DEFMP). Two interconnected sub-control loops are distinguished. The inner loop describes the failure management process for the reactive and proactive handling of failure cases and the corresponding accumulation of quality knowledge. The outer control loop presents the procedure for developing extended analysis methods. Both sub-control loops rely on continuous monitoring and diagnosis. Established procedures and software applications are necessary to acquire relevant data along the entire product life cycle. The inner and outer control loop and the principle of their interaction are explained below.

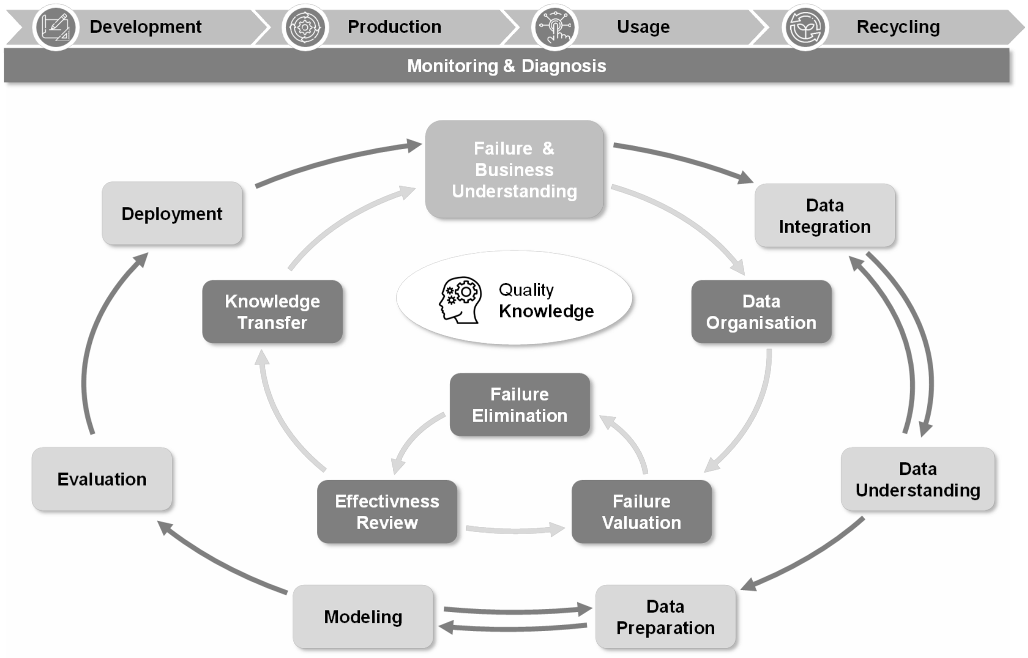

Fig. 1: Data Enabled Failure Management Process across the Product Value Chain

4.1 Inner control loop - Building Quality Knowledge

The failure management process presented in the inner control loop of the DEFMP is based on the previously presented CFM model (see chapter 2.1). Compared to the reference model, the failure management process is built as a loop. This considers the continuous learning process, and necessary feedback loops during the resolution process are represented. Starting with the phase of *Failure and Business Understanding* serves to investigate the problem prior to the failure handling itself. In addition, an initial assessment of significant influencing factors and relevant information is included. For manual assembly, the employee in charge carries out the initial assessment of the problem and the initiation of further action. This phase can also include comprehensive project management, which defines responsibilities and allocates resources and capacities in case of more complex issues. An important part is the failure identification along all considered processes. For this purpose, several quality sensors must be available, which, on the one hand, support the continuous process monitoring and diagnosis and, on the other hand, identify occurring or occurred failures as early as possible. *Quality Knowledge* forms the centrepiece of failure handling. It reflects the expertise in dealing with quality-oriented issues. The existing quality knowledge is used to process failures. In addition, the knowledge base is supplemented or updated according to the results gained during the loop. Findings on cause-effect correlations and effective and ineffective measures are incorporated following failure processing. Therefore, several data sources must be considered. Proper information management for structured and comprehensive *Data Organization* benefits this context. Targeted documentation and provision of relevant information for the considered case is thus a critical business resource. A well-structured and systematically implemented failure database provides fast access to existing failure knowledge. Identified failures are described or coded according to predefined rules and supplemented with further information. By comparing the data with explicit failure descriptions or codes, documented knowledge can be accessed easily. Particularly when recurring failures or similarities occur, problems that have already been solved provide essential assistance in identifying root causes and deriving suitable measures.

The *Failure Valuation* is carried out with the help of already documented failure information. This step can be described as pre-analysis and evaluates the failure's severity and relevance. It is beneficial in the case of many failure events to be processed. Based on the relevance, prioritization can be performed. By comparing detected characteristics with the existing quality knowledge, it is possible to derive indications for problem-solving. Based on the existing quality knowledge, measures declared successful are selected to resolve the failure rapidly. If there is no documentation of measures, a solution-finding process is needed; for example, within the project team defined at the beginning. The actual failure handling takes place within the *Failure Elimination and Prevention*. Following the elaboration, measures are initiated. A distinction can be made between immediate and long-term measures. The former address failure symptoms and are intended to prevent further failure consequences. In addition, long-term measures address the root cause for preventing failure repetition. Initiated countermeasures must be checked with an *Effectiveness Review*. If a measure has not led to the expected success, the failure case must be re-evaluated, and further initiatives must be developed. If the measure is successful, the information is made usable for future failure processes. For this purpose, a *Knowledge Transfer* is included, which incorporates the findings of the failure management process into the quality knowledge. According to the step of data organization, a systemic, structured recording is beneficial as a supplement to the failure description.

Established failure management is a prerequisite for initiating extended, data-based analysis tools. The process step *Failure and Business Understanding* interconnect both control loops. The expertise gained during historical failure processing and the resulting quality knowledge is incorporated into developing data-based decision support. Insights from data analyses and permanently applicable solutions supplement established failure management routines, see chapter 4.2 and 4.3.

4.2 Outer control loop – Evolution through Data Integration

The outer loop of the DEFMP likewise begins with *Failure and Business Understanding*. The digitization potential of a failure management use case is evaluated during the failure process's initiation by the project team in charge. The resources and capabilities required, the objectives pursued, and the associated analysis strategy must be defined. After this initial assessment, the outer control loop can be triggered by the group of process and data experts. The next phase is *Data Integration*, which is not part of the CRISP-DM approach. However, it plays an essential role in cross-value chain failure management, as data from different sources must be included in the decision-making process. Accordingly, a stand-alone process phase is introduced in DEFMP to address this challenge. In industrial practice, products are usually assigned by identification numbers to enable mapping to captured data (entity matching). It is usually sufficient to create an assignment logic for simple problems in an industrial context. For more complex matching problems, sophisticated automatic or rule-based approaches must be developed [22]. Another crucial aspect is the selection of a suitable digital infrastructure. Established databases and platforms rely on data integration in a single, trusted source. Recent research approaches investigate data ecosystems based on decentralized data sources combined with a management system to provide semantics and access controls (cf. [23]). Both architectures are subject to precise data security requirements to restrict access to authorized individuals, protect data from tampering, and ensure accessibility.

Already during the integration phase, data quality is of high importance [24]. Therefore, steps of *Data Preparation* and *Data Integration* are iterated when beneficial. An example is the preliminary data reduction to reduce the storage requirements throughout data integration. Following the additional data integration phase, the established phases of CRISP-DM are likewise relevant in failure management. Regarding *Data Preparation* and *Modeling*, typical challenges of failure management are the classification of process success (good / not good), regression models to predict points of failure and anomaly detection, classification models to predict failure causes and suitable measures or clustering to identify unknown failures. For *Evaluation*, using model accuracy as a performance metric is often insufficient. Many cases in the failure management context contain a relatively small ratio of failures, consisting of imbalanced datasets. Recall, MCC and F1 score are relevant metrics in such cases.

Deployment in DEFMP needs to be suited to provide decision support regarding specific actions after failure recognition and to uncover areas for improvement. For this purpose, suitable options for displaying anomalies and incidents and key figures for assessing criticality must be established as part of the deployment. The realization of such a decision support system requires close communication with experts from different departments. For this purpose, communication mechanisms that enable an immediate valuation of the generated recommendations for action must be included. On this basis, a knowledge management system is implemented that enriches the quality knowledge and cleans it of erroneous correlations. The step-by-step data optimization increases the performance of the models.

4.3 Interaction of the control loops – The Data-enabled Failure Management

DEFMP comprises the two control loops to combine knowledge and data-driven approaches to failure management. Focusing on efficient actions for problem solving, the inner loop requires rapid technical understanding of the failure and expertise-driven actions. The outer circle utilizes existing quality knowledge and supplements it with expanded data from relevant value chain stages. Using data analysis methods, failure management-related decision-making processes are systemized. Despite the different approaches, the two control loops are highly codependent and can enable one another. The inner loop of DEFMP benefits from data-enabled failure information. A quantified failure analysis facilitates the prioritization of failures and the definition of fast and decisive actions. This is particularly important if security concerns or high-quality costs are associated with a specific failure. Quantified transparency regarding the number of potentially affected products can aid in the initial assessment.

As product complexity increases, cause-and-effect relationships of failures are difficult to distinguish. Especially machine learning models need to be equipped to uncover if two events are correlated or caused by one another. Therefore, expert and domain knowledge are necessary to use machine learning in failure management effectively. Likewise, the outer loop in DEFMP is enabled. Hence, the inclusion of quality knowledge and domain expertise is required to develop effective data-enabled decision support systems.

5. Evaluation

DEFMP is implemented and tested on use cases in the logistics and commercial vehicle industry for cross-value chain assessment. One use case deals with expertise- and data-based failure warning systems based on existing failure handling processes. The goal is to identify relevant failure accumulations that occur in the utilization phase of trailers at an early stage. Currently, the identification of relevant failure accumulations is primarily based on the experience and subjective assessment of employees in quality management. The preparation of quality data is carried out manually and on request. Each analysis requires a particular dataset and time-consuming pre-processing. In addition, resulting reports are static, therefore preventing further investigations on-the-fly. Anomalies are communicated in weekly steering committees for failure management. In these panels, results of root-cause analyses for specific failure patterns are discussed, and appropriate measures for their elimination are defined. Furthermore, already implemented measures are evaluated, and a knowledge database is used to document the collected findings. In conclusion, current activities in failure management are limited to the inner loop displayed in Fig. 1 and, therefore, heavily rely on quality knowledge stored in employees' minds.

DEFMP now offers an approach to extend the existing failure management process with data-driven analytics to accelerate the identification of relevant failure accumulations. As an intermediate result, a web-based dashboard was developed, providing data insights to employees in quality management. After uploading a data sample, initial analytical processes are automatically performed, and their results are presented to the user, thus allowing for quick insights on key metrics. Furthermore, dynamic filter options were implemented to enable on-the-fly analysis as a basis for steering committee discussions and explorative data analytics. Besides, rule-based valuation of failure criticality and standardized data processing algorithms provide increased objectiveness.

A key challenge is integrating data from multiple sources along the value chain. Here, the iterative nature of DEFMP allows for the gradual implementation of these sources one by one. This helps break down the complexity of data integration into smaller, more manageable tasks while enabling learning from experience. The focus is on ensuring a uniform structure of failure data and its enrichment with further information required for developing AI models. In this case, the primary data source is customer complaints with a corresponding service contract. Using an existing tool, failures are documented by service workshops. Standardized selection masks are used to describe the location and type of failure. All information is mapped to a specific vehicle via the vehicle identification number. This way, further information from different data sources can easily be added. As of now, it is already possible to observe failure frequencies and costs.

Following the guideline provided by DEFMP, future efforts will focus on implementing advanced machine learning algorithms for automated anomaly detection and trend evaluation. In addition, appropriate alert mechanisms must be defined, allowing for effective communication that provides a user-oriented indication of failure accumulations. For such instances, the inner loop focusing on expert-driven actions and developing new solutions for problems remains indispensable. With inner and outer control loop operating alongside the existing failure management process is enhanced by a data-driven decision support system enabling increased quality and speed of failure assessment.

6. Conclusion

The DEFMP represents a framework that enables the initiation of data-based analyses for cross-value chain failure management. A logical linkage with existing procedures, including the quality knowledge of a company, was explicitly highlighted. The inner circle of the process model contains the activities to quantify and resolve a failure through immediate actions. Likewise, data-enabled methods in the outer loop are incorporated to expand the quality knowledge and provide decisions to solve quality issues. Integrating data from different value chain stages require additional measures to ensure data security, especially with increasing parties involved. For this reason, data-oriented reference models were expanded to include data integration as a fundamental activity. Applied in the commercial vehicle industry, the cross-value chain data integration approach for failure management enables the quantified linkage of failures with production data.

In future activities, data integration approaches, including aspects of data security, must be explored further to handle different use cases. Subsequent studies will focus on deriving a standardized procedure for evaluating existing systems and data structures. The goal is to gain insight into existing interdependencies, data types, and data quality. Based on an ideal reference process, existing structures and data streams will be identified, and gaps in information availability will be revealed. This approach prepares the further development of decision support by identifying stakeholders within the processes requiring systemic support. In addition, the focus is on developing standardized data architecture models for the operational implementation of data integration. Furthermore, methods of the modelling phase are to be applied that make the data volume processable for comprehensive decision support.

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References

[1] Türtmann, R., Glöckner, H., Falk, B., Schmitt, R., 2017. Conceptual Modelling in the Failure Management Process in Manufacturing Industry. Total Quality Management & Business Excellence 28, 1041-1053.

[2] Exner, R., 2019. Quantitatives Modell zur Unterstützung des Fehlermanagements, Aachen.

[3] Schmitt, R., Falk, B., Voet, H., Fels, A., Rüßmann, M., 2016. Smart Quality – QM im Zeitalter von Industrie 4.0.

[4] Thiele, T., Hoffmann, M., Meisen, T., 2017. Industrial Big Data: Tieferes Prozessverständnis durch Daten Modernes Informationsmanagement in der Produktion. Industrie Management 4, 57–60.

[5] Wang, S. et al., 2016. Implementing Smart Factory of Industrie 4.0: An Outlook. International Journal of Distributed Sensor Networks 1/12.

[6] Geilgens, J., 2021. Wie können Lieferketten mithilfe intelligenter Datennutzung und Datenintegration fit für die Zukunft gemacht werden? Wirtschaftsinformatik & Management 13, 14–19.

[7] Groggert, S., Wenking, M., Schmitt, R.H., Friedli, T., 2017. Status Quo and Future Potential of Manufacutring Data Analytics - An Empirical Study, in: 2017 IEEE International Conference on Industrial Engineering and Engineering Management. pp. 779-783.

[8] F. Martínez-Plumed et al., 2019. CRISP-DM Twenty Years Later: From Data Mining Processes to Data Science Trajectories," in: IEEE Transactions on Knowledge and Data Engineering, vol. 33, no. 8, 3048-3061.

[9] Türtmann, R., Rüssmann, M., Schröder, M., Schmitt, R., 2016. Challenges and Design of a Dataoriented Complaint and Failure Management, in: Total Quality Management & Business Excellence, 16., Nr. 9, 1-12.

[10] Linß, G., 2018. Qualitätsmanagement für Ingenieure, Munich.

[11] Beckschulte, S., Liang, J., Günther, R., Schmitt, R.H., 2021. Managing Complex Interactions between Production and Failure Management: a System-theoretical Model, in: 2021 IEEE International Conference on Electrical, Computer and Energy Technologies. pp. 1-5.

[12] Hofmann, P., 1990. Fehlerbehandlung in flexiblen Fertigungssystemen. Einführung für Hersteller und Anwender, Nuremberg.

[13] Ellouze, W., 2010. Entwicklung eines Modells für ein ganzheitliches Fehlermanagement. Ein prozessorientiertes Referenzmodell zum effizienten Fehlermanagement. Berichte aus der Fertigungstechnik. Shaker, Aachen.

[14] Tuertmann, R., Ruessmann, M., Schroeder, M., Linder, A., Schmitt, R., 2016. Challenges and design of a data-oriented complaint and failure management. Total Quality Management & Business Excellence 27, 885–896.

[15] Beckschulte, S., Günther, R., Kiesel, R., Schmitt, R. H., 2022. Quality Improvement through Data Analysis – Qualification of Failure Management by Standardized Failure Recording in Manual Assembly, in: Behrens B.A, Brosius A, Drossel W.G, Hintze W, Ihlenfeldt S, Nyhuis P, editors. Production at the Leading Edge of Technology. WGP 2021. Lecture Notes in Production Engineering, 574-582.

[16] Shafique, U., Qaiser, H., 2014. A Comparative Study of Data Mining Process Models (KDD, CRISP-DM and SEMMA). International Journal of Innovation and Scientific Research 12 (1), 217–222.

[17] Wirth, R., Hipp. J., 2000. CRISP-DM: Towards a Standard Process Model for Data Mining, in: Proceedings of the 4th international conference on the practical applications of knowledge discovery and data mining. pp. 29–39.

[18] Martinez-Plumed, F., Contreras-Ochando, L., Ferri, C., Hernandez-Orallo, J., Kull, M., Lachiche, N., Ramirez-Quintana, M.J., Flac, P., 2021. CRISP-DM Twenty Years Later: From Data Mining Processes to Data Science Trajectories. IEEE transactions on knowledge and data engineering 33 (8), 3048–3061.

[19] Schröer, C., Kruse, F., Gómez, J.M., 2021. A Systematic Literature Review on Applying CRISP-DM Process Model. Procedia Computer Science 181, 526–534.

[20] Schafer, F., Zeiselmair, C., Becker, J., Otten, H., 2018. Synthesizing CRISP-DM and Quality Management: A Data Mining Approach for Production Processes, in: 2018 IEEE ICTMOD. pp. 190–195.

[21] Huber, S., Wiemer, H., Schneider, D., Ihlenfeldt, S., 2019. DMME: Data mining methodology for engineering applications – a holistic extension to the CRISP-DM model. Procedia CIRP 79, 403–408.

[22] Günther, R., Beckschulte, S., Wende, M., Mende, H., Schmitt, R. H., 2022. AI-Based Failure Management: Value Chain Approach in Commercial Vehicle Industry, in: Procedia CIRP, Volume 109, 251-256.

[23] Isele, R., 2014. Methoden der Linked Data Integration, in: Pellegrini, T., Sack, H., Auer, S. (Eds.), Linked Enterprise Data. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 103–120.

[24] Otto, B., 2022. The Evolution of Data Spaces. in: Otto, B., ten Hompel, M., Wrobel, S. (eds) Designing Data Spaces.

[25] Jain, A. Patel, H., Nagalapatti, L., Gupta, N., Mehta, S., Guttula, S., Mujumdar, S., Afzal S., Mittal, R.S., Munigala, V., 2020. Overview and Importance of Data Quality for Machine Learning Tasks, in: Gupta, R. (Eds.), Proceedings of the 26th ACM SIGKDD. ACM, New York, pp.3561–3562.

Biography

Robin Günther (*1988) studied industrial engineering at RWTH Aachen University. Since 2018, he has been working on his doctorate as a research assistant at the Laboratory for Machine Tools and Production Engineering of RWTH Aachen University, focusing on quality intelligence and failure management.

Matin Wende (*1993) studied mechanical engineering at Technical University of Darmstadt. Since 2021, he is a research associate at Fraunhofer Institute for Production Technology. His focus lies on the application of artificial intelligence for anomaly detection in production processes and intelligent failure management.

Sebastian Baumann (*1987) studied mechanical and process engineering at TU Darmstadt and worked as research associate at the Institute of Flight Systems and Automatic Control (FSR). As founder and CEO, he establishes DATAbility GmbH as the decision support company enabling AI-powered analysis and interpretation of complex system and process data for automated optimizations and recommendations.

Felix Bartels (*1996) studied industrial engineering at Leibniz University Hannover. Since 2021, he works as project manager at Krone Business Center GmbH & Co. KG focusing on the implementation of AI-solutions for failure management, predictive quality and predictive maintenance in the commercial vehicle sector.

Sebastian Beckschulte (*1990) studied industrial engineering at the University of Duisburg-Essen. Since 2019, he has been working on his doctorate as a research assistant at the Laboratory for Machine Tools and Production Engineering of RWTH Aachen University, focusing on quality intelligence and failure management.

Goy Hinrich Korn (*1964) studied computer science at the TU Braunschweig and earned his doctorate as Dr. Ing. in 1995 (TU Braunschweig). Since 2004, he works as CIO for the Krone Group (Spelle) and since 2020 also as CDO. Since 2019 he is Management Director of the Krone Business Center GmbH & Co. KG.

Robert H. Schmitt (*1961) has been professor of Chair of Metrology and Quality Management and Member of the Board of Directors at Laboratory for Machine Tools and Production Engineering WZL of RWTH Aachen since 2004. He is also Member of the Board of Directors at Fraunhofer Institute of Production Technology (IPT).

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Systematisation Approach: Handling Insufficient Data Quality

Tobias Schröer[1], Jokim Janßen[1], Günther Schuh[1], Volker Stich[1]
[1]Institute for Industrial Management (FIR) at RWTH Aachen, Aachen, Germany

Abstract

Current megatrends such as globalisation and digitalisation are increasing complexity, making systems for well-founded and short-term decision support indispensable. A necessary condition for reliable decision-making is high data quality. In practice, it is repeatedly shown that data quality is insufficient, especially in master and transaction data. Moreover, upcoming approaches for data-based decisions consistently raise the required level of data quality. Hence, the importance of handling insufficient data quality is currently and will remain elementary. Since the literature does not systematically consider the possibilities in the case of insufficient data quality, this paper presents a general model and systematic approach for handling those cases in real-world scenarios. The model developed here presents the various possibilities of handling insufficient data quality in a process-based approach as a framework for decision support. The individual aspects of the model are examined in more detail along the process chain from data acquisition to final data processing. Subsequently, the systematic approach is applied and contextualised for production planning and supply chain event management. Due to their general validity, the results enable companies to manage insufficient data quality systematically.

Keywords

Data Quality; Insufficient Data; Production Planning; Supply chain event management; SCEM

1. Introduction

Efficient execution of business processes in increasingly complex value chains is based on data-driven and automated decision making. A key success factor here is suitable data quality as a basis. While companies are increasingly collecting data in large volumes and increasing the number of data-based decisions, problems with data quality often lead to reduced acceptance among decision-makers. This is not surprising, since these very decision makers are regularly not involved in the process of data collection or at least not responsible for it. In order to counteract this decoupling of the decision-making basis (data) and the decision-makers, we develop in this paper a structured approach to consider data quality relevant aspects in relation to the decision to be made. The model provides a descriptive basis for improving decision quality and acceptance.

2. State-of-the-art

Data quality is commonly defined as data being fit for use by the data consumer [1] following the commonly used definition from quality management [2]. In the context of data-based decision-making, the data consumer relates to the model using the data as an input. Fitness for use therefore relates to the suitability

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of the data for the model to work as intended. Although the definition clearly states that data quality can only be measured for a specific intended application, most research follows a data-centric generic approach not considering the respective application.

Extensive research has been conducted on describing data quality and its aspects, usually referred to as data quality dimensions [1]. However, this research is not suitable from a decision-maker's perspective as the dimensions are receivable at most, but not directly to be influenced. In the domain of production planning and control, Günther et. al propose a method to assess data quality [3] but without a specific focus on the improvement. Therefore, a more process based seems to be reasonable. Miller and Mork present a value chain for big data [4] which provides a framework for the life cycle of data for decision making but lacks the data quality aspect.

Multiple models for managing data quality in companies have been developed. English presents a method for Total Data Quality Management consisting of data definition quality, an information quality assessment, nonquality information costs and reengineering and improvement aspects [5]. Some work has been conducted on applying the concepts of quality function deployment (QFD) in the domain of data quality. Wang et. al. [6] use the house of quality to correlate a desired quality with data engineering aspects. Pinto [7] describes the application of QFD concepts in database planning. Vaismann develops an approach specifically for designing databases for decision support systems [8]. However, all approaches assume a desired data quality can be defined a priori and all approaches remain data-centric.

Overall, a research gap was identified in data quality research from a decision-maker's perspective. Models for a process-oriented view on the quality of input data for decision making can contribute to better decisions and a better acceptance of decisions.

3. Research questions and approach

This work aims to provide decision-makers with a universally applicable structured approach to handle the fact of data being insufficient in real world scenarios. We formulate the main research question for this paper as follows: How can the quality of input data be considered in data-based decision-making?

We follow a research approach in three steps. First, we conduct a systematic literature review [9] and examine strategies for handling insufficient data quality. In a second step, we develop a model based on the extracted handling strategies. Finally, we present two cases from the domain of supply chain event management and production planning, in which we apply the structured approach of handling insufficient data quality in decision-making.

4. Examining strategies for handling of insufficient data quality

The initial search within scopus results in 63 articles. After scanning the title and abstract of the results, 45 remain. Relevant work in the context of this paper should be defined as those containing at least one specific approach to deal with insufficient data in decision-making. Therefore, results with a mere focus on the measurement of data quality were not ranked as relevant. Applying these criteria yields a total of 13 relevant articles we examined in detail. We structured those articles in three different categories: Data source and accessibility, Data manipulation and Data usage and model (table 1). Following this, we describe our findings from the studies and extract the relevant aspects for handling the insufficient data quality.

Table 1: Structured literature

Data source and accessibility	Data manipulation	Data usage and model
Arnold et al. [10]	Reuter et al. [11,12]	Altendorfer [13]
Brauer et al. [14]	Lingitz et al. [15,16]	Busert et al. [17]
Büscher et al. [18]		Herold [19]
Gustavsson [20]		Krishnamurthy [21]
Messner et al. [22]		

4.1 Data source and accessibility

Arnold et al. highlight the relevance of correct data from production, which are still regularly based on manual data capture [10]. They propose a combined approach of using new sensor technologies such as Bluetooth Low Energy for location or Near Field Communication and applying data fusion concepts to improve the data quality of the target dimensions. Another approach focuses on the accessibility of data. In some cases data are available locally or databases are not connected. In this case connecting actual data sources to consumers can be a reasonable approach. Brauer et al. propose a Virtual Scheduling and Transportation Model to connect production scheduling and logistics tasks [14]. Büscher et al. present a similar data integration approach for the domain of production and factory planning [18]. Messner et al. propose a closed-loop approach to overcome integration issues and the factor of potential human errors [22]. Gustavsson studies the effects of organisational integration on data quality and shows, that a higher level of integration leads to less quality deficiencies [20].

4.2 Data manipulation

Data manipulation means taking the data as it is and no improvement of the data source. Reuter et al. present an approach based on data mining to deal with missing information and known inconsistencies in databases [11,12]. This provides improved data for the data-consuming decision model. Lingitz et al. use a simulation based evolutionary approach to predict expected values from historical data, which is a typical problem in production planning models like MRP [15,16].

4.3 Data usage and model

Altendorfer [13] shows the effect of information quality in terms of customer orders. While in theory a more detailed knowledge is preferrable, the overall costs in the examined model are only marginally influenced by data quality according to their findings. Another study shows a similar effect for demand information in pull production control systems [21]. While the integration of demand integration shows a significant impact, the actual quality of this data (i.e. variance) only has a marginal impact on system performance. If specific knowledge about the actual quality of data is available, Busert et al. suggest to model uncertainties by applying fuzzy logic [17]. However, this approach requires specific decision models, and it needs to be determined how fuzzy data leads to decisions. Another approach focuses just on the model by suggesting a model that is less data intensive. Therefore, it mitigates data quality issues by bypassing the nonquality data [19].

5. Conversion into a systematisation model

The necessary data quality for data-based decision-making is always application-specific. To determine this, a distinction can be made between two perspectives. The first perspective deals with the necessary data quality for decision-making (data quality requirement). This perspective is closely connected to the benefit of data quality, which continuously decreases with increasing data quality. In contrast to the data quality requirement, the second perspective looks at the available data and its quality (data quality availability). In the cost-benefit analogy, this reflects the cost side since the costs increase exponentially as the available data quality increases. Even if, ideally, the required and available data quality match, this is not automatically the case in practice. Accordingly, the goal of data-driven decision-making is to close the gap between data quality needs and availability. To enable this systematically, the following model illustrates the different strategies based on the data value chain from data collection to use.

The data value chain begins in the data source area with the process step gathering, which describes the recording and collection of the data. The next three process steps are in the integration area and are often described as the ETL process [23]. In the first step of the ETL process, the data is extracted from various sources and temporarily stored in a workspace (extract). In the second step, this temporary intermediate storage enables the necessary transformation of the data into uniform data formats and structures (transform). Finally, the data is loaded into the target system and the temporary storage is deleted again (load). Following the ETL process, the data is used so that decisions can be made based on analyses and evaluations (use). [24,4]

This value chain can now be used to classify the different approaches to dealing with insufficient data quality. These in turn can be categorised into four strategies (see Figure 1).

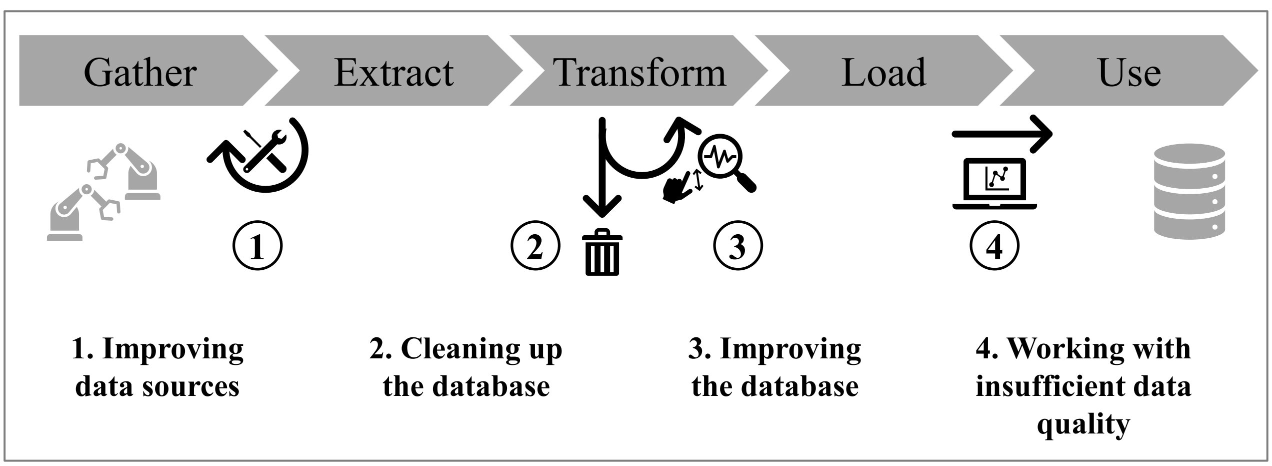

Figure 1: Strategies for handling insufficient data quality

The strategy "**Improving data sources**" can be assigned to the transition between gathering and extraction. This includes all approaches that improve data gathering from data sources. This may mean, for example, installing new sensors for data collection or recalibrating or reconfiguring the existing sensors. Another possibility is that the data collection processes are changed in such a way that the quality of the collected data is significantly improved. Unlike the other strategies, however, the focus here is not on the symptoms (insufficient data quality), but on tackling the causes (e.g., errors in data collection). This in turn means that the strategy only leads to improvements for future data sets and the insufficient data quality of the previous data sets remains.

The next two strategies can be assigned to the transformation step. Part of the transformation of the data stock into the standard data formats and structures is to check and improve the data quality. This means that if data with insufficient data quality is found during the transformation, the strategy "**Cleaning up the database**" can be applied, for example. Here, data records with insufficient data quality are filtered out of the data flow and not processed further. The remaining data flow then only contains corresponding data records with sufficient data quality.

The "**Improving the database**" strategy also filters out the records with insufficient data quality in the first step, but with a different goal. In contrast to the "do not consider further" in the previous strategy, the records with insufficient data quality are improved here. There are various methods for this improvement (excerpt)

- Replacement with other data: An improvement is possible by replacing data from other sources (e.g., reference data sets). External databases or internal sources can be used for the reference data. In addition, it is also possible to determine corresponding reference values from previous data sets.
- Derivation from other data: Furthermore, corrections for erroneous data can be derived from other data of the same data record or previous data records. In contrast to replacement, here values are determined by dedicated models and not simply taken over.
- Use of default values: In some cases, incorrect values can be replaced by default values. The condition is that a "meaningful" default value can be defined in advance for each situation.
- Removal of duplicates: Another method to clean up redundant data is to remove duplicates. Before removal, however, the redundant data must be consolidated. It should be noted that it would be wrong to use only the record with the most correct data and ignore the others.
- Splitting erroneous summaries: The opposite of the method "Removal of duplicates" is "Splitting erroneous summaries". Records that contain data on different real objects are split. The data set is thus split into two different data sets during the improvement.

Just like the selection of the right strategy, the selection of the methods presented here is also very dependent on the use case and the corresponding data.

The strategy "**Working with insufficient data quality**" can be placed in the transition to the process step use and describes the possibilities to consciously continue working with insufficient data quality. To make this possible, it is necessary to change the application context so that the existing data quality is sufficient for the necessary decision. This means that the requirements for the data quality are changed so that it is sufficient. For example, this can mean that the uncertainty regarding the data quality and the associated decisions is consciously dealt with for the use case and communicated accordingly. Another example would be that for specific use cases, robust algorithms are used in the decision-making process, which has lower data quality requirements.

It can be summarised that different approaches can be used to reduce the gap between required and available data quality. The strategies "Improving data sources", "Cleaning up the database" and "Improving the database" deal with improving the available data quality. In contrast, the strategy "Working with insufficient data quality" focuses on reducing the required data quality and thus closing the gap. The selection of the right strategy depends fundamentally on the use case and the associated decision-making process.

6. Case Studies

To evaluate the introduced model, we have examined two exemplary case studies from different fields of application following the Design Science Research Methodology [25]. First, the use case was briefly described before the different strategies of the model were applied and analysed.

6.1 Supply Chain Event Management

Event-based systems such as supply chain event management are used to reduce the complexity of our supply chains and support decision-making for the planning of production and the associated processes [26]. The data basis for supply chain event management are events, which describe every physical status change of objects in a standardised way (cf. EPCIS events) [27]. Based on this, supply chain event management comprises five core functions: The monitoring function tracks events across the supply chain and collects them in an event repository. The second function, reporting, describes the notification of critical deviations. The consequences of the deviations identified by the notification as well as possible reactions are analysed in the third function. The fourth function, Control, then selects and implements the best possible alternative course of action. The last function, measure, evaluates the reactions to improve the previous functional steps for future deviations. By reacting only to critical deviations, this is a management-by-exception concept. To ensure the functionality of event-based systems, special attention must be paid to data quality. [28,29] In practice, it turns out that the data quality of event data can vary greatly, so that a precise analysis of data quality availability and data quality needs is necessary [30,31].

For a systematic approach to improving the difference between data quality needs and data quality availability, the four main strategies can now be considered in detail:

- Improving data sources: In this use case, the event data is recorded by the various actors in the supply chain (e.g., 2nd tier supplier, 1st tier supplier, forwarder, etc.). In practice, it has been shown that this is precisely where the cause of poor data quality often can be found. In concrete terms, this can be, for example, an incorrectly set RFID gate or typing errors during manual recording. [30] The strategy of improving the data source is helpful in theory, but difficult to implement in practice. The reason for this is that the actors (e.g., manufacturers) who criticise the available data quality are not the same actors (e.g., suppliers) who record the data. Often the power relations are not such that the manufacturer can force the supplier to improve the data recording.
- Cleaning up the database: Cleansing the database of data records with insufficient data quality is a possible strategy in this case. This can avoid erroneous automatic reactions by the simulate and control functions, which in turn eliminates some overreactions and waste. The challenge here lies in determining the events with insufficient data quality in comparison to critical exception events, since the occurrences of the events are often similar, especially regarding the content-related data quality. According to the use case, it is particularly important to ensure that no critical exception events are sorted out, as otherwise the purpose of the overall system is not achieved.
- Improving the database: If events with insufficient data quality have been identified, they can also be improved depending on their appearance. Specifically, the approaches of Replacement with other Data can be used particularly well. On the one hand, data fields can be validated or completed by other IT systems. Another possibility is the correction of event data with the help of historical event data of the same or similar objects.
- Working with insufficient data quality: In contrast to data quality availability, when considering data quality requirements, the possible reactions must be considered, especially for the functions of simulating and controlling. The data quality requirement decreases for a system that is less sensitive

- regardless of whether the lower sensitivity results from the system modelling or the simulation algorithms used. However, if the system is too insensitive, it will no longer react to critical exceptional events, which is contrary to the concept.

The concrete consideration of the case study shows that the model with its systematisation approach of the strategies can be applied.

6.2 Production Planning

Production planning and control in companies has been supported for decades by data-based models in systems such as Enterprise Resource Planning, Manufacturing Execution Systems or Advanced Planning and Scheduling Systems. However, the underlying algorithms and model assumptions there are often based on very simplified assumptions, and the models are deterministic. This automatically results in a large number of potential data quality problems, as the studies analyzed have already shown.

In this case, the focus is on a company that uses detailed planning in production control and regularly fails to adhere to the specified order operation sequences and thus reschedules manually. According to the model, the following options for dealing with insufficient data arise:

- Improving data sources: In this case, detailed planning is system-supported, but the data basis is based on manual feedback from production. For reasons of cost and effort, this feedback is not carried out individually for each operation today; instead, standard times serve as the basis for planning. There is potential here to pursue this strategy and to develop a more detailed and qualitatively better data basis by means of detailed and automated recording of feedback data. However, this requires the introduction of new systems, which is time-consuming and associated with high costs. In this case, linking with further production data does not make sense, since new sensor technology would have to be purchased for this purpose and known and basic measures have not yet been exhausted. Even without the improved acquisition of live data, however, static optimization is conceivable. Since today's data are already default times, a check of the actuality is possible with a small effort and thus has the potential to improve the decision quality in the short term.
- Cleaning up the database: The quality of the data in the planning system is based on standard times, the data volumes are thus rather small. Individual data records are not expected to have a significant influence on the planning result. Nevertheless, a review of the input data and a correction of outliers can be implemented with little effort.
- Improving the database: Without a detailed collection of feedback data, the data basis for improving the data is not available. This strategy is therefore not very promising
- Working with insufficient data quality: The further the assumed data and models used deviate from reality, the less they contribute to good decision quality. Particularly in detailed planning with low granularity of the feedback data, less data-intensive alternatives thus present themselves. Following the lean concept, procedures such as Kanban can also be used here, depending on the concrete order and product structure. Here, significantly less information is required, and disadvantages such as supposedly larger inventories are not relevant in practice, because inadequate detailed planning regularly causes shortfalls. Other procedures in production control can also be suitable and achieve production with fewer exceptional situations due to lower complexity with lower data requirements.

7. Conclusion

In practice, it is evident that dealing with insufficient data quality for decision-making repeatedly leads to problems. Accordingly, this paper is the first to present an integrated approach for decision-making that takes a complete look at data quality from the data source to data use. In particular, the two perspectives of data quality needs and data quality availability were examined. A concretisation based on two use cases shows the basic usability of the model. However, there is a need for further research in the details, the further structuring, and the transfer to individual domains. It should be investigated how the individual strategies affect the individual domains, which strategies are the most promising and how they can be implemented in the best possible way.

Appendix

The structured literature search was conducted using the following search terms in scopus: TITLE-ABS-KEY (("data quality" OR "information quality") AND ("production planning" OR "production control" OR "manufacturing planning" OR "manufacturing control" OR "supply chain event management"))

References

[1] Wang, R.Y., Strong, D.M., 1996. Beyond Accuracy: What Data Quality Means to Data Consumers. Journal of Management Information Systems 12 (4), 5–33.

[2] Gryna, F.M., 2001. Quality Planning and Analysis: From Product Development Through Use, 4th ed. ed. McGraw-Hill, Boston, Mass., 730 pp.

[3] Günther, L.C., Colangelo, E., Wiendahl, H.-H., Bauer, C., 2019. Data quality assessment for improved decision-making: A methodology for small and medium-sized enterprises. Procedia Manufacturing 29.

[4] Miller, H.G., Mork, P., 2013. From Data to Decisions: A Value Chain for Big Data. IT Prof. 15 (1), 57–59.

[5] English, L.P., 1999. Improving data warehouse and business information quality: Methods for reducing costs and increasing profits. Wiley, New York, xxvi, 518 s.

[6] Wang, K., Tong, S., Roucoules, L., Eynard, B., 2009. Analysis of Consumers' Requirements for Data/Information Quality by Using HOQ, in: IEEM 2008. International Conference on Industrial Engineering and Engineering Management, Singapore. 08.12.2008 - 11.12.2008, pp. 213–217.

[7] Pinto, M., 2006. Data representation factors and dimensions from the quality function deployment (QFD) perspective. Journal of Information Science 32 (2), 116–130.

[8] Vaisman, A., 2006. Requirements Eliciation for Decision Support Systems: A Data Quality Approach, in: Proceedings of the Eighth International Conference on Enterprise Information Systems. 8th International Conference on Enterprise Information Systems, Paphos, Cyprus. 23.05.2006 - 27.05.2006. SciTePress - Science and and Technology Publications, pp. 316–321.

[9] Tranfield, D., Denyer, D., Smart, P., 2003. Towards a Methodology for Developing Evidence-Informed Management Knowledge by Means of Systematic Review. Br J Management 14 (3), 207–222.

[10] Arnold, D., Wilmsmeier, S., Denkena, B., Dayeg, A., 2021. Desire and Reality of Operational Data Quality A Look at Production Data Collected in the Industry [Betriebsdaten und ihre aktuellen Potenziale Ein Blick auf die in der Industrie erfassten Produktionsdaten]. ZWF Zeitschrift fuer Wirtschaftlichen Fabrikbetrieb 116 (11), 852–855.

[11] Reuter, C., Brambring, F., 2016. Improving Data Consistency in Production Control. Procedia CIRP 41.

[12] Reuter, C., Brambring, F., Weirich, J., Kleines, A., 2016. Improving Data Consistency in Production Control by Adaptation of Data Mining Algorithms. Procedia CIRP 56.

[13] Altendorfer, K., 2019. Effect of limited capacity on optimal planning parameters for a multi-item production system with setup times and advance demand information. International Journal of Production Research 57 (6), 1892–1913.

[14] Brauer, K., Zesch, F., Motta, M., Wagenitz, A., 2009. An information model for integrated production scheduling and transportation planning. International Conference on Harbor, Maritime and Multimodal Logistics Modeling and Simulation, HMS 2009, Held at the International Mediterranean and Latin American Modeling Multiconference, I3M 2009.

[15] Lingitz, L., Sihn, W., 2020. Concepts for improving the quality of production plans using machine learning. Acta IMEKO 9 (1), 32–39.

[16] Ryback, T., Lukas, L., Gaal, A., Gallina, V., Gyulai, D., 2019. Improving the planning quality in production planning and control with machine learning. 16th IMEKO TC10 Conference 2019 "Testing, Diagnostics and Inspection as a Comprehensive Value Chain for Quality and Safety"

[17] Busert, T., Fay, A., 2018. Information Quality Dimensions for Identifying and Handling Inaccuracy and Uncertainty in Production Planning and Control. IEEE International Conference on Emerging Technologies and Factory Automation, ETFA 2018-September.

[18] Büscher, C., Voet, H., Krunke, M., Burggräf, P., Meisen, T., Jeschke, S., 2016. Semantic Information Modelling for Factory Planning Projects. Procedia CIRP 41.

[19] Herold, F., 1997. Optimization of order processing with knowledge-based holistic planning [Optimierung der auftragsabwicklung mit wissensbasierter ganzheitlicher planung]. ZWF Zeitschrift fuer Wirtschaftlichen Fabrikbetrieb 92 (7-8), 380–382.

[20] Gustavsson, M., 2008. Information quality implications of planning process integration. Journal of Manufacturing Technology Management 19 (8), 933–952.

[21] Krishnamurthy, A., Claudio, D., 2006. Impact of information quality in pull systems with advance demand information. 2006 IIE Annual Conference and Exhibition.

[22] Messner, M., Pauker, F., Mauthner, G., Frühwirth, T., Mangler, J., 2019. Closed loop cycle time feedback to optimize high-mix / low-volume production planning. Procedia CIRP 81.

[23] Patel, M., Patel, D.B., 2021. Progressive Growth of ETL Tools: A Literature Review of Past to Equip Future, in: Rathore, V.S., Dey, N., Piuri, V., Babo, R., Polkowski, Z., Tavares, J.M.R.S. (Eds.), Rising Threats in Expert Applications and Solutions, vol. 1187. Springer Singapore, Singapore, pp. 389–398.

[24] Lettner, C., Stumptner, R., Bokesch, K.-H., 2014. An Approach on ETL Attached Data Quality Management, in: Bellatreche, L., Mohania, M.K. (Eds.), Data Warehousing and Knowledge Discovery. 16th International Conference, DaWaK 2014. Springer International Publishing, Cham, pp. 1–8.

[25] Hevner, A.R., March, S.T., Park, J., Ram, S., 2004. Design Science in Information Systems Research. MIS Quarterly: Management Information System 28 (1), 75.

[26] Nissen, V., 2002. Supply Chain Event Management als Beispiel für Electronic Business in der Logistik, in: Gabriel, R., Hoppe, U. (Eds.), Electronic Business. Theoretische Aspekte und Anwendungen in der betrieblichen Praxis. Physica, Heidelberg, pp. 429–445.

[27] 2012. EPCIS – EPC Information Services: Prozess-Transparenz in Echtzeit, Köln. https://www.gs1-germany.de/fileadmin/gs1/basis_informationen/epcis_epc_informationservices.pdf. Accessed 26 July 2021.

[28] Bensel, P., Fürstenberg, F., Vogeler, S., 2008. Supply-Chain-Event-Management: Entwicklung eines SCEM-Frameworks. Digitale Schriftenreihe Logistik Technische Universität Berlin Nr. 3. Deutsche Nationalbibliothek. https://depositonce.tu-berlin.de/handle/11303/2243. Accessed 30 January 2022.

[29] Tröger, R., 2014. Supply Chain Event Management – Bedarf, Systemarchitektur und Nutzen aus Perspektive fokaler Unternehmen der Modeindustrie. Diss., Leipzig.

[30] Janßen, J., Schuh, G., Stich, V., 2022. Typification of Incorrect Event Data in Supply Chain Event Management. publish-Ing, Hannover.

[31] Konovalenko, I., Ludwig, A., 2019. Event processing in supply chain management – The status quo and research outlook. Computers in Industry (105), 229–249.

Biography

Tobias Schröer (*1991) has been working at the Institute for Industrial Management (FIR) at the RWTH Aachen since 2016, first as a project manager and since 2020 as head of the department Production Management. As such he leads a variety of applied research and consulting projects. In his research he focuses on the real-world applications of business software for operations in production and logistics.

Jokim Janßen (*1993) works as a project manager and scientific assistant at the Institute for Industrial Management (FIR) at the RWTH Aachen since 2019. Before that, he gained experience in supply chain management at Miele & Cie. KG and developed a strong background in event-based systems. In his current work as the group leader in supply chain management, he is managing projects in the context of digitalized supply chain management in research, consortia, and consulting projects.

Prof. Dr.-Ing. Dipl.-Wirt.-Ing. Günther Schuh (*1958) is the director of the Institute for Industrial Management (FIR) at RWTH Aachen University, holds the Chair for Production Systems at the WZL, and is a member of the board of directors of the Fraunhofer Institute for Production Technology IPT in Aachen. Professor Schuh is a member of several supervisory boards and boards of directors.

Prof. Dr.-Ing. Volker Stich (*1954) has been head of the Institute for Industrial Management (FIR) at the RWTH Aachen University since 1997. Prof. Dr.-Ing. Volker Stich worked for 10 years for the St. Gobain-Automotive Group and lead the management of European plant logistics. In addition, he was responsible for the worldwide coordination of future vehicle development projects.

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Towards A Design Of A Software-Defined Manufacturing System Based On A Systematic Literature Review For Enabling A Decentralised High-Rate Electrolyser Production

Alexander Brandstetter[1], Monika Risling[1], Henry Himmelstoss[1], Daniel Schel[1], Michael Oberle[1]
[1]*Fraunhofer IPA, Stuttgart, Germany*

Abstract

Hydrogen is critical for the transition to an environmentally sound and reliable energy supply. This transition requires large capacities of performant and cost-effective electrolysers. Although performant electrolysers already exist, they cannot yet be manufactured at a high rate in series production. The project H2Giga-FRHY is researching a reference factory for large-scale production of electrolysers, developing new production and testing modules. As an essential building block of the reference factory, a research group at Fraunhofer IPA is designing and implementing a comprehensive software-defined manufacturing system (SDMS), which supports the decentralized high-rate production of electrolysers and allows for far-reaching insights regarding high-rate capability, quality, and cost of products, processes, and technologies involved. For the SDMS implementation, different enterprise architecture (EA) approaches are considered and evaluated in the scope of a structured literature review with respect to criteria arising from the project context and related research questions. In this paper, an approach to designing a software-defined manufacturing system is described, and its necessity is based on the use case-specific criteria discussed.

Keywords

Software-Defined Manufacturing; Enterprise IT Architecture; High-Rate Production; Decentralised Manufacturing; Greenfield; Electrolyser Production

1. Introduction

With the European Green Deal and the associated goal of climate neutrality for the EU by 2050, hydrogen is expected to play an important role [1]. The demand for hydrogen can only be estimated as of today, but many current estimations point to an increasing demand. In its hydrogen roadmap, Fraunhofer ISE forecasts a hydrogen demand in Europe of 800 TWh in a low scenario and 2,250 TWh in a high scenario. These hydrogen needs translate into a corresponding increase in electrolysers that can produce it [2]. To satisfy this upcoming market necessity, high-rate production is needed. In order to keep up with the changing demands that electrolysers need to meet in the current environment, PEM electrolysers are particularly well-suited [3]. The use of this clean electrolyser production is not widely prevalent in Europe. Furthermore, it will need a lot of efficient and affordable electrolysers with high capacities to meet Germany's demand for green hydrogen. Although efficient electrolysers are on the market now, they are often still made by hand in small quantities [4].

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In order to research high-rate production of high-performance electrolysers, the H2Giga-FRHY project brings together the expertise of various Fraunhofer institutes. The resulting distributed reference factory for large-scale production of electrolysers is to be linked using information and communication technologies to form a coherent virtual production line. This will be realized through a SDMS. SDMSs leverage Industry 4.0 technologies and paradigms such as the Industrial Internet of Things or cloud-based manufacturing to provide flexible, adaptive, and scalable manufacturing systems [5]. Rauch et al. describe distributed manufacturing systems as logical consequence of cooperating manufacturing companies and the resulting production networks, which further strengthen the characteristics of distributed manufacturing systems [6].To address the resulting challenges and its increasing complexity, we present an approach for the design and development of a SDMS for distributed high-rate electrolyser production in a greenfield environment.

H2Giga-FRHY is a Fraunhofer-overarching project funded by the German Federal Ministry of Education and Research. The aim of the project is to design a reference factory as a flexible, multidirectional, technologically advanced solution for the large-scale production of electrolysers. New types of production and testing modules are being developed. The production is distributed across five locations in addition to the main IT site. The envisioned SDMS in the Fraunhofer IPA subproject is based primarily on the three pillars of a digital representation concept, an edge cloud platform-based manufacturing operation management, and an evaluation system to support product improvement decision-making.

2. Method and data

This work aims to identify suitable architectures for a SDMS in the context of the H2Giga-FRHY project. A systematic literature review, following the guidelines of Kitchenham [7], was conducted to identify potentially suitable architectural approaches for a SDMS for distributed high-rate electrolyser production in a greenfield environment. Based on the use case of the H2Giga-FRHY project, criteria were defined to select and evaluate architectural approaches. The first research question (RQ) arises here:

- RQ1: Which architectures for distributed SDMSs do exist?

RQ1 aims to identify existing SDMS architectures. RQ2 - RQ6 evaluate the identified architectures against criteria, which are relevant in the context of the H2Giga-FRHY project. The criteria are derived from stakeholder requirements, elicited from stakeholders through expert interviews guided by predefined categories for functional and non-functional requirements. Phrase templates ensure that the requirements are well-structured, prioritized, uniform, and unambiguous [8]. As a result, 135 functional requirements, 25 non-functional requirements, and 7 constraints are elicited. In section 2.2, a criterion is established for each RQ. The papers are examined regarding the occurrence of the respective criterion in order to assess the extent to which they address dimensions that are relevant in the context of the H2Giga-FRHY project.

- RQ2: Which SDMS architectures are suitable for a scalable high-rate production?
- RQ3: Which SDMS architectures can give distributed production sites access to coherent digital production functionalities?
- RQ4: Which SDMS architectures are particularly suitable in a greenfield environment?
- RQ5: Which SDMS architectures are service-oriented architectures?
- RQ6: Which SDMS architectures enable a central provision of relevant information and functionalities of distributed production assets?

2.1 Search process and selection criteria

In the first stage of the literature search, the umbrella term "Enterprise Architecture" was searched in the five selected databases following the results as seen in Table 1. EA is a more common term than SDMS, since the latter is used domain-specific mostly and would decrease possible results. Therefore, the literature search looked for EAs that can be used as SDMS. Due to their importance in scientific research, the chosen databases are frequently utilized for literature reviews. Despite their similarities, the databases are not entirely the same and can cover various literature [9–11].

Table 1: Results of the Literature Query, searching “Enterprise Architecture” in five databases (January 2023)

	Scopus	Web of Science	ACM Digital Library	Dimensions AI	IEEE Explore
Number of results	5,183	2,474	839	4,976	1,310

As these results are too broad and comprehensive, the search query has been specified as:

> (Distributed Manufacturing" OR "Value added network" OR "Distributed Manufacturing Systems" OR "cloud*manufacturing") AND ("Manufacturing" OR "Production") AND ("Architecture" OR "Enterprise Architecture" OR "Software defined" OR "enterprise architecture framework" OR "IT framework") AND ("Industr* 4.0" OR "Digital Manufacturing" OR "Digitali*ation" OR "Digital Twin") AND NOT ("logistic*").

The Query is divided into five parts. The first specifies the type of manufacturing that the architecture model should be created for, as the given use case addresses distributed manufacturing. The first search queries showed an overwhelming amount of education and governmental EA. Therefore, use case-specific criteria for production or manufacturing were added. The next criteria section shows the targeted information that are researched: an enterprise architecture framework. In order for the results to meet the current standards of a digital greenfield production, criteria on the topic of digitalisation are added. Since it is about production with its value-adding processes, logistic results were excluded. Due to the search terms, the resulting papers are all written in English. Therefore, there is no filtering by language necessary. Subsequently, the results are filtered as seen in Figure 1. Resulting in the following seven papers: Newman [12]; Guo [13]; Hung [14]; Roque Rolo [15]; Novak [16]; Shao [17]; and Sreedhanya [18].

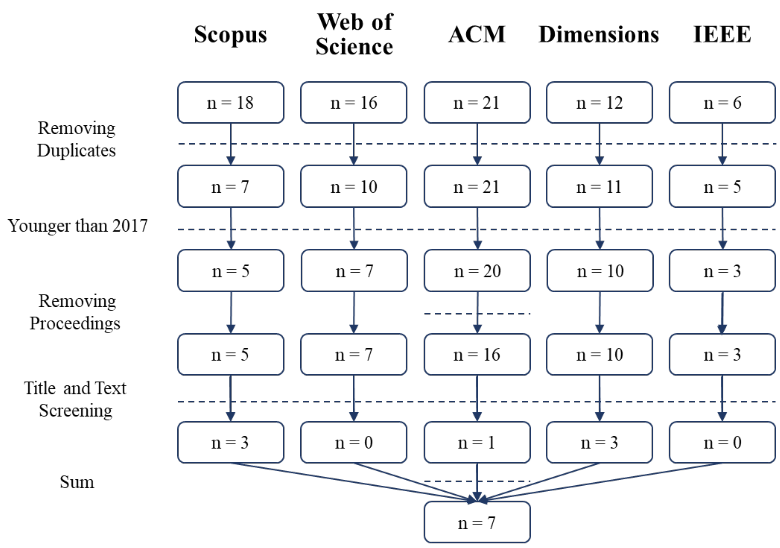

Figure 1: Filtering the papers through the criteria in the first column and the five selected databases (January 2023)

2.2 Quality assessment and data analysis

The resulting papers are evaluated according to the criteria extracted in chapter 2. This evaluation is shown in Table 2. The evaluating criteria answer the previously identified Research questions (RQ2 to RQ6) and arise from the requirements of the reference-factory. The rating of these criteria uses a system of circles, with empty circles (○) indicating that the criterion is not addressed, half-filled circles (◑) indicating partial coverage, and full circles (●) indicate that the criterion is comprehensively addressed in the proposed architecture. All in all, the papers provide insights but do not provide a suitable SDMS architecture for high-rate production with distributed locations in a greenfield environment. Therefore, methods to create an appropriate EA are examined in the next chapter.

Table 2: Evaluation of the papers against the use case specific criteria. Evaluation in 3 levels

Criteria	Newman	Guo	Hung	Roque Rolo	Novak	Shao	Sreedhanya
Domain suitable	○	○	○	○	○	○	○
Central access for distributed locations	○	◑	◑	●	◑	◑	●
Greenfield suitable	◑	◑	◑	○	○	◑	◑
Service-oriented architecture	○	●	◑	○	●	○	●
Provision of product and production data	○	◑	◑	○	◑	●	●

2.3 Enterprise Architecture Methodologies

Yesilyurt's TOGAF ADM-based approach is used to create an EA design in a greenfield environment which is successful in battery cell manufacturing and recommended for electrolyser production but does not cover the challenges of distributed systems [19]. Other studies have found that agile EA in distributed environments faces obstacles, and have proposed lightweight TOGAF-based methodologies for digital transformation, but need to address production and manufacturing [20,21]. The systematic literature review of Ansyori [22] shows that most EA frameworks and methodologies are used in the public or educational sector outside of Europe [23–26] As the five most relevant Enterprise Architecture frameworks Zachman methodology, TOGAF, FEA(F), DoDAF, and Gartner Framework are listed [27–29]. Nonetheless, TOGAF is the only of these frameworks suitable for designing, planning, implementing and managing Software-Defined Manufacturing systems [22].

3. Solution Proposal

This chapter presents an approach for designing a SDMS using the TOGAF ADM cycle while addressing domain-specific challenges and proposing additional architecture assets. It focuses on the system design phases of the ADM, specifically the Architecture Vision, Business Architecture, Information Systems Architecture and Requirements Management phases (see Figure 2). The approach by Yesilyurt described in [19] is therefore adjusted. The Requirements Management phase is emphasized throughout the entire ADM cycle to ensure relevant requirements are continuously identified and managed. The proposed requirement engineering process is iterative and recursive [30,31].

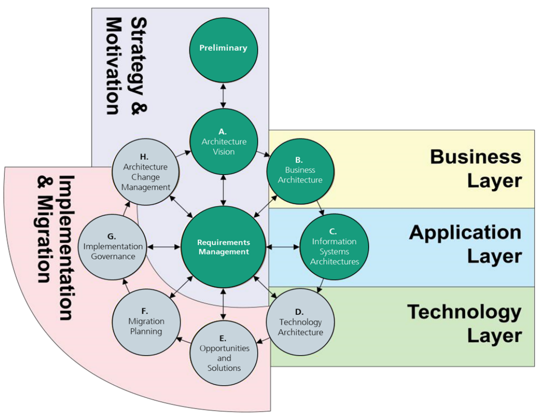

Figure 2: Simplified Mapping between ArchiMate and the TOGAF ADM, according to [32]

3.1 Architecture Vision

The Architecture Vision phase of TOGAF ADM aims to establish the scope and goals of an architecture, and create a high-level vision of the capabilities and business value it will deliver. This is demonstrated through the electrolyser reference factory use case of H2Giga-FRHY. The target architecture vision is presented in Figure 3. It illustrates shopfloors of different operating locations using a digital representation concept using the AAS standard to ensure continuous control and adaptation of products during manufacturing. This standard is currently under development in International Electrotechnical Commission project 63278-1, to ensure interoperability of heterogeneous production assets [36]. Shopfloor, testing sites, and IT headquarters have their own platform on local server hardware, connected through the digitalization platform and the AAS for cross-location communications and services. Suppliers, customers and partners can connect through a partner portal.

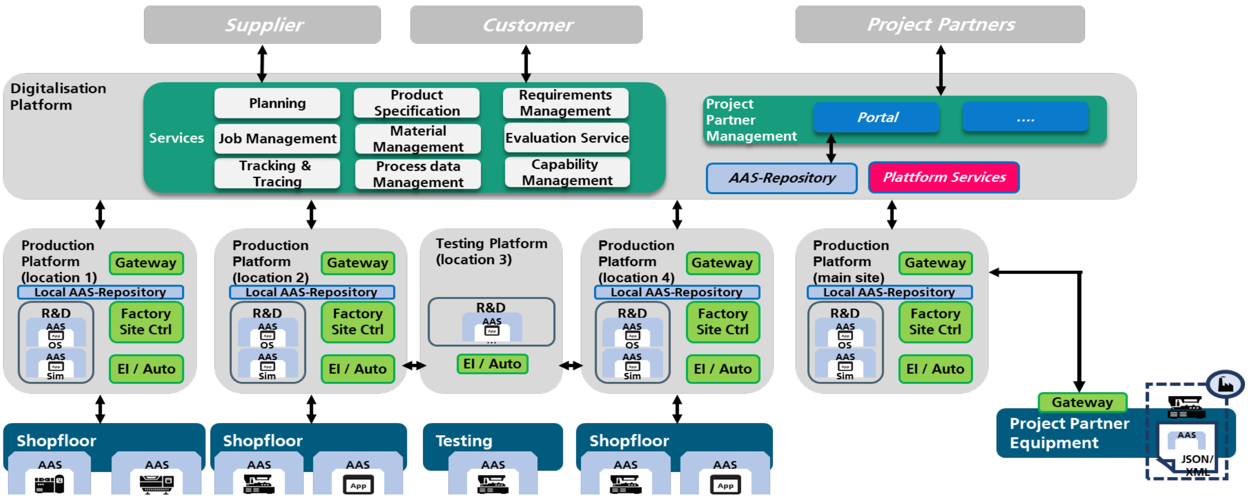

Figure 3: Architecture vision for the Software-Defined Manufacturing System based on the use case of a distributed electrolyser production

3.2 Business Architecture

This chapter describes the business architecture of the use case, including the value stream mapping and the gap analysis. It is divided into three steps: rough documentation; deepening per sub-product; and verification with review. The rough documentation includes important production processes sorted by sub-products and their relation. To design the business architecture the open and standardized modelling language ArchiMate based on the ISO/IEC/IEEE 42010:2011 standard [33] is used. Its modelling layers were used in the business architecture and the information systems architecture according to the mapping in Figure 3. The business architecture is developed through expert surveys by defining processes for each sub-product using a single business model and representing the relation between production and process through assignment relationships. The processes were described using EU harmonized terminology [34] to ensure uniform understanding and were reviewed by process experts. Interviews were held with experts in subpart-specific groups to obtain detailed process models, and with all experts to capture relationships and identify potential overall process failures.

The H2Giga-FRHY project includes six process steps for electrolyser production divided among five locations, with a focus on the subparts bipolar plate (BPP), porous transport layer (PTL), and catalyst-coated membrane (CCM) as it aims for a connected distributed production. Each process step is assigned to a production site and various design possibilities are presented as different processes are not completely clear at the beginning of greenfield manufacturing design.

3.3 Information Systems Architecture

The information system architecture aims to identify and describe data and application building blocks that support the business architecture and overall architecture vision, as well as identify gaps between the current and target architecture [31]. The previously elicited set of requirements is transformed into a high-level functional view of the SDMS. Requirements are grouped into application functions (AF) that represent automated behaviour and are clustered into cohesive, interrelated application components (AC), resulting in a high-level description of the target information system architecture, consisting of seven high-level ACs. This includes key ACs such as manufacturing operation management (MOM), digital twin (DT) and evaluation ACs.

3.3.1 Manufacturing Operation Management Application Component

The IEC 62264 standard provides terminology as well as information and activity models for MOM [35]. This makes it a valuable architecture asset for the design of the MOM AC. Our approach is based on combining the TOGAF ADM and IEC 62264 [18]. The manufacturing operation models defined in [35] provide support in defining the scope of the MOM AC. The detailed activity models defined in [36] provide guidance and support for transforming and aggregating stakeholder requirements to well defined AFs in the area of MOM as well as identifying additional AFs. The information flows described in the activity models in [36] support the definition of the interaction between different AFs. We report that combining TOGAF ADM and IEC 62264 as proposed by [19] is an effective approach for identifying AFs for the design of a MOM in the context of distributed high-rate electrolyser production. However, this approach does not take into consideration the proposed target architecture, which allows for a holistic and integrated planning, scheduling and dispatching of the distributed manufacturing processes as well as a for an overarching tracking and tracing of the electrolysers. Moreover, each module must be able to function autonomously in case of errors or downtime of a single module. Therefore, multiple connected MOM ACs at each production module, with proper integration and synchronization are required. This aligns with the findings of current design challenges in MOM in [37].

3.3.2 Digital Twin Application Component

The AAS provides uniform access to information and services of assets and forms the basis of our digital representation concept to ensure a continuous control and adaptation of relevant products during manufacturing. The AAS is based on the Reference Architecture Model Industry 4.0 (RAMI 4.0), whose hierarchy levels to classify assets within an Industry 4.0 environment are based on the models and terminology provided in IEC 62264 [38]. This common foundation enables the design of a coherent architecture with complementary MOM and DT ACs. A DT is a general concept that can be tailored for a particular problem and domain. This domain-dependence results in a huge variety of theoretical and practical models for designing and implementing DTs [39]. ISO 23247 series defines international standards for making and maintaining DT in manufacturing [40]. Consequently, the reference architecture defined in ISO 23247 provides guidance for implementing DT in manufacturing. Additionally, the guidelines for the digital representation of manufacturing elements provided in ISO 23247 are based on the information models defined in ISO 62264. Therefore, the combination of the AAS and ISO 23247 form the foundation of the future design and research activities regarding the DT AC throughout the subsequent TOGAF phases.

3.3.3 Evaluation Application Component

The evaluation system shall support strategic decision-making in product improvement. It is based on the captured requirements and provides capabilities for product error evaluation, process evaluation, product performance evaluation, and cost evaluation. These align with use cases described in literature for data analysis in product planning. However, it does not include use cases that use product data to assess product performance or that support decision-making in development by assessing costs [41]. Moreover, Lindner's doctoral thesis also focuses on improving products based on the analysis of usage data. It explicitly describes the lack of data models that enable the integrated management of data from product development and product usage [42]. This challenge is to be met with the DT based on the Asset Administration Shell (AAS) that covers and administrates product-related data over the entire lifecycle of an asset [38].

To support in product development, decision-making should be based on concrete values by specifying the extent to which a requirement is met. If descriptive statistics are not sufficient, key performance indicators (KPIs) must be defined. Here, one can fall back on already established KPIs that describe the economic productivity or the technical operation of a product. If there is a need for further measurement, a system of KPIs can be developed [42]. To provide decision support, digital services are being developed that make use of analytical methods. For this purpose, the use cases specific to the application are modelled at the beginning in order to derive the submodels of the AAS on the basis of the modelling. This is to ensure the provision of data for the evaluation services.

4. Discussion

Several SDMS architectures are described in the literature review above but they do not fulfill the defined criteria completely. As an alternative to these existing SDMS architectures (due to results reached the umbrella term EA), EA methods for developing new architectures were investigated. From both the partially matching EA and the partially matching methodologies, appropriate standards were put together to develop a proposal to fill the scientific gap. TOGAF combined with domain specific standards provides guidance to design a suitable SDMS architecture for the H2Giga-FRHY project. It is presumable that the method is transferable to use cases with similar domain specific challenges, including high-rate production, greenfield, and highly monitored manufacturing. A comprehensive verification of this statement is pending and would be desirable. However, in the project it shows that the proposed methodology can provide functioning subsystems of the SDMS. Including the architecture vision that provided a good foundation for the following TOGAF phases and it is recommended to have a similar detail-level in the strategy. Furthermore, ArchiMate functioned well as modelling language for its wide scope and conformance to TOGAF. As predicted in [19], IEC62264 worked well with the TOGAF steps. This corresponds with the authors of [37] who suggest that new design challenges for next generation MOM arise in the era of industry 4.0. This includes standardization, interoperability, software customization, modularity and an increasing need for decentralization of MOM solutions.

5. Conclusion and Future Work

This paper explored the design of a software-defined manufacturing system to enable the enterprise architecture of a benchmark factory for electrolysers. The H2Giga-FRHY project focuses on a greenfield, decentralised and digitalised high-rate production of electrolyses that concentrates on the technology sub-parts. A research gap in the area of design frameworks for distributed greenfield productions was identified through a systematic literature review.

The literature review showed missing potential for enterprise architecture and software-defined manufacturing systems for high-rate manufacturing that are highly monitored like the electrolyser production. A design method was developed to address the found research gap. The method uses TOGAF, requirements engineering standards, AAS, and IEC 62264 to identify and design the necessary services and submodels for the use case. It is based on ArchiMate's layer models. The design method used in the project works well as a software-defined manufacturing system in the use case, and it can be adopted by similar domains. Apart from these use cases, a verification of the methods used on the basis of further production use cases would be interesting and desirable.

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References

[1] Hydrogen – the key to more climate action in Europe, 2020. https://www.bundesregierung.de/breg-en/service/eu-hydrogen-strategy-1796388. Accessed 4 November 2022.

[2] Hebling, C., Ragwitz, M., Fleiter, T., et al., 2019. Eine Wasserstoff-Roadmap für Deutschland. Fraunhofer-Institut für System- und Innovationsforschung ISI, Fraunhofer-Institut für Solare Energiesysteme ISE. Accessed 3 November 2022.

[3] Töpler, J., Lehmann, J., 2017. Wasserstoff und Brennstoffzelle. Springer Berlin Heidelberg, Berlin, Heidelberg.

[4] Project Management Jülich, 2021. How the H2Giga flagship project aims to mass produce electrolysers for the production and scale-up of hydrogen, Germany.

[5] Thames, L., Schaefer, D., 2016. Software-defined Cloud Manufacturing for Industry 4.0. Procedia CIRP 52, 12–17.

[6] Rauch, E., Seidenstricker, S., Dallasega, P., Hämmerl, R., 2016. Collaborative Cloud Manufacturing: Design of Business Model Innovations Enabled by Cyberphysical Systems in Distributed Manufacturing Systems. Journal of Engineering 2016, 1–12.

[7] Kitchenham, B., 2004. Procedures for Performing Systematic Reviews. Joint Technical Report. Software Engineering Group, Department of Computer Science, Keele University.

[8] Glinz, M., van Loenhoud, H., Staal, S., Bühne, S. Handbook for the CPRE Foundation Level according to the IREB Standard: Education and Training for Certified Professional for Requirements Engineering (CPRE), 143 pp. Accessed 25 October 2022.

[9] Martín-Martín, A., Orduna-Malea, E., Thelwall, M., Delgado López-Cózar, E., 2018. Google Scholar, Web of Science, and Scopus: A systematic comparison of citations in 252 subject categories. Journal of Informetrics 12 (4), 1160–1177.

[10] Mongeon, P., Paul-Hus, A., 2016. The journal coverage of Web of Science and Scopus: a comparative analysis. Scientometrics 106 (1), 213–228.

[11] Visser, M., van Eck, N.J., Waltman, L., 2021. Large-scale comparison of bibliographic data sources: Scopus, Web of Science, Dimensions, Crossref, and Microsoft Academic. Quantitative Science Studies 2 (1), 20–41.

[12] Newman, D., Parto, M., Saleeby, K., Kurfess, T., Dugenske, A., 2019. Development of a Digital Architecture for Distributed CNC Machine Health Monitoring. Smart Sustain. Manuf. Syst. 3 (2), 20190038.

[13] Guo, L., Cheng, Y., Zhang, Y., Liu, Y., Wan, C., Liang, J., 2021. Development of Cloud-Edge Collaborative Digital Twin System for FDM Additive Manufacturing, in: 2021 IEEE 19th International Conference on Industrial Informatics (INDIN). 2021 IEEE 19th International Conference on Industrial Informatics (INDIN), Palma de Mallorca, Spain. 21.07.2021 - 23.07.2021. IEEE, pp. 1–6.

[14] Hung, M.-H., Lin, Y.-C., Hsiao, H.-C., Chen, C.-C., Lai, K.-C., Hsieh, Y.-M., Tieng, H., Tsai, T.-H., Huang, H.-C., Yang, H.-C., Cheng, F.-T., 2022. A Novel Implementation Framework of Digital Twins for Intelligent Manufacturing Based on Container Technology and Cloud Manufacturing Services. IEEE Trans. Automat. Sci. Eng. 19 (3), 1614–1630.

[15] Roque Rolo, G., Dionisio Rocha, A., Tripa, J., Barata, J., 2021. Application of a Simulation-Based Digital Twin for Predicting Distributed Manufacturing Control System Performance. Applied Sciences 11 (5), 2202.

[16] Novak, P., Douda, P., Kadera, P., Vyskocil, J., 2022. PyMES: Distributed Manufacturing Execution System for Flexible Industry 4.0 Cyber-Physical Production Systems, in: 2022 IEEE International Conference on Systems, Man, and Cybernetics (SMC). 2022 IEEE International Conference on Systems, Man, and Cybernetics (SMC), Prague, Czech Republic. 09.10.2022 - 12.10.2022. IEEE, pp. 235–241.

[17] Shao, G., Kibira, D., 2018. Digital Manufacturing: Requirements and Challenges for Implementing Digital Surrogates, in: Simulation for a noble cause. 2018 Winter Simulation Conference : December 9-12, 2018, the Swedish Exhibition & Congress Centre, Gothenburg, Sweden. 2018 Winter Simulation Conference (WSC), Gothenburg, Sweden. 12/9/2018 - 12/12/2018. IEEE, Piscataway, NJ, pp. 1226–1237.

[18] Sreedhanya, L.R., Balan, S., 2023. Industry 4.0 Framework Using 7-layer Architecture for Smart Factory Application, in: Kaiser, M.S., Xie, J., Rathore, V.S. (Eds.), Information and Communication Technology for Competitive Strategies (ICTCS 2021), vol. 401. Springer Nature Singapore, Singapore, pp. 323–332.

[19] Yesilyurt, O., Schlereth, A., Oberle, M., Risling, M., Schel, D., 2022. Enterprise IT Architecture Greenfield Design Combining IEC 62264 and TOGAF by Example of Battery Manufacturing.

[20] Alzoubi, Y.I., Gill, A.Q., 2022. Can Agile Enterprise Architecture be Implemented Successfully in Distributed Agile Development? Empirical Findings. Glob J Flex Syst Manag 23 (2), 221–235.

[21] Trovao, H., Mamede, H.S., Da Silva, M.M., 2017. Enabling distributed SME, in: 2017 12th Iberian Conference on Information Systems and Technologies (CISTI). 2017 12th Iberian Conference on Information Systems and Technologies (CISTI), Lisbon, Portugal. 21.06.2017 - 24.06.2017. IEEE, pp. 1–8.

[22] Ansyori, R., Qodarsih, N., Soewito, B., 2018. A systematic literature review: Critical Success Factors to Implement Enterprise Architecture. Procedia Computer Science 135, 43–51.

[23] Ebrahim, Z., Irani, Z., 2005. E-government adoption: architecture and barriers. Business Process Management Journal 11 (5), 589–611.

[24] Guijarro, L., 2007. Interoperability frameworks and enterprise architectures in e-government initiatives in Europe and the United States. Government Information Quarterly 24 (1), 89–101.

[25] Hermawan, R.A., Sumitra, I.D., 2019. Designing Enterprise Architecture Using TOGAF Architecture Development Method. IOP Conf. Ser.: Mater. Sci. Eng. 662 (4), 42021.

[26] Sofyana, L., Putera, A.R., 2019. Business architecture planning with TOGAF framework. J. Phys.: Conf. Ser. 1375 (1), 12056.

[27] Al-Nasrawi, S., Ibrahim, M., 2013. An enterprise architecture mapping approach for realizing e-government, in: 2013 Third International Conference on Communications and Information Technology (ICCIT). 2013 International Conference on Communications and Information Technology (ICCIT), Beirut, Lebanon. 19.06.2013 - 21.06.2013. IEEE, pp. 17–21.

[28] Dumitriu, D., Popescu, M.A.-M., 2020. Enterprise Architecture Framework Design in IT Management. Procedia Manufacturing 46, 932–940.

[29] Qurratuaini, H., 2018. Designing enterprise architecture based on TOGAF 9.1 framework. IOP Conf. Ser.: Mater. Sci. Eng. 403, 12065.

[30] International Organization for Standardization, 2018. ISO/IEC/IEEEE 29148: Systems and software engineering - Life cycle processes - Requirements engineering. IEEE, S.l.

[31] The Open Group, 2018. The TOGAF® Standard, Version 9.2 ISBN: 1-947754-11-9, 532 pp. https://pubs.opengroup.org/architecture/togaf9-doc/arch/. Accessed 25 October 2022.

[32] Josey, A., Lankhorst, M., Band, I., Jonkers, H., Quartel, D., 2016. An Introduction to the ArchiMate® 3.0 Specification.

[33] International Organization for Standardization, 2011. ISO/IEC/IEEE 42010:2011: Systems and software engineering — Architecture description. IEEE.

[34] European Commission, Joint Research Centre, Tsotridis, G., Pilenga, A., 2019. EU harmonised terminology for low temperature water electrolysis for energy storage applications. Publications Office. https://data.europa.eu/doi/10.2760/138987.

[35] International Electrotechnical Commission, 2013. Enterprise-control system integration: Part 1: Models and terminology, 2nd ed. ISBN: 978-2-83220-734-5.

[36] International Electrotechnical Commission, 2017. Enterprisecontrol system integration: Part 3: Activity models of manufacturing operations management, 12th ed. ICS 35.240.50.

[37] Mantravadi, S., Møller, C., LI, C., Schnyder, R., 2022. Design choices for next-generation IIoT-connected MES/MOM: An empirical study on smart factories. Robotics and Computer-Integrated Manufacturing 73, 102225.

[38] Bader, S., Barnstedt, E., Bedenbender, H., et al., 2022. Details of the Asset Administration Shell: Part 1 - The exchange of information between partners in the value chain of Industrie 4.0. Specification. Accessed 4 November 2022.

[39] Sharma, A., Kosasih, E., Zhang, J., Brintrup, A., Calinescu, A., 2022. Digital Twins: State of the art theory and practice, challenges, and open research questions. Journal of Industrial Information Integration 30, 100383.

[40] International Organization for Standardization, 2021. ISO 23247: Automation systems and integration-Digital twin framework for Manufacturing.

[41] Meyer, M., Panzner, M., Koldewey, C., Dumitrescu, R., 2022. 17 Use Cases for Analyzing Use Phase Data in Product Planning of Manufacturing Companies. Procedia CIRP 107, 1053–1058.

[42] Lindner, A. Methodik zur Verbesserung standardisierter Produkte auf der Basis der Auswertung von Nutzungsdaten deren Vorgängergenerationen. PhD Thesis.

Biography

Alexander Brandstetter (*1995) is researcher at the Fraunhofer Institute for Manufacturing Engineering and Automation IPA since 2021 where he is working in the department competence centre for Digital Tools in Manufacturing and in the field of smart manufacturing.

Monika Risling (*1997) is researcher at the Fraunhofer Institute for Manufacturing Engineering and Automation IPA since 2021 where she is working in the department competence centre for Digital Tools in Manufacturing and in the field of smart manufacturing.

Henry Himmelstoß (*1991) is researcher and project leader at the Fraunhofer Institute for Manufacturing Engineering and Automation IPA since 2019 where he is working in the department competence centre for Digital Tools in Manufacturing..

Daniel Schel (*1986) is researcher and group leader at the competence centre for Digital Tools in Manufacturing at the Fraunhofer-Institute for Manufacturing Engineering and Automation IPA since 2011. He has managed and conducted a number of research projects as technical director and software architect, focusing on novel approaches to IT solutions in production.

Michael Oberle (*1984) is a computer scientist and group leader working in the field of smart manufacturing with a focus of data-driven and event- driven production control services. One of his main achievements is the fully connected cloud-controlled battery manufacturing pilot line at Fraunhofer IPAs technical centre for battery manufacturing.

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An Approach Towards Securing Future Viability Of SMEs In A VUCA World Using Artificial Intelligence To Increase Resilience

Lena Wecken[1], Tobias Heinen[2], Peter Nyhuis[1]
[1]*Institute of Production Systems and Logistics, Garbsen, Germany*
[2]*GREAN GmbH, Garbsen, Germany*

Abstract

Global crises pose major challenges for production companies: Rising material and energy costs, supply bottlenecks and the lack of planning certainty due to the dynamics of a pandemic or war weaken the planning stability. In this volatile, uncertain, complex and ambivalent environment (VUCA world), companies need responsible employees who recognise the individual need for action and initiate concrete measures early to increase a company's resilience. These measures affect multiple divisions. For example, disruptions in the supply chain are mitigated by various configuration elements such as expanding the supplier network or increasing stock in the company's own production. Therefore, measures encompass every element of the value network, whether in production or logistics. The example also shows that measures to increase resilience can influence other target characteristics of a company: Inventory increases can buy resilience at the expense of resource efficiency. Thus, measures must be defined for each design element depending on individual requirements in terms of resilience and must consider the scope for action of the respective company. This poses a great challenge, especially for small and medium-sized enterprises (SMEs). Here, decision-making is done by generalists who often do not have the detailed knowledge for this specific problem or the capacity for this additional task. The danger is that SMEs will take insufficient measures that do not secure their future viability in a VUCA world. In this paper, a solution approach for a methodology is presented, that allows to derive influences on production companies from the developments in a VUCA world and measures to increase resilience can be identified depending on individual company characteristics. Furthermore, a possible conceptualisation of the methodology in an AI-based software product is presented, which supports SMEs in the outlined complex problem by enabling them to apply the methodology. Both will be realised in a research project.

Keywords

VUCA, Resilience, Resilience Measurements, Future Viability, SME

1. Introduction and need for research

The times when companies could still plan under stable and thus calculable environmental conditions have been over since the 1980s at the latest. Technical progress, especially in logistics, and the introduction of the internet enabled the globalisation of goods and information flows and led to the interconnection of production in networks [1]. This was not only accompanied by opportunities for companies. The global economy, the environment, politics, society and technology have always had an influence on companies that must be taken into account in order to continue to do business in a future viable manner [1]. Due to advancing globalisation, the influencing factors listed above are also subject to permanent change. Due to this increasingly rapid, short-cycle and erratic change in environmental conditions, the predictability of influences on companies became more and more challenging - a trend that continues today [2,3]. The

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business environment is therefore now described as volatile, uncertain, complex and ambivalent and referred to as a VUCA world [4]. Examples from the last two years, such as the crises caused by COVID-19 or the war in Ukraine, as well as singular events such as the blockade of the Suez Canal, illustrate this [5–8]. In addition to crises or singular events, a VUCA world is shaped by the consequences of climate change, which companies increasingly have to deal with as they already have an impact on production systems [9,10]. For example, an increasing frequency of extreme climate events leads to the destruction of production facilities and transport routes or a shortage of raw materials and intermediate products required for production. In addition, there is a demand from politics and society that companies produce in an ecologically sustainable manner in order to contain the consequences of climate change and make the global economy climate-friendly [5,6,11]. With these changing influences on companies, their strategies for dealing with them have also changed. While flexibility, reconfigurability or adaptability were still considered success factors for future competitiveness a short time ago [1,12], they are no longer sufficient today [10]. In order to be prepared for the diverse and disruptive influences described above, resilience is the solution approach to design companies in a future viable manner **(prerequisite 1)** [13]. Resilience is the ability of a system to maintain the functionality necessary for its existence when disruptive events occur and to recover its operation as quickly as possible by implementing appropriate measures [14].

To increase the resilience of manufacturing companies, it is the task of factory planners to adapt factory operations to current requirements of a VUCA world. Factory operations tasks include operating, steering, controlling and maintaining as well as other services [1,15]. This is becoming increasingly challenging for companies [16]. Measures to ensure future viability through resilience cannot be limited to one area of consideration within the company. For example, disruptions in the supply chain can be countered by various design objects such as expanding the supplier network or increasing inventory in the company's own production. Measures can therefore encompass every element of the entire value network, whether in production or logistics **(prerequisite 2)**. The example also shows that measures often contradict themselves: With the help of inventory increases, resilience can be bought at the expense of resource efficiency and vice versa. Factory planners therefore need a precise understanding of their company's system in order to define measures according to their individual requirements. In conclusion, the selected measures must be aligned with the company's characteristics, which depend, for example, on the strategic company goals or the possibilities for action **(prerequisite 3)**. In order for companies to be able to apply the measures to their system as easily as possible, measures must be described in concrete and practical terms **(prerequisite 4)**. This task has become a demanding ongoing task for factory planners due to the increasing and challenging influences on manufacturing companies in a VUCA world, which force a permanent adaptation of the factory and factory operations [15].

In large companies, measures defined in factory planning projects are developed by an interdisciplinary project team with a wealth of experience and knowledge [1]. These are often accompanied by comprehensive changes, which are usually decided by the management. In large companies, the management is thus comprehensively supported by specialist planners in the definition of measures. This is not possible in SMEs, for example, due to fewer personnel resources and a lack of expertise. Another complicating factor is that the management of SMEs is usually busy with day-to-day business and not only lacks the detailed knowledge for these additional tasks, but also does not have the capacity to deal with them sufficiently [17]. As a result, there is a danger that SMEs will not recognise the influences from a VUCA world. Therefore, they will not correctly assess the consequences and resulting demands on their own company, or will not be able to adapt to the requirements in a targeted manner with the help of suitable measures. Consequently, this means that SMEs are not able to position themselves future viable in a VUCA world. However, for Germany as a production location dependent on SMEs, this is of great relevance [18]. It follows that SMEs need decision support for this task that can be applied at a low-threshold level, e.g. by implementation through a software product **(prerequisite 5)**. In summary, the following requirements apply to decision support for SMEs to ensure their future viability in a VUCA world:

1. Increasing entrepreneurial resilience
2. Taking into account the design fields of production and logistics
3. Consideration of individual company characteristics
4. Definition of concrete and practice-oriented measures for action
5. Low-threshold applicability

A literature review identified approaches that enable companies to become more resilient [6,19–25] in the face of influences from a VUCA world. Above all, the approaches to increasing resilience primarily describe organisational recommendations that are aimed at a strategic orientation of the companies and are consequently not very concrete. The table below compares approaches that include methods for increasing resilience not only at the organisational level and examines them with regard to the prerequisites listed above.

Table 1: Overview of existing research approaches

Research Approach	Prerequisite				
	1	2	3	4	5
Triple R-Supply-Chain-Modell [6]	x	x		(x)	
World Class Manufacturing performance measurement [26]	(x)		x	(x)	
BEVUCA [27]	(x)			(x)	
Resilience and Relocalisation [28]	x	(x)		(x)	
Measurement-Resilience Roadmap [29]	x	(x)	(x)		
ERUC [30]	(x)	(x)	x	x	x

x fulfils
(x) with restrictions

The Triple R supply chain model [6] is a method for increasing the resilience of primarily the supply chain. Furthermore, although the model provides options for action, these are not concrete and are not geared to individual company characteristics, so that this must be done by the user. The World Class Manufacturing performance measurement [26] provides an approach for companies to strategically select best management practices depending on their specific needs in a VUCA world. However, it does not explicitly address resilience and the management practices are not concrete. BEVUCA [27] provides an approach to business excellence in a VUCA world by identifying success factors that can serve as orientation for companies. Though, concrete measures for action are not given and the requirements of resilience is not explicitly addressed. The approaches presented are management approaches with only little reference to practice. Moreover, none of the approaches offers a low-threshold application, e. g. through software or other support. In the study "Resilience and Relocalisation" [28], resilience in SMEs is analysed and recommendations for action are based on this. However, these are not described in a concrete and practice-oriented enough manner and do not take into account company-specific characteristics. In addition, although the area of logistics is examined immediately but production and the measures that can be taken here are not. The Measurement-Resilience Roadmap [29] is a five-step procedure that supports companies in increasing the resilience of the supply chain according to their individual requirements; aspects of production are not taken into account. Concrete measures are not described, but are still to be developed by the SMEs themselves. ERUC [30] is a software-based decision support tool for selecting measures with which companies can increase their resilience according to their individual requirements. However, the tool can only be used to support ramp-up management, which means that no measures are given in production and logistics over the entire factory life cycle. Measures for the preventive design of the production system against future-critical influences of a VUCA world are therefore not possible through ERUC and measures for improving entrepreneurial resilience are limited to the specific use case of a production ramp-up.

It becomes clear that so far, no approach exists that fulfils all the requirements identified and listed above. Above all, most approaches do not take into account the individual company characteristics and the low-threshold application of the approaches, e. g. through software. In this context, low-threshold means that no prior knowledge is required for the application and no high time capacities are needed. SMEs in particular, as already explained, do not have the personnel capacities to derive concrete measures from the standardised approaches and to work out a future viable solution.

2. Idea to close the research gap

In order to close the research gap and provide SMEs with the necessary support in a VUCA world, a methodological approach is to be developed that fulfils prerequisites one to four. The procedure for this is described below in section 2.1. To ensure that prerequisite five is met, the method is to be made available to SMEs via a low-threshold AI-based software tool. The development of the software support is described in Section 2.2. Thus, an approach is presented below that closes the previously described research gap.

2.1 Methodological approach

Figure 1 illustrates the methodological approach that fulfils prerequisites one to four and forms the basis for the software solution. The approach is described in more detail in the following section.

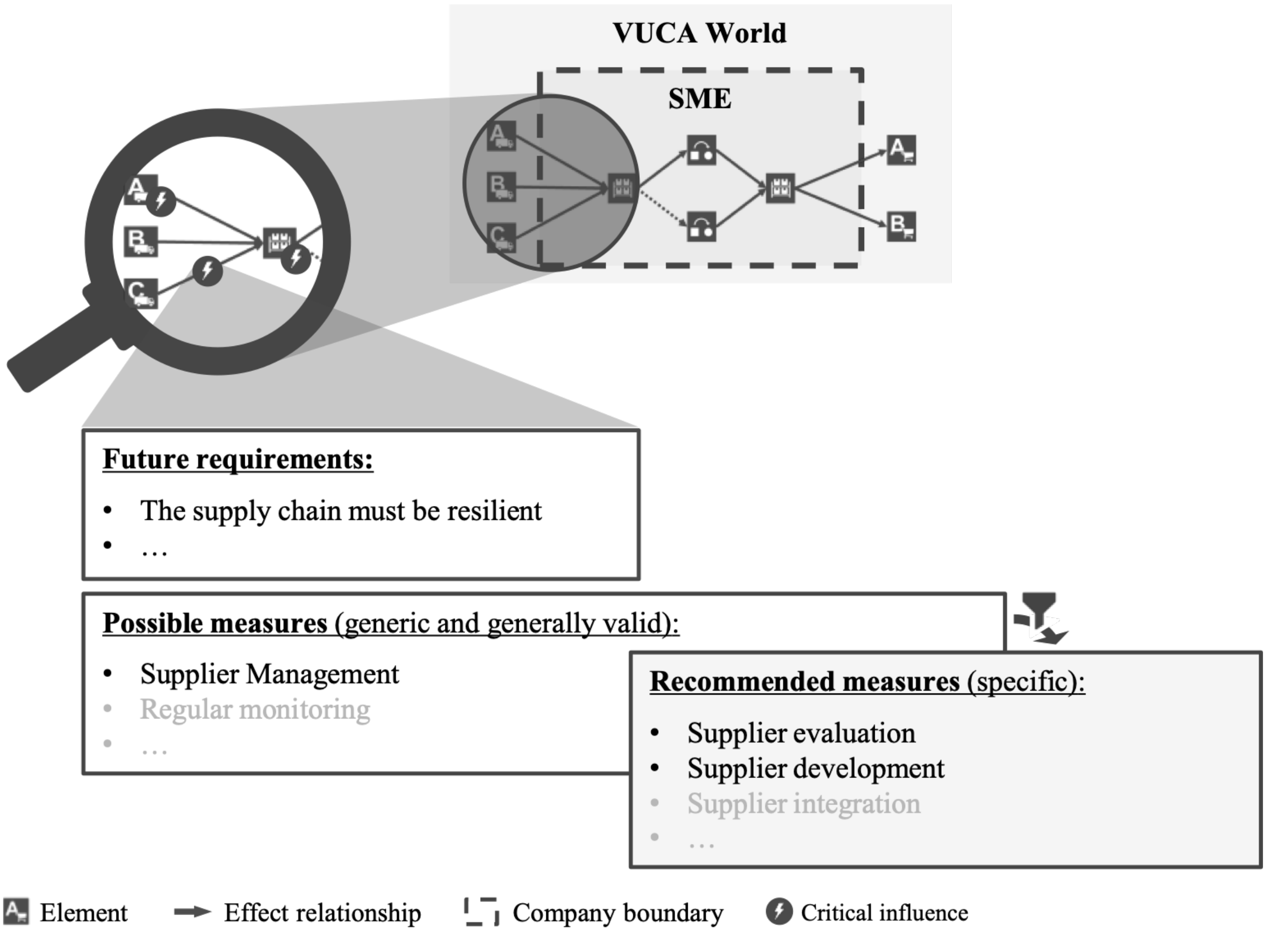

Figure 1: Methodological approach

In order to meet the needs of a large number of SMEs with the approach, they should be able to model their production systems and individual system behaviour realistically through multi-method modelling in the subsequent software application. In order for this to be taken into account in the subsequent development of the software, the first step is to identify the elementary elements and effect relationships as components of production systems. The smallest elements of a production system are located at the workplace level, such as operating resources or manual workplaces. This level of consideration is too detailed for the methodology to be applicable at a low level. A meaningful level of consideration for the project is the sub-area level with exemplary elements such as work systems. In order for the production system to be considered as part of the value network in a VUCA world, additional elements and effect relationships outside the system boundary must be added, such as suppliers or customers. To be able to model the behaviour of the production system realistically, the elements and effect relationships must also be parameterised. Relevant parameters for work systems are, for example, the scope of work or the number of operating resources. Additional information that is relevant for characterising the element or the effect relationships must also be acquired and parameterised, such as location information of the production system under consideration or its suppliers and customers. Anonymised data from industry partners are used to identify and parameterise the elements and effect relationships.

Building on this, the next step is to outline the relevant development scenarios of a VUCA world with the help of scenario management in order to determine the resulting critical influences on the previously identified elements and effect relationships. For this purpose, the scenario fields to be analysed in the further project must first be defined and limited. Therefore, the value creation networks and the general political and social environment of SMEs are systematised as areas of influence that allow a structured search for influencing factors. Selected sectors in which SMEs are particularly strongly represented will be focussed on to achieve this. In the long term, however, the aim is to further develop the methodology so that it can be applied to production systems in all sectors. To subsequently determine the influencing factors, expert interviews will be conducted with industry representatives and SMEs. These are to be supplemented by a literature search. In order to reduce the number of influencing factors to be investigated to a manageable number, the critical factors for the future viability of an SME in a VUCA world are identified. For these, possible and realistic development scenarios are formed using historical data and supplementary expert interviews, which represent the critical influences on SMEs in a VUCA world.

Determining the influences is a necessary step in order to be able to define ideal conditions for each element and each effect relationship. This must be done depending on possible company-specific configurations, such as economic, social or ecological company goals. For an element or effect relationship under consideration, several ideal states can therefore result for each influence. Requirements for the future viable design of the elements and effect relationships are then derived from the ideal states, for which specific measures can then be defined. For some requirements, measures already exist that can be compiled from the experience of past industrial projects and a supplementary literature research. All measures must be described in concrete terms. This means that the measure must include a concrete guideline for action as well as the required methodological knowledge. The measure "supplier management", for example, includes the procedure and relevant criteria for supplier evaluation as well as strategies for dealing with suppliers based on the evaluation results. The measures should also be systematised in a comparable way. This makes it possible to filter the generic catalogue of measures according to certain criteria, e.g. the scenario to be considered, the sector and the company goals. These filtered measures represent the recommendations for action tailored to the SMEs.

2.2 Development of AI-based software tool

In order to make this methodological approach available to SMEs in a low-threshold manner, it is to be transferred into an intuitively operated and on narrow AI-based software tool after conceptualisation. The software tool is composed of various self-learning algorithms, which each assume partial functionalities. Three basic requirements must be met for this: One, data describing the partial problems must be defined, provided and prepared. These are then also used to train and validate the AI. Two, the algorithms for the individual software functionalities must be programmed and three, these must be transferred into a software architecture.

Data is fundamental to the project and must be appropriately defined, provided and prepared for further use. The different requirements, e.g. in terms of scope or level of detail, for the data sets are to be *defined* depending on the individual partial problems of the research project. A data set consists of several data instances that are described by attributes. The individual attributes make it possible to describe the circumstances to be investigated with the software tool. For example, the development of the electricity price is to be forecast as a possible factor influencing companies in the VUCA world. For this purpose, all identified development-determining characteristics, such as gas price, concession fees or grid charges, must be combined as attributes into data instances. The decision on the number and relevance of the attributes is already relevant for the quality of the results of the later software tool. On the one hand, it is important to limit the attributes so that the algorithm does not become unnecessarily complex. On the other hand, no relevant attributes should be excluded in order to avoid exclusion bias. For the respective partial problems, different data are *provided* in each case. With the help of past geopolitical and economic data, the developments of the influencing factors can be described. In combination with anonymised industrial data, the influencing factors can be identified as future-critical and assigned to the relevant elements and effect relationships of the production systems. The historical geopolitical and economic data are available in sufficient quantity through public news agencies or authorities and the industrial data can be obtained from cooperating SMEs. Depending on the data quality, the facts to be described and the outcome, the data must be *prepared* differently. In any case, this includes data cleansing and evaluation, and in the case of self-learning algorithms, standardisation and labelling depending on the type of training.

The **algorithms** to be programmed should apply the methodology described in section 2.1 applicable for SMEs through functionalities in a software. In particular, the three functionalities of scenario building in a VUCA world, trouble shooting of the production systems and filtering of the action catalogues are to be realised. *Scenario building* from developments in a VUCA world serves to predict the relevant future-critical influences on the respective SMEs. The influencing factors identified during the creation of the methodology serve as the basis for scenario building. A forecasting algorithm, modelled on scenario management and based on current geopolitical and -economic information, describes the realistic future developments of the influencing factors. Since the algorithm works numerically, the influences must be parameterised. The developments of the influencing factors are grouped into influences affecting SMEs with the help of a grouping algorithm. A classifying algorithm is used to identify the influences that are critical for the future. During the software application, influences can become relevant with which the algorithm has not been trained. To ensure that these are nevertheless recognised and that scenario building remains applicable as a software functionality, this functionality is to be realised by a self-learning algorithm. *Trouble shooting* is used to allow the future-critical influences identified through scenario building to affect elements and effect relationships of the production systems and to identify resulting vulnerabilities. With the help of a classifying algorithm, the future-critical influences are assigned to the respective elements and effect relationships, which are defined as classes. This algorithm must also be self-learning so that it can still assign the influences to the correct elements and effect relationships during the software application that were not yet taken into account in the training phase. The model of the production system created by the user can be supplemented with the influence parameters on this basis. The prerequisite for this is that the model modules allow this addition through appropriate design and that the influencing parameters are systematised in a compatible manner. The vulnerabilities are then identified by simulation. They are valid for individual companies because the company-specific characteristics are taken into account through modelling and parameterisation of the production systems. The filtering of the measure catalogues serves to filter specific measures for the company-specific vulnerabilities of the elements and effect relationships from the previously defined generally valid and already defined measure catalogues. The filtering is to be realised with the help of a classifying self-learning algorithm that assigns the identified weak points to the specific measures, i.e. the classes, taking into account the filter criteria. Criteria to be considered in the filtering process include not only the design requirements for the elements and effect relationships, but also, for example, the economic, social or ecological corporate goals. The algorithm must be self-learning so that specific measures in the software application can be identified even for vulnerabilities not taken into account during the training phase. The algorithms can be based on different techniques, e.g. k-Nearest-Neighbour or Support Vector Machine in order of classification. Depending on the data, the techniques that describe the respective circumstances realistically and generate the smallest possible bias must be determined. A decision on the technique to be used is therefore not meaningful in advance, but must be precisely selected during the implementation.

The purpose of the **software architecture** is to develop the back- and frontend of the software. Development task of the *backend* is to integrate the previously described algorithms as software functionalities. During software application, it must be ensured that the algorithms are constantly fed with the latest data on developments in a VUCA world. Therefore, interfaces to data mining-based monitoring services such as Google Alerts, Awario or Mention have to be considered in the software architecture. Development of the *frontend* must succeed in making the software low-threshold to use. For this purpose, the user interfaces are to be designed intuitively according to the mock-up visualized in Figure 2 as a reference. For example, the elements and interdependencies required to describe the system behaviour must be transferred to a System Dynamics model in which the users can map their individual company structure via drag & drop.

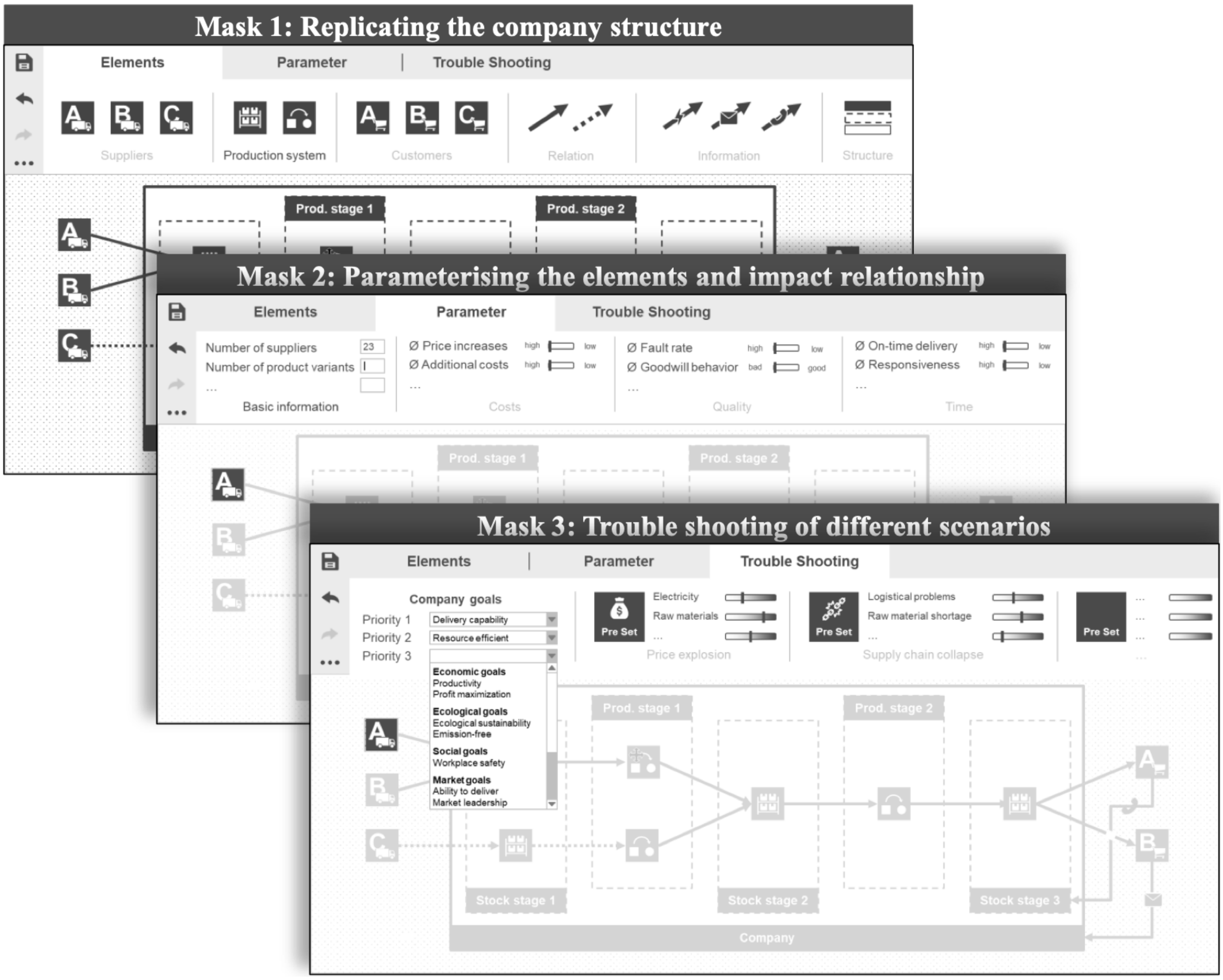

Figure 2: Mock-up of the possible front end of the software solution

3. Challenges and action strategies

For the project to be successful, the methodology described in section 2.1 must be valid and the development of the AI-based software support described in section 2.2 must be successful. The difficulty in developing the methodology is to summarise all elements and effect relationships of different production systems in a generally valid way without neglecting relevant features. This is also relevant for the algorithms to be subsequently programmed in order to avoid over- or underfitting of the AI. By successively testing the defined elements and effect relationships for applicability, this potential source of error can be prevented as early as possible. The acquisition and preparation of reliable data is the greatest challenge for the realisation of AI-based software support. Section 2.2 describes in detail which data must be used and prepared in order to train the respective algorithms. The procurement of historical data is unproblematic due to their easy availability. The systematic processing and labelling of the data for the various algorithms, on the other hand, is time-consuming. Particularly the labelling of the data requires great care, as this determines the solution spaces of the classifying algorithms and has a corresponding influence on the recommended measures for SMEs. The labels must therefore be validated before training. Obtaining the industry data, on the other hand, is more challenging. Data sets of several SMEs per area of the production system are needed, which have been identified as elementary elements and effect relationships to describe the system behaviour. It is to be expected that the data quality as well as the quantitative availability of the required data sets is not sufficient in all SMEs for the project. For each of the data sets, data requirements lists are therefore to be defined, with which the quantitative and qualitative availability of the data in the SMEs is to be checked in advance. If individual data sets cannot be procured in sufficient quantity or quality, these areas of the production system are excluded from the horizon of consideration for the time being. As soon as data availability can also be ensured for these data sets, the methodology for the respective areas of the production system is to be further developed. The consideration of all design fields of production and logistics is an advantage of the project compared to other approaches and is therefore a unique characteristic that should not be neglected. One challenge in the application is that SMEs are comparatively sceptical about AI-based solutions. In order to counteract this, cooperating SMEs are involved in the project as early as possible, both through data procurement and through the validation of the interim results. On the one hand, this ensures the applicability of the methodology as well as the software tool in SMEs and, on the other hand, increases the willingness of SMEs to use it.

4. Summary and outlook

So far, there is no approach that offers companies adequate support to adapt to the influences of a VUCA world in a future-oriented way. This is a major challenge for SMEs in particular, which they find difficult to overcome due to a lack of resources and expertise. The method outlined above not only enables companies to recognise the requirements arising from a VUCA world, but also provides specific recommendations for action, for the future viable design of the respective production system. Future research activities of the Institute of Production Systems and Logistics (IFA) and GREAN GmbH will develop the valid methodology and transfer it into a low-threshold and AI-based software tool so that it can be ensured that the methodology is applicable for SMEs.

References

[1] Wiendahl, H.-P., Reichardt, J., Nyhuis, P., 2014. Handbuch Fabrikplanung: Konzept, Gestaltung und Umsetzung wandlungsfähiger Produktionsstätten, 2., überarb. und erw. Aufl. ed. Hanser, München, Wien, 628 pp.

[2] Warnecke, H.-J., 1993. Revolution der Unternehmenskultur: Das Fraktale Unternehmen, 2. Auflage ed. Springer Berlin Heidelberg, Berlin, Heidelberg, s.l., 283 pp.

[3] Westkämper, E., Wiendahl, H.-H., Pritschow, G., Rempp, B., Schanz, M., 2000. Turbulenz in der PPS – eine Analogie. wt Werkstattstechnik 90 (5), 203–207.

[4] Bennett, N., Lemoine, G.J., 2014. What a difference a word makes: Understanding threats to performance in a VUCA world. Business horizons (57), 311–317.

[5] Gaubinger, K., 2021. Hybrides Innovationsmanagement für den Mittelstand in einer VUCA-Welt. Springer Berlin Heidelberg, Berlin, Heidelberg.

[6] Kleemann, F.C., Frühbeis, R., 2021. Resiliente Lieferketten in der VUCA-Welt: Supply Chain Management für Corona, Brexit & Co, 1st ed. 2021 ed. Springer Fachmedien Wiesbaden; Imprint Springer Gabler, Wiesbaden, 51 pp.

[7] Krauss, S., Plugmann, P. (Eds.), 2022. Innovationen in der Wirtschaft. Springer Fachmedien Wiesbaden, Wiesbaden.

[8] Kremer, R.B., 2022. Resiliente Supply Chains und der Faktor Mensch: Digitalisierung und Automatisierung im Rahmen innovativer Logistikkonzepte in Krisenzeiten, in: Krauss, S., Plugmann, P. (Eds.), Innovationen in der Wirtschaft. Springer Fachmedien Wiesbaden, Wiesbaden, pp. 77–90.

[9] Dombrowski, U., Marx, S., 2018. KlimaIng - Planung klimagerechter Fabriken. Springer Berlin Heidelberg, Berlin, Heidelberg.

[10] Roos, M., 2022. Wirtschaft in der Transformation: Von der Effizienz- zur Resilienzorientierung?, in: Wannöffel, M., Gensterblum, Y. (Eds.), Wirtschaft, Arbeit und Leben mit und nach der Corona-Krise. Nomos Verlagsgesellschaft mbH & Co. KG.

[11] Sihn-Weber, A., Fischler, F., 2020. CSR und Klimawandel. Springer Berlin Heidelberg, Berlin, Heidelberg.

[12] Hernández, R., 2002. Systematik der Wandlungsfähigkeit in der Fabrikplanung, Hannover.

[13] Hingst, L., Wecken, L., Brunotte, E., Nyhuis, P., 2022. Einordnung der Robustheit und Resilienz in die Veränderungsfähigkeit.

[14] Hingst, L., Park, Y.-B., Nyhuis, P., 2021. Life Cycle Oriented Planning Of Changeability In Factory Planning Under Uncertainty. Hannover : publish-Ing.

[15] Schenk, M., Wirth, S., Müller, E., 2014. Fabrikplanung und Fabrikbetrieb: Methoden für die wandlungsfähige, vernetzte und ressourceneffiziente Fabrik, 2., vollst. überarb. und erw. Aufl. ed. Springer Vieweg, Berlin, 832 pp.

[16] Hellmuth, R., Frohnmayer, J., Sulzmann, F., 2020. Design and Application of a Digital Factory Model for Factory Restructuring. Procedia CIRP 91, 158–163.

[17] Haag, P., 2021. KMU- und Start-up-Management. Springer Fachmedien Wiesbaden, Wiesbaden.

[18] Statistisches Bundesamt, 2022. Verteilung des Umsatzes der Unternehmen in Deutschland nach Unternehmensgröße im Jahr 2020.

[19] International Organization for Standardization, 2017. Security and resilience — Organizational resilience — Principles and attributes.

[20] Sáenz, M.J., Revilla, E., 2013. Creating more resilient supply chains. MIT sloan management review.

[21] Chopra, S., Sodhi, M.S., Lücker, F., 2021. Achieving Supply Chain Efficiency and Resilience by Using Multi-level Commons. SSRN, S.l., 36 pp.

[22] Alarcon-Gerbier, E., Chokparova, Z., Ghondaghsaz, N., Zhao, W., Shahmoradi-Moghadam, H., Aßmann, U., Oruç, O., 2022. Software-Defined Mobile Supply Chains: Rebalancing Resilience and Efficiency in Production Systems. Sustainability 14 (5), 2837.

[23] Borgmann, F., Kalbe, N., Günter, A., 2022. Resiliente und wandlungsfähige Produktion von morgen: Matrixproduktion schrittweise gedacht. Zeitschrift für Wirtschaftlichen Fabrikbetrieb 117 (3), 104–108.

[24] Fisher, D.M., Law, R.D., 2021. How to Choose a Measure of Resilience: An Organizing Framework for Resilience Measurement. Applied Psychology 70 (2), 643–673.

[25] Knothe, T., Oertwig, N., Woesthoff, J., Sala, A., Lütkemeyer, M., Gaal, A., 2021. Resilienz durch dynamisches Prozessmanagement. Zeitschrift für Wirtschaftlichen Fabrikbetrieb 116 (7-8), 520–524.

[26] Andrade, C.T.A. de, Gusmão, A.P.H. de, Silva, W., 2021. World Class Manufacturing performance measurement using a maturity model and the FlowSort method. International Journal of Production Research 59 (24), 7374–7389.

[27] Saleh, A., Watson, R., 2017. Business excellence in a volatile, uncertain, complex and ambiguous environment (BEVUCA). TQM 29 (5), 705–724.

[28] Gittenberger, E., Kleissner, A., Voithofer, P., 2021. Resilienz und Relokalisierung: Wie KMU Krisen besser bewältigen können. Bundesministerium für Digitalisierung und Wirtschaftsstandort, Wien.

[29] Scholz, S., Kraut, A., 2021. Supply-Chain-Gestaltung im Mittelstand: Robuste Lieferketten als Erfolgsfaktor. Zeitschrift für Wirtschaftlichen Fabrikbetrieb 116 (6), 423–427.

[30] Knothe, T., Scholz, J.-A., Oertwig, N., Petrusch, N., 2020. Schnell erholen dank Resilienz im Unternehmen. Zeitschrift für Wirtschaftlichen Fabrikbetrieb 115 (12), 860–863.

Biography

Lena Wecken (*1995) studied industrial engineering with focus on production technology at Leibniz University Hannover and Athens University of Economics and Business. She works as a research Associate in the specialist factory planning group at the Institute of Production Systems and Logistics (IFA) at the Leibniz University Hanover since 2021.

Tobias Heinen (*1981) has been managing partner of GREAN GmbH, a production consultancy based in Hanover, since 2011. Before that he was a research assistant in the Factory Planning Group at the Institute of Production Systems and Logistics (IFA) at Leibniz Universität Hannover between 2006 and 2011. He has a lectureship in "Sustainability in Production" at Leibniz University Hanover.

Peter Nyhuis (*1957) studied mechanical engineering at Leibniz University Hanover and subsequently worked as a research associate at Institute of Production Systems and Logistics (IFA). After completing his doctorate in engineering, he received his habilitation before working as a manager in the field of supply chain management in the electronics and mechanical engineering industry. He is heading the IFA since 2003.

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Path Prediction For Efficient Order Release In Matrix-Structured Assembly Systems

Peter Burggräf[1,2], Tobias Adlon[1], Esben Schukat[1], German Bluvstein[1]

[1] *Laboratory for Machine Tools and Production Engineering (WZL) of RWTH Aachen University, Aachen, Germany*
[2] *Chair of International Production Engineering and Management (IPEM), University of Siegen, Siegen, Germany*

Abstract

Numerous research papers have already demonstrated the theoretical benefits of matrix-structured assembly systems. Nevertheless, such assembly systems have hardly been used in practice so far. The main reason for this, apart from the technical integration, is the complexity of controlling matrix-structured assembly systems. In theory, decentralized, agent-based control architectures have proven to be particularly suitable. However, order release has been largely neglected so far. Accordingly, the authors' previous work includes a conceptual approach for capacity-oriented order release in matrix-structured assembly systems. This previous approach calculates possible sequences of an order and their capacity requirements on operation and system level considering both routing and sequence flexibility. Furthermore, by combining the possible sequences of released orders with orders to be released and comparing them with the available capacity, the previously suggested approach can systematically carry out capacity-oriented release decisions. However, the NP-hard problem arising from the consideration of all possible sequences in the capacity analysis limits the scalability and real-time capability of the former approach. The present paper aims to extend the previously developed approach. For this, before analysing any capacity implications in order release, a most likely sequence is selected. This is done by deriving possible paths of an order through the assembly system using the given sequences of operations from the assembly precedence graph. Selecting the path and that leads the shortest transportation time, the number of sequences for capacity analysis can be drastically reduced. Doing so, the NP-hardness of the previously developed approach can be circumvented. The paper describes the logic of path prediction in detail and evaluates its impact on order release. This work contributes to the practical realization and economic operation of matrix-structured assembly systems.

Keywords

Matrix-structured assembly systems; assembly control; multi-agent system; order release; simulation

1. Introduction

Matrix-structured assembly systems promise to reduce line balancing efforts in assembly planning and to facilitate the rapid integration of new products into existing production environments. For this purpose, the rigid linkage of assembly stations, as it is common in assembly line production, is eliminated in favour of assembly stations arranged in matrix form. This allows orders to take individual paths through the assembly system depending on their configuration features or the availability of assembly stations. Irrelevant or occupied assembly stations can be skipped. [1] The coordination and assignment of orders to assembly stations is handled by an assembly control system. [2] In general, assembly control refers to all actions and activities that directly affect the assembly system during its operation. The objectives of assembly control are the management of a proper flow of resources and materials, the optimization of capacity utilization, and the monitoring of assembly processes. [3,4]

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In matrix-structured assembly systems, assembly control presents a particular challenge. This is caused by the consideration of flexibility of the assembly precedence graph as well as the redundancy and multifunctionality of assembly stations. The assembly control has to react to events such as malfunctions at short notice and is consequently dependent on real-time data from the assembly system. Literature suggests two architectures for the design of assembly control in matrix-structured assembly systems: centralized and decentralized. [4] The latter, which can be modelled with the help of multi-agent systems (MAS) [5–7], has been found to be more suitable in the present context [8] For example, BURGGRÄF et al., MAY et al. and MAYER et al. present agent-based assembly control systems for matrix-structured assembly systems. [2,9,10]

One task of the assembly control is order release. Order release changes the status of an order from proposed to released and thus triggers the production process. [11] According to SCHÖNSLEBEN, this includes an evaluation of necessary and available capacities to process an order [11]. This capacity evaluation is a complex task in matrix-structured assembly systems. [12,13] Orders are reactively assigned to assembly stations while orders can take various different paths through the assembly system. Consequently, a deterministic prediction of a specific path and thus a general valid capacity evaluation is not possible. Instead, the capacity evaluation must anticipate and combine all possible sequences of orders already released with the possible sequences of orders yet to be released. [13] Based on this motivation, the authors presented a method for capacity-based order release in matrix-structured assembly systems in a previous paper. This former approach describes a capacity evaluation considering all possible operation sequences of released as well as to be released orders. However, this approach shows to NP-hardness (NP: non-deterministic polynomial-time) and thus limitations in terms of scalability for larger problem instances. Accordingly, a suitable approach has to be found to address this deficit. [13] To this end, the present paper extends previous work on capacity-oriented order release in matrix-structured assembly systems. It suggests an approach to limit the sequences used in the capacity evaluation by processing possible paths and related transportation times. For this purpose, the preliminary work in the area of order release in matrix-structured assembly systems is first described and the shortcomings are shown. This is followed by a derivation, description and simulative evaluation of the solution approach. Hence, a concrete test case will be introduced. The paper concludes with a discussion as well as a summary of the results.

2. Order release in matrix-structured assembly systems

2.1 Shortcomings of agent-based assembly controls in multi-agent systems

The known research work on assembly control has so far focused in particular on the core function of assembly control, i.e. assigning orders to the available assembly stations and triggering specific assembly operations at assembly stations. However, other essential functions of assembly control also include material supply, coordination of assembly personnel and order release. [13] Material supply in matrix-structured assembly systems has already been the subject of a wide range of research activities. [14–19]

The coordination of the assembly personnel should be based on the assembly object and thus on the value creation process. Before taking a deeper look at the coordination of assembly personnel, it is therefore first necessary to examine assembly control with regard to order release. For the previous simulation studies, simplified approaches were used. For example, SCHÖNEMANN et al. provided a ConWIP-control, where orders are released in random order from an order pool to limit the number of orders in an assembly system.[20] BOCHMANN implemented an order release with Linear Programming, where orders are sorted by completion date. [21] MAYER et al. also present a ConWIP-control. [10,22] MAYER & ENDISCH use periodic order release [23], as do GÖPPERT et al. and HÜTTEMANN which both model order release as a stochastic process [24,25]. None of the known studies offers a detailed elaboration of order release to take into account short-term changes in capacity availability within the assembly system or the changes in the order pool. Nevertheless, different authors point out the relevance of order release. For example, MAYER et al. expect that by improving order release, more stable lead times can be achieved while reducing deadlocks of orders in the assembly system. [22] GRESCHKE also points out the necessity to consider order release as a part of assembly control and to design it in a combined way. [4] Only SCHUKAT et al. propose a conceptual approach for order release in matrix-structured assembly systems, hence it is detailed below. [13]

2.2 Capacity-based order release in matrix-structured assembly systems

In their previous work, the authors presented a methodology for order release for matrix-structured assembly systems. It is implemented as part of an agent-based assembly control by BURGGRÄF et al. [8] as separate order release agent (ORA) that specifically takes control of order release. To do so, the ORA communicates with a manager agent, which triggers the ORA. The ORA retrieves information from the environment and evaluates the system based on the available capacity. Once the capacity situation is evaluated, it communicates in case a suitable order for release was found.

To evaluate the capacity situation of the assembly system and take release decisions, the ORA creates capacity profiles for each order already released and for each possible release candidate. A capacity profile describes the time-specific demand for assembly operations of an order. These are represented as a matrix, where each column represents a unit of time and each row represents the demand for an assembly operation as a binary variable. The number of columns covers the entire time horizon until the completion of an order. The sequence of assembly operations is based on the assembly precedence graph. A widely branched precedence graph offers more possibilities for different assembly sequences resulting in a higher number of capacity profiles per order. Thus, one capacity profile is created for every valid sequence of assembly operations for each order. Capacity profiles also present the current state of the job. Accordingly, orders with completed assembly operations have less capacity profiles than unprocessed orders while also having fever filled columns as the time horizon until completion is shorter. In order to keep calculations between matrices possible, the size of every capacity profile is stretched to the longest possible sequence in the system and filled with zeroes in time steps that exceed the actual demand for assembly operations.

Each capacity profile thus reflects a possible load of the assembly system by an order. Since all assembly sequences and thus all capacity profiles can occur in reactive assembly control, all capacity profiles are still taken into account. In order to map the current capacity load of the assembly system, all combinations of the capacity profiles of the orders currently being processed are added up. This results in an operation- and time-specific prediction of the system load. All these combinations are then extended with capacity profiles of unprocessed orders. Those so-called matched capacity profiles must be compared with the available processing capacity of the assembly system. The available processing capacity of one assembly station is described with a vector containing the operation-specific capability. By summing of those vectors, the overall processing capacity of the system can be described. The resulting vector describes the system supply. Now, for each time unit, the overall system supply can be compared column-wise with the matched capacity profiles. If the demand for a certain operation exceeds the available processing capacity, the matched capacity profiles is rejected. Nevertheless, a different matched capacity profile of the same order may be accepted.

The non-rejected profiles or rather their unprocessed orders are then evaluated in terms of best capacity fit. For this purpose, these orders are initially distinguished exclusively by the assembly operations they contain. Identical assembly operations of an order are interpreted as identical products. Thus, these orders are equated at first. The capacity fit is the sum the free capacity of the system for all operations, calculated by subtracting the matched capacity profile from the available processing capacity over all time steps. The product which utilizes the system the most is then selected for further evaluation on order specific level. Here, a scored-based decision considering due dates or expected profit is used to select a specific job for release. When no order was selected due to the overload constraint, no order is dispatched and the agent goes into standby.

2.3 Limitations of capacity evaluation regarding path planning

The presented ORA as part of the assembly control provides a framework to perform release decisions based on current system information. Therefore, all released and waiting orders are considered with their potential sequences and capacity implications by the ORA. However, this leads to NP-hardness. If an additional order is considered, not only one further capacity profile is calculated. Instead, the matched capacity profiles are multiplied by the factor of the possible capacity profiles of the additional order. Thus, this profile combination scales exponentially when adding orders, but also operations or assembly stations. Consequently, it is expected that the approach fails for large problem instances. In order to circumvent the NP-hardness, SCHUKAT et al. suggested to reduce the number of capacity profiles e.g. by taking a limited number of randomly selected capacity profiles instead of calculating all capacity profiles. [13] However, this can lead to matching orders being excluded at random. Likewise, no linear scaling is achieved. In the following, a different approach will be introduced. To reduce the number of created and evaluated (matched) capacity profiles, possible operation sequences of orders are analyzed with respect to the resulting path through the assembly system. To do so, the transport times are estimated based on current routing algorithms of the order agent using the given sequences. This approach is further detailed in the next chapter.

3. Approach

3.1 Correlation of sequences and lead time

Although it seems evident that the assembly sequence impacts the lead time, a statistical analysis was performed to prove the correlation between those. In a matrix-structured assembly system, a product can have multiple assembly sequences. Consequently, completed orders containing the same product may show different assembly sequences after being processed. Same applies for the paths that describe the actual route an order takes through an assembly system. If several assembly station offer the same operation, orders with the same sequences might face different paths through the system and visit different assembly stations.

The lead time consists of three elements: working time, transport time and waiting time. The working time is the sum of all operation processing times at all stations that an order passes through. The transport time is the time that an order takes moving from one destination to another. The waiting time is the time an order spends waiting in queues at stations. While the working time for similar products remain the same, the waiting and transport time can vary depending on the chosen sequence and resulting path. The selection of the next assembly station is carried out by an order agent, considering real-time factors such as the estimated transport time to the available assembly stations. Besides the estimated transport time, the current waiting time at possible next assembly stations are taken into account. Depending on the strategy of an order agent, a shorter route to the next work station can be prioritized. However, to avoid long queues, longer routes might be accepted nevertheless. This lead to varying assembly sequences, depending on the current occupation and availability of the assembly stations.

To conduct the analysis, a basic test case was simulated matrix-structured assembly system. The test case consists of 16 stations, one product type and 1000 orders. The product requires four operations that can result in 12 different sequences total. The simulation environment is a MAS containing an assembly control system based on the proposed model by BURGGRÄF et al. [8] While 12 sequences are theoretically possible for the given product, only 8 actually occurred in the simulation run. The frequency of occurrence of the sequences followed the Pareto principle with 20% of the sequences accounting for 80% of the jobs. It also has the lowest minimal transport time and generally the lowest quartile of all sequences and the lowest median transport time. Furthermore it has the lowest estimated impact on the transport time. This finding correlates with the logic of the assembly job agents as they try to choose operations in such a way that optimizes the potential transport time, while considering other factors as well.

These results highlight that the transport time and related path depends on the chosen sequence. Furthermore, the frequency of an individual assembly sequence correlates with the average transport time that results from a sequence. That means that an assembly sequence appears more frequent if it results in a lower average transport time. This matches the intuitive thought that the assembly sequence directly impacts the transportation time of a job. These findings can be used to develop a method to limit the sequences that are used to calculate the capacity profiles of the ORA.

3.2 Approach for capacity profile limitation

This work proposes selecting only one sequence for every job in the capacity profile generation by anticipating the estimated transport times. Selecting only one sequence means that no matter how many jobs are released in the system or how many different sequences are possible, it will always result in one capacity profile per product and order, and thus only one matched capacity profile being calculated for the release decision. Within this paper, the estimation of the transport time will be done using the routing algorithms of the agents. The routing algorithms already include the planning of a trajectory that an order can take to be transported between to assembly stations without crossing another assembly station directly. For every operation in a sequence, there is a certain number of assembly stations that can process that operation. Using the current location of the assembly job agent, the distance and resulting transport time to these stations can be calculated. One station will be selected according to a selection criterion and it will act as the origin coordinate for the next assembly operation. This process repeats for every assembly operation in a given sequence. The process can be summarized with the following steps:

1. Retrieve all capable assembly stations for the first operation in the assembly sequence
2. Take the current position of the job and calculate the transport time to all capable stations
3. Select a station according to a selection criterion and use its position in the system as the next position of the job
4. Add the transport time of the selected station to the sequence's total transport time estimate
5. Retrieve all capable assembly stations for the next operation
6. Calculate the transport time to all capable stations using the updated position of the job and repeat the process until all operations of a sequence are accounted for

This process is done for every job's possible sequence. Once the transport time estimate has been calculated for every sequence, the algorithm selects the sequence with the lowest transport time estimate and passes it to the capacity profile generation.

3.3 Transport time estimation

Similar to *branch and bound algorithms*, the shortest path to complete an order does not necessarily result from always taking the shortest route to the next available assembly station. Thus, the criterion used to estimate the overall transport time is a crucial aspect. It should be noted that finding the shortest path in graph theory is called *shortest path problem*. To solve basic variation of this problem, there are multiple established algorithms such as *Dijkstra's algorithm*. [26] In a dynamic environment, with additional constraints this problem becomes NP-hard and additional computational resources are required to solve this issue. As the matrix-structured assembly is a dynamic environment and additional constraints other than the transport time are considered in the routing of the agents, finding the actual smallest transport time becomes another NP-hard optimization problem. As the main goal of this approach is to circumvent the NP-hardness of the capacity profile creation and selection, creating another NP-hard problem contradicts the goal. Because of this, an estimation is chosen that doesn't result in an NP-hard solution.

The selection criterion consists of four calculated paths to avoid the issue that may result when only choosing the next assembly station showing the lowest transport time. The calculated paths are created with the help of all possible operation sequences from the assembly precedence graph, which are related to the assembly stations and layout of the assembly system. Accordingly, the capabilities of assembly stations are taken into account. The first path is calculated by always choosing the station with the lowest transport time. The second path is calculated by always choosing the station with the highest transport time. The third and fourth paths are alternating between lowest and highest transport times. The third path starts with the station that has the shortest transport time and continues to alternate from there. The fourth path starts with the station that has the highest transport time and continues to alternate from there. This results in four calculated transport times for each sequence. These times are then added up for every sequence and then compared with each other. Afterwards, the sequence with the lowest sum of its four paths is used for the capacity profile calculation. Due to the dynamic behavior of the assembly system, it is crucial to consider the paths with potential higher transport times as they might become relevant in case of malfunctions and station breakdowns. In these situations, job agents may decide to take longer routes to avoid unnecessary waiting times.

4. Evaluation

4.1 Framework and Test case

To evaluate the functionality of the proposed approach, a simulation-based comparison with the random profile selection was conducted. For this, the ORA was implemented in an evaluation environment. In general, an evaluation environment is defined as a technology platform that serves the purpose of validating methodologies, models and theories developed in innovation projects. By integrating these into a common environment, the acceptance of new approaches can be increased. An evaluation environment allows multiple stakeholders to gain a common understanding of a program and the evaluation process. [27,28] In the present context, an evaluation environment must include an agent-based assembly control for matrix-structured assembly systems, provide an order pool, simulate the assembly processes, and also record all results and make them available for output. Such an evaluation environment was developed accordingly based on the logic for assembly control suggested by BURGGRÄF et al. [8] The evaluation environment was coded in TypeScript. It allows users to set specific production programs, assembly system configuration as well as export key figures after simulation.

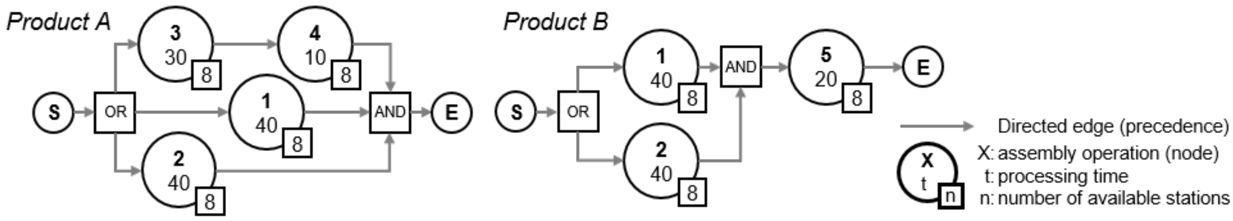

Figure 1: Assembly precedence graphs of Product A and Product B

For this paper, the production program contains two fictional product namely Product A and Product B, each having its individual precedence graph. A total of 30 products is assembled per simulation run: 10 of Product A and 20 of Product B. Product A was also used for the statistical analysis of the transport times in Chapter 3.1. Product A requires operations 1, 2, 3 and 4 while Product B requires operations 1, 2 and 5. This results in a total processing time of 120 seconds for Product A and 100 seconds for Product B.

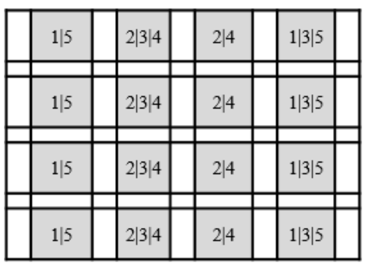

Figure 2: Station layout

The assembly system configuration is defined by the layout, assembly stations as well as their capabilities. The layout shows a total of 16 stations, which are all arranged in a matrix form leaving space for transportation between the assembly stations. The distances in x and y direction are all equal for each neighboring station. The stations are fitted to carry out multiple operations with 8 stations being able to perform three different operations and the other 8 stations being able to carry out two operations. When a station switches between operations it requires a certain setup time to change the tools required.

The key figure system was defined to quantitatively evaluate the behavior and impact of the ORA for each simulation run. The following key indicators for the test case were defined:

- Total assembly run time [s]
- Average lead time [s]
- Average transport time [s]
- Average waiting time [s]
- Total utilization rate [%]
- Percentage of waiting time [%]
- Percentage of processing time [%]

4.2 Results

To test the suggested approach, it was implemented and compared to the former approach for capacity-based order release in matrix-structured assembly systems. To circumvent the known shortcoming of the former approach, the generation of matched capacity profiles was limited using a threshold while creating capacity profiles randomly. In total, four simulation runs were analyzed. The used thresholds for the generation of matched capacity profiles were 1 (ORA-1), 50 (ORA-50) and 100(ORA-100). The newly suggested approach is referred to as ORA-P. The simulations were carried out on an Intel® Core™ i5-8600 6 core CPU at a base clock of 3.1 GHz and 8GB of RAM. The results are summarized in figure 3.

Dispatcher type	Total assembly run time [s]	Average lead time [s]	Average transport time [s]	Average waiting time [s]	Total utilization rate [%]	Waiting time [%]	Processing time [%]	Relative difference of total assembly run time [%]	Relative difference of average lead time [%]	Relative difference of average transport time [%]	Relative difference of average waiting time [%]	Relative difference of total utilization rate [%]
ORA-1	506	210	62	42	47	11	50	8	4	2	22	8
ORA-50	479	211	65	40	50	20	50	3	4	6	18	3
ORA-100	466	210	63	41	51	20	50	0	4	4	21	0
ORAP	465	201	61	33	51	16	53	-	-	-	-	-

Figure 3: Testing results

The total assembly run time to process all orders for ORAP was slightly less compared to ORA-1 (~8%) and ORA-50 (~3%). For ORA-100, no effect can be seen. Using ORAP leads to decrease of average lead time per job by 9 seconds. The average transport time was about 6% slower for ORA-50, 4% for ORA-100 and 2% for ORA-1 compared to ORAP. The most significant difference was found in the average waiting time. The ORAP outperformed the other simulation runs by 18-22%. Using ORAP the waiting time amounted for 16% of the total time while for the other runs it was 20%. The percentage of the processing time on the total time also improved using ORAP from 50% to 52%. ORAP shows a higher total utilization rate of the assembly stations than ORA-1 and ORA-50 and about the same rate as ORA-100. Given the shown performance indicators, the results demonstrate an overall better performance using ORAP.

5. Discussion and limitations

In matrix-structured assembly systems with multifunctional assembly stations, it is not possible to predict the exact path of an order when using reactive assembly control. This is a challenge not only for the determination of material supply positions, but also for the capacity evaluation of the order release. While the authors' previous work on capacity evaluation suggests considering all possible sequences, the transport time estimation approach developed in this paper allows limiting the sequences considered in capacity evaluation. By estimating the possible transport time through the average between four probable path finding methods, the approach determines exactly one sequence per order that can be used for the generation of the order's capacity profile. The simulations performed indicate the ORA. The simulations indicate improved scalability, more consistent results and greater reproducibility, while significantly reducing the waiting times of orders at stations. Accordingly, the developed approach can be used as basis for further evaluation, improvement and additions to the ORA compared to the former approach. Furthermore, limiting the number of capacity profiles, the inherent NP-hardness of the previous research is addressed. This allows to test larger problem instances using an advanced order release logic.

However, the presented approach is subject to the constraint that assembly control is designed to reduce transportation times. The current transport time estimation was only tested for a rather simple and consistent layout. Complex assembly layouts could lead to inaccurate predictions. Therefore, the developed profile limiting approach should be considered primarily as a prototype demonstration rather than an optimal solution.

6. Summary and outlook

This paper presents an approach to improve the capacity evaluation in order release for matrix-structured assembly systems. The approach determines one assembly sequences for each order that can be used to assess the capacity fit within order release.

To show the potential of the suggested approach, it has been implemented in an evaluation environment containing an agent-based assembly control. It was compared to the former approach for capacity-oriented order release. For the former approach, random sequence selection was used to reduce the number of sequences and thus calculations. The simulation results show that newly developed approach outperforms the former approach, e.g. by a reduction of 20% of waiting time. However, with more random profiles being considered, this effect declines. Thus, it can be assumed that the random profile selection outperforms the suggested profile limiting approach if the number of random profiles selection covers almost all possible sequences. This can be explained with the nature of the random profile generation. As the number of matched capacity profiles increases, so does the probability that a combination leading to an optimal order release decision occurs. However, this still has the downside of requiring significantly more computational power.

Further research should transfer the routing algorithms from assembly control into the path prediction. This potentially improves the transport time estimation and sequence selection. Consequently, the agent-based order will obtain better results, while maintaining its flexibility and real-time capability. Furthermore, the use of a deep neural network should be considered, as it can extract hidden features of the system and estimate path finding functions.

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References

[1] Greschke, P., Schönemann, M., Thiede, S., Herrmann, C., 2014. Matrix Structures for High Volumes and Flexibility in Production Systems. Procedia CIRP 17.

[2] Burggräf, P., Dannapfel, M., Adlon, T., Riegauf, A., Schukat, E., Schuster, F., 2020. Optimization approach for the combined planning and control of an agile assembly system for electric vehicles. CPSL 2020.

[3] Eversheim, W., 1989. Organisation in der Produktionstechnik: Fertigung und Montage, 2nd ed. Springer, Berlin, Heidelberg.

[4] Greschke, P., 2016. Matrix-Produktion als Konzept einer taktunabhängigen Fließfertigung. Dissertation, S.225.

[5] Libert, S., Chisu, R., Luft, A., 2010. Softwarearchitektur für eine agentenbasierte Materialflusssteuerung, in: Günthner, W., Hompel, M. ten (Eds.), Internet der Dinge in der Intralogistik. Springer Berlin Heidelberg, Berlin, Heidelberg, S.95-106.

[6] Unland, R., 2015. Industrial Agents, in: Leitão, P., Karnouskos, S. (Eds.), Industrial agents. Emerging applications of software agents in industry, First edition ed. Elsevier, Amsterdam, Netherlands.

[7] Valckenaers, P., van Brussel, H., 2015. Design for the unexpected: From holonic manufacturing systems towards a humane mechatronics society, Oxford, UK.

[8] Burggräf, P., Dannapfel, M., Adlon, T., Kahmann, H., Schukat, E., Holtwiesche, L., 2020. Multi-agent systems in agile assembly: Real-time scheduling of flexible operation sequences on multifunctional assembly stations. wt 110 (04).

[9] May, M.C., Kiefer, L., Kuhnle, A., Stricker, N., Lanza, G., 2021. Decentralized Multi-Agent Production Control through Economic Model Bidding for Matrix Production Systems. Procedia CIRP 96.

[10] Mayer, S., Gankin, D., Arnet, C., Endisch, C., 2019. Adaptive Production Control with Negotiating Agents in Modular Assembly Systems, in: 2019 IEEE International Conference on Systems, Man and Cybernetics (SMC). IEEE, pp. 120–127.

[11] Schönsleben, P., 2020. Integrales Logistikmanagement: Operations und Supply Chain Management innerhalb des Unternehmens und unternehmensübergreifend.

[12] Mueller, D., Schmitt, T.V., 2020. Production planning in autonomous and matrix-structured assembly systems: Effects of similarity of precedence graphs on order release sequencing. Procedia CIRP 93, 1358–1363.

[13] Schukat, E., Rachner, J., Maidl, A., Göppert, A., Adlon, T., Burggräf, P., Schmitt, R.H., 2022. Agent-based Order Release In Matrix-Structured Assembly Systems. CPSL 2022, 652–661.

[14] Filz, M.-A., Gerberding, J., Herrmann, C., Thiede, S., 2019. Analyzing different material supply strategies in matrix-structured manufacturing systems. Procedia CIRP 81, 1004–1009.

[15] Fries, C., Wiendahl, H.-H., Assadi, A.A., 2020. Design concept for the intralogistics material supply in matrix productions. Procedia CIRP 91, 33–38.

[16] Kern, W., Lämmermann, H., Bauernhansl, T., 2017. An Integrated Logistics Concept for a Modular Assembly System. Procedia Manufacturing 11, 957–964.

[17] Popp, J., 2018. Neuartige Logistikkonzepte für eine flexible Automobilproduktion ohne Band. Universität Stuttgart.

[18] Ranke, D., Bauernhansl, T., 2021. Evaluation of Material Supply Strategies in Matrix Manufacturing Systems, in: Weißgraeber, P. (Ed.), Advances in Automotive Production Technology - Theory and Application. SCAP2020, pp. 80–88.

[19] Scholz, M., Serno, M., Franke, J., Schuderer, P., 2017. A Hybrid Transport Concept for the Material Supply of a Modular Manufacturing Environment. Procedia Manufacturing 11, 1448–1453.

[20] Schönemann, M., Herrmann, C., Greschke, P., Thiede, S., 2015. Simulation of matrix-structured manufacturing systems. Journal of Manufacturing Systems 37, 104–112.

[21] Bochmann, L.S., 2018. Entwicklung und Bewertung eines flexiblen und dezentral gesteuerten Fertigungssystems für variantenreiche Produkte.

[22] Mayer, S., Hohme, N., Gankin, D., Endisch, C., 2019. Adaptive Production Control in a Modular Assembly System – Towards an Agent-based Approach, in: 17th International Conference on Industrial Informatics (INDIN), Helsinki, Finland. 7/22/2019 - 7/25/2019. IEEE, pp. 45–52.

[23] Mayer, S., Endisch, C., 2019. Adaptive Production Control in a Modular Assembly System Based on Partial Look-Ahead Scheduling, in: Proceedings. 2019 IEEE International Conference on Mechatronics (ICM). IEEE, pp. 293–300.

[24] Göppert, A., Rachner, J., Schmitt, R.H., 2020. Automated scenario analysis of reinforcement learning controlled line-less assembly systems. Procedia CIRP 93, 1091–1096.

[25] Hüttemann, G., 2021. Model-based a priori analysis of line-less mobile assembly systems. Dissertation.

[26] Gao, Y., 2011. Shortest path problem with uncertain arc lengths. Computers & Mathematics with Applications 62 (6), 2591–2600.

[27] Fynn, J.F., Hardeman, W., Milton, K., Jones, A.P., 2020. A scoping review of evaluation frameworks and their applicability to real-world physical activity and dietary change programme evaluation. BMC public health 20 (1), 1000.

[28] Koch, R., 2011. Systemarchitektur zur Ein- und Ausbruchserkennung in verschlüsselten Umgebungen. Zugl.: München, Univ. der Bundeswehr, Diss., 2011. Books on Demand, Norderstedt, 490 pp.

Biography

Prof. Dr.-Ing. Peter Burggräf (*1980) is scientific head of the Department of Factory Planning at the Laboratory of Machine Tools and Production Engineering WZL of RWTH Aachen University and has been head of the Institute of International Production Engineering and Management at the University of Siegen since 2017.

Tobias Adlon (*1989) has been head of department of Factory Planning at Laboratory of Machine Tools and Production Engineering WZL of RWTH Aachen University since 2020.

Esben Schukat (*1993) has been research associate in the Department of Factory Planning at Laboratory of Machine Tools and Production Engineering WZL of RWTH Aachen University since 2019. In 2022 he took over the group lead of the research group 'Assembly Planning' while continuing his research activities on matrix-structured assembly systems.

German Bluvstein (*1995) was a master thesis student and student research assistant at the Laboratory of Machine Tools and Production Engineering WZL of RWTH Aachen University in 2022.

4th Conference on Production Systems and Logistics

Event-driven IT-architectures As Enabler For Industry 4.0

Sebastian Kremer[1], Leon Konrad[1], Max-Ferdinand Stroh[1], Günther Schuh[1]
[1]FIR e.V. at RWTH Aachen University, Aachen, Germany

Abstract

Originating in 2011, Industry 4.0 describes the digital revolution of industry and has since become a collective term for smart, mutable and data driven factories. During the last decade, systemic and methodical solutions were designed and implemented that enable corresponding data-driven use cases for producers. While an assessment of expectations around Industry 4.0 results in requirements within the domains of modifiability, connectivity, data and organisation for an IT-architecture, many such solutions are found to be violating essential requirements such as systemic flexibility and data-availability. Not only is this a relevant matter for architectural purists, but it highlights real problems that the industry is still facing while applying digitalisation measures in pursuit of Industry 4.0.

While event-driven architectures go back to the design of modern operating systems, the emergence of powerful, resilient and cheap broker-technologies has risen the polarity of event-driven IT-architectures for businesses in the last decade. Many prominent manufacturers have since begun their transformation into an event-driven IT-architecture. Reasons for this architectural adaptation include exceptional data availability, resilience, scalability and especially data sovereignty. An assessment of event-driven IT-architecture's properties and implications reveals an excellent fit for the architectural requirements of Industry 4.0.

In this work, the subject of Industry 4.0 is analysed along with literature to derive a collective understanding of expectations from a factory implementing Industry 4.0. Subsequently, IT-architectural requirements are derived that describe an architecture capable of satisfying these expectations. Then event-driven IT-architectures are analysed regarding their structural composition and capabilities. Finally, the fit of event-driven IT-architecture is evaluated against the architectural requirements of Industry 4.0, discussing congruence and divergence.

Keywords

event-driven IT-architecture; EDA; Industry 4.0; Smart Factory; Digital Transformation

1. Introduction

Digitalisation in the producing industry offers a fertile ground for scientists, engineers and businesses alike, to shape and utilise digital technologies for the realisation of modern use cases and the generation of rewarding benefits in the competitive market. Origination in Germany, the term Industry 4.0 has since been adopted internationally to shape a common vision and describe the common goal of adapting digital technologies for a digitally enabled production. While many showcases of Industry 4.0 have been realised [1] and system providers offer a wide range of such product-integrated solutions, the overall progress of extensively beneficial digitalisation in real-life productions is, in experience, perceived as poor.

From experience, the identified problem lies within the current approach towards digitalisation measures. A realistic approach to the grand showcase of Industry 4.0 often boils down to focused "lighthouse projects", designed to address a specific digitalisation use case and increase the attractiveness for further measures.

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Often these use cases do work as intended but do not integrate into the overall business landscape well, as their design was limited to the scope of a single application. Existing IT-architectures do usually not support a broad distribution of collected data. An alternative approach is the acquisition of a complex third-party system designed for a collection of specific use cases. From experience, those systems do indeed increase the extent of digitally enabled use cases (usually after a lengthy implementation phase) but do not solve the complexity of procedurally adapting to the ever-changing landscape due to new use cases as envisioned by Industry 4.0. While solving an acute problem by extensively incorporating complex third-party systems without the need for comprehensive technical expertise, the almost always associated dependency towards the vendor can be expected to hinder the long-term pursuit of Industry 4.0.

The proposed solution to this problem lies in the architectural view of the communicated target: the pursuit of Industry 4.0 describes a data-driven system landscape that is open to adapting itself to new challenges. Instead of focusing on the realisation of specific use cases or the development of systemic solutions a more fundamental look at the IT-architectural design should be made. Considering the IT-architecture early in the development stage, allows for building a resilient digital base as a fertile ground for a flexible and business-wide data-driven ecosystem. During research and industry projects event-driven IT-architectures were perceived to be a suitable match for the proposition, which is to be investigated.

This investigation hence focuses on determining the match between traits of event-driven systems and the requirements of Industry 4.0. It aims to further answer the following research questions: Which goals and aspects are associated with Industry 4.0? What architectural requirements does Industry 4.0 place on information systems in companies? What properties and characteristics distinguish event-driven IT-architectures in the context of producing companies?

2. Methodology

To determine the generally perceived definition and architectural requirements of Industry 4.0, extensive literature research was conducted on works taken from the platforms Science-Direct, IEEE, Google Scholar and the Library of RWTH Aachen University and their corresponding sub-references. The architectural requirements were consolidated using the qualitative content analysis by Mayring [2] and are clustered into related subjects analogous to the separation of concern method [3]. A second research iteration focused on more recent works from the last three years, to weigh-in a more recent understanding into the investigation.

The analysis of event-driven IT-architecture was conducted similarly. The actual comparison was then carried out in pair-wise qualitative comparison of requirements and traits. The results are visualised in a matrix and rated along the dimension of fit using Harvey Balls.

3. Digitalisation in the producing industry

The investigation´s base lies in the analysis of Industry 4.0 and event-driven architectures. The following chapter describes the vision of Industry 4.0, as collected from various sources, an introduction to event-driven architectures and a short overview of the current adaption trend regarding event-driven architectures.

3.1 Vision of Industry 4.0

The term Industry 4.0 has, since its emergence over one decade ago [4], been the main talking point around digitalisation in the production industry. The ex-ante declaration of the next industrial revolution not only delivered an orientation for development but also allowed a broad and mutable understanding of its actual, realised composition. Hence the vision of Industry 4.0 not only varies along advocates and representatives but was also shaped over time along the ideation of Industry 4.0 use cases. Therefore, such investigations need to compile a common understanding of Industry 4.0, as represented in literature and workings.

The vision of a digitalised and smart industry, namely Industry 4.0, was motivated in Germany by its economy's urge to use digital developments around the turn of the millennium for faster-paced product development, a high degree of individualisation in production and a general increase of a production's flexibility and decentralisation [5–7]. The subsequent vision of such a digitally enhanced production was first introduced in 2011 at the Hannover Messe under the title of Industry 4.0 as the working title of the academy for technical research called acatech [4]. With the foundation of the Platform Industry 4.0 in 2013 the vision of the fourth industrial revolution was specified towards basic definitions, goals and first approaches [8]. This ex-ante specification offers by no means a handbook for digitally enhancing a production but can rather be interpreted as a marketing strategy, which is supposed to lay the foundation for a shared, target-oriented development [9]. Hence definitions and interpretations vary widely across pursuers.

The general interpretation of the Platform Industry 4.0 defines Industry 4.0 as an "intelligent networking of machines and procedures within the industry enabled by information and communication technologies. There are many possibilities for companies to use intelligent networking" [5]. Additionally, the definition lists flexibility of production, changeable factories, customer-oriented solutions, optimised logistics, extensive usage of data and circular economies as exemplary realisations of Industry 4.0. Interpretations from other sources extend the term towards a demand-pull from the customer side and technology-push from the industrial side [7], a tautologic self-evidence by the sheer use of digital technologies in the industry [10], a completely new level of flexibility and automation [11] and an inclusion of technologic structures (as Big Data) or specific optimisation potentials [6]. These interpretations occasionally substantiate specific use cases encapsulated within the production's domains.

The term Industry 4.0 gained popularity in international research regarding digitalisation within the following five years of its origination [6,4]. Similar concepts like the Internet of Things (IoT) or the Industrial Internet offered anchors for discussion and joint research. The term Internet of Things describes an ecosystem of internet-based connected objects [12,13]. The term Industrial Internet describes the similarly declared IT-Revolution from the United States, which focuses on the whole product life cycle and connectivity-enabled products and services [12], in contrast to Industry 4.0's machine and process focused approach. Overall, the investigation focuses on the definition of Platform Industry 4.0 since it focuses on the substantial connectivity of processes and endpoint in the producing industry. Core aspects are the general digitalisation and interconnectivity of IT-systems and processes in the value chain.While the interpretations of Industry 4.0 currently transform into tangible products, offered by prominent system providers in the production domain, the experienced state of digitalisation within the production does not meet the proposed vision. Complex system solutions not only increase the perceived complexity of the system solution but also hinder the users in the horizontal and vertical interconnectivity of a multitude of heterogeneous data sources and sinks. The presumed problem lies in the encapsulation of data within (third-party) systemic ecosystems that shift the required expertise from widely usable programming skills towards system-specific knowledge. Hence users, who try to bypass self-responsible digital development, end up configuring third-party systems and still have limited capabilities in flexibly manipulating the system for new needs. The result is reduced scope for self-determined, autonomous action and in the worst case a future vendor lock-in.

In summary, Industry 4.0 aims towards more data-driven and modular approach to allow for incorporation of learnings and optimisation into an ever-changing landscape of technologies and use cases. The overall goal lies within optimisation and flexibility of processes and system-landscapes.

3.2 Event-driven architectures

The event-driven architecture (EDA) describes an architecture, in which its components communicate predominantly through the distribution of events and corresponding data payload. In contrast to a more procedural structure of conventional architectures motivated by synchronous business processes and hierarchies, the event-driven architecture relies on a broad distribution of domain-specific information in a network of information producers and consumers. In short, any status change or yield of information caused by both real-life events and data transformation within systems is communicated and distributed as an addressee-agnostic (no need for a specific addressee) event. Consumers of events obtain these from a central hub ("broker") instead of the source, which effectively decouples components in these kinds of architectures (compare Figure 1). [14–16]

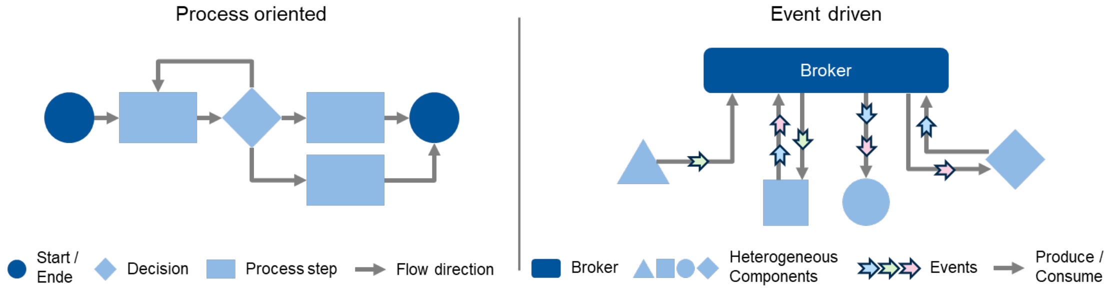

Figure 1: Schema of an event-driven architecture in comparison to process oriented procedures

Event-driven architectures are usually deployed in complex systems with distributed functionality and a multitude of specialised domains. Hence, they historically became an integral part of modern operating systems and are a favoured design principle of complex software products, which are composed of numerous modular software components like prominent ERP- and ME-Systems [14]. Since the development of performant open-source brokerage systems in the last decade, like Apache Kafka and RabbitMQ, event-driven architecture became easily adaptable on an enterprise level as a fundamental IT-architecture.

3.3 Rising popularity of event-driven IT-architectures

With the rising interest in digital solutions by conventional businesses and the emergence of e-commerce, IT-landscapes need to digitally represent and manage several modular business domains. This results in an increase in complexity of IT-landscapes, which in turn impedes their concurrent development and management [17,18]. With the development of high-performance event-brokers (also known as event-streaming platforms), businesses started to adopt the event-driven principle as an IT-architecture to interconnect and manage business functionality implemented in distributed systems, services and applications [19,20,15,21]. Prominent representatives of event-driven IT-architectures are for example Netflix, Intel, Bosch, BMW and Tesla [22–26].

The application of event-driven IT-architectures in the producing industry consists of a manageable set of prominent producers, mainly in the automotive industry. Even though the producing industry with multiple business domains (such as planning, production and logistics) and "smartifiable" physical assets (such as machinery, sensors and material) possesses great potential for the adaptation of such an open data platform, in experience its actual spread is comparably low. The assumed problem lies in a combination of the complicated interdisciplinary field of technical and digital expertise, the deeply rooted system solutions that have historically evolved into a highly complex system and the rapid appearance of smart assets integrated into proprietary data ecosystems. To open the field for further research and workings into realisations of an event-driven smart factory, the actual architectural fit between Industry 4.0 and EDA is to be investigated.

4. Investigation of the architectural match between Industry 4.0 and EDA

This investigation aims to determine the architectural fit between event-driven IT-architectures and the requirements derived from the vision of Industry 4.0. Hence the architectural requirements of Industry 4.0 and the traits of event-driven architectures are evaluated. This chapter presents the identified requirements of Industry 4.0, the traits of EDA and their corresponding match.

4.1 IT-architectural requirements of Industry 4.0

A compilation of the investigated sources led to a general understanding of a common vision of Industry 4.0, as shown in 3.1. The central vision of Industry 4.0 lies within the extensive digital integration of processes and "things" both horizontally along the value stream & product life cycle and vertically across hierarchical IT-layers within the company [27].

The vertical integration describes the interconnectivity of low-level components as sensors and actuators, mid-level as control and management systems and high-level planning and business systems. Its goal is the improved transparency through different hierarchical layers, the availability of precises real time information in abstract business processes and the abolishment of layers of gateway systems that can impact data consistency. The motivation lies in direct availability of data, regardless of organisational structures, and the establishment of more extensive monitoring and analysis functionality to improve/optimise processes and manage the production's rising complexity. [28–30]

The horizontal integration describes the connectivity of business resources towards a value creation network [28]. The digital representation of machines, operating resources and products tie processes along the object's life cycle and can span across company borders. The goal is data consistency and improved availability across the stages of development, production and servicing (incl. maintenance and diagnosis) [30]. The motivation spans from extensive transparency over forecastability to adaptability empowered by the usage of data. Hence the realisation of a fully integrated value creation network requires a horizontal integration of components, a vertical integration of IT layers and a broad adaptability of included systems and processes, to utilise data-driven learnings [30]. The result is often depicted as a digital and intelligent "smart factory", which can digitally represent real-life states and information [31–33,4].

On a more precise level, a smart factory requires the real-time availability of data points across system domains, to enable use cases proposed under Industry 4.0 such as early warning systems, advanced planning and feedback loops [30]. A direct and responsive system design is of the essence, as it is vital for the continuous productivity of costly assets. The use case of predictive maintenance makes use of such readily available data to not only generate a measurable economic benefit, but also offers a foundation for data-driven value creation [32,33]. Furthermore, the increasing amount of collected data and data-driven use cases raises questions about data usability, to actually generate a tangible use of vastly collected data [12,27]. A corresponding IT-architecture is hence not only required to reliably transport data but also be able to manage its usability via e.g. contextualisation [33].

Considering digital technologies such as cloud computing and the imminent growth of complexity due to increasing numbers of smart components, another requirement lies in the manageability of complexity by e.g. the domain-oriented divisibility of system components and functionality. This ability is identified to be a relevant factor for competitiveness [10]. The actual technological implementation is thought to be of lesser essence than the ability to individually offer suitable solutions for each functionality and still be able to manage the integration of several domains.

At last, the proposed usage of data envisions a higher degree of automation [34], which with respect to complexity requires domain autonomy or more commonly a higher degree of decentralisation. Aged depictions envision automation layers which are doomed to be deprecated in light of intelligent and decentralised cyber-physical systems (CPS) [30]. Conservative layers of ERP and MES are replaced by a service-oriented network of decentralised and autonomous CPS [30]. By replacing the top-level, centralised intelligence with a more essential centralised understanding of shared data, the data-oriented components are more flexible and adaptable as envisioned by Industry 4.0 [35,30].

This investigation summarises the derived architectural requirements of Industry 4.0 into four categories, namely *Change* (architectural development and adaptability), *Interconnectivity* (of components), *Data* (nature and usage of information) and *Organisation* (business organisational aspects). The results presented in Table 1 and are further described below.

Table 1: Categorised requirements of Industry 4.0 toward IT-architectures

Change	Interconnectivity	Data	Organisation
• Flexibility • Speed and agility • Complexity management and control	• Openness and interoperability • Scalability • Downwards compatibility • IT-Security	• Integration • Data consistency • Data-driven-ness (analytics and smart factory)	• Globalisation and culture • Ergonomics and human-machine-interaction (HMI) • Autonomy (production domains and smart factory)

The category *Change* addresses the ability of a production to react to drastic changes in regional and global conditions due to accelerated technological progress. The IT-architecture must enable its components to adapt to new problems and potentials and hence promote **flexibility** in IT-systems and components. This requirement is often addressed in the context of Industry 4.0 but contrasts the experienced rigidity of big-scale and complex system solutions, which promote inflexibility due to vendor lock-in. To allow incorporation of disruptive technological changes without disrupting the whole system, the IT-architecture must be **agile** enough, and to enable change efficiently, it must be able to do so **quickly**. This addresses the ability to conduct the more frequently expected change (preferably) independently and with manageable effort. Lastly, implemented changes should not have a significant impact on the overall complexity, which is addressed by appropriately **managing and controlling complexity** in the IT-architecture. This is to allow the sustainable development of the systemic landscape, without negatively affecting the ability to conduct change in the future.

Interconnectivity addresses the full IT OT integration of production processes and systems to fully enable the digital landscape depicted by Industry 4.0. Most significantly this requires an overall **openness** (non-proprietary and interfaceable) and **interoperability** (standardisable on at least a corporate level) of architectural components. This is to combat systemic data encapsulation which directly hinders the broad use of already captured data. **Scalability** addresses the resilience of interconnectivity with respect to change. This not only includes overcoming technical limitations, such as bandwidth but also allows for structural modularity promoting growth and continuous comprehensibility in the growing data space. This architectural requirement is tied to the **downward compatibility** of the whole system. The increasing interconnectivity must allow its components to be resistant to external changes. An overall identified fourth requirement regarding interconnectivity is the need for effective **IT-security** [12,36,30], which is (also in disregard of Industry 4.0) generally accepted as an underlying requirement for IT-architectures. The ever-increasing number of smart devices and hence endpoint increases the overall vulnerability of the network.

The *Data* category comprises the heart of the data-driven vision of Industry 4.0. The overall **integration** describes the unification of information available in the company. This translates into ensuring the capturing and faultless distribution of relevant data. The requirement of **data consistency** then extends the integration with a unified distribution of data aided by structural organisation and contextualisation. This is intended to promote an overall consistency of the perceived data truth. Lastly, the actual usage of data is described in the **data-drivenness** of the components as a data sink (like analytics) or a part of the complex system (smart factory). The architecture should enable components to function data-driven and promote endpoint intelligence.

The category *Organisation* offers an (business-)organisational view to the requirements of the IT-architecture, which ties the technological and processual views regarding a company's strategies and goals. More often companies pursuing digitalisation find themselves competing in a more **globalised**

environment. This requires the IT-architecture to be able to handle internationally distributed value chains and harmonisation of corporate culture (like varying processes and conventions) across multiple production sites. Furthermore, the enhanced digitalisation of oftentimes still manual processes needs to be able to allow for **ergonomics** for users and support for human interaction. Hence the architecture needs to be able to provide suitable endpoints and structuring to promote human interaction and manageability. The overall rising complexity and trend towards decentralisation need to be accompanied by an IT-architecturally enabled **autonomy** of production domains. Specifically, this describes a rejection of strictly hierarchical delegation mechanisms in favour of a self-determining role within an individually specifiable domain.

In summary, Industry 4.0 requires IT-architectures to manage heterogeneity than forcing homogeneity more significantly, in prospect of anticipating changes in use cases and system-landscape. Specifically, this means that connectivity towards an open (independent) but common data truth, feeding decentralised intelligence, is of essence. This directly contrasts conservative IT-system oriented solutions, which favour system-connectivity over data availability, effectively unifying data and systemic functionality. In short, Industry 4.0 should not require the user to know, which specific system to connect to, to receive and use data.

4.2 Traits of event-driven systems

The investigation of the traits of event-driven systems allowed a compilation of characteristics and core properties regarding an IT-architecture. The identified features are listed in Table 2, based on [14], and further elaborated in 4.3 in comparison with Industry 4.0.

Table 2: Features of event-driven architectures

Structural features	Functional features
Central broker / middleware	Publish-subscribe (or similar) principle
Distributed system / multiple components	Asynchronous communication
Event-driven communication	Decision-making at the sink (intelligent endpoints)
Encapsulation and modularity	
Loose coupling	

Event-driven architectures, as described in 3.2, can be classified as **distributed** systems enabling **service-oriented** functionality, which mainly borrows its traits from modular and encapsulated service-oriented architecture [37,38]. Its core features include a centralised broker (or **redundant** broker-cluster) that **enables communication** in the format of generally addressee-agnostic events which effectively **decouples components** of the network, analogous to event-driven software design [39,37,40]. The **asynchronous** nature of event-driven communication contrasts conservative request-response patterns not only by decoupling components but also **increasing the availability of data** towards the whole network (one-to-one vs. n to n) [14,41]. More often these architectures encourage a "**smart endpoint**, dumb pipes" philosophy which promotes **autonomy** across the participating domains [14]. By leveraging a **standardised structure of events and topics**, organisations can enforce domain-specific **contextualisation** and hence better **usability** due to congruence with domain-specific language [42,43].

From experience, these traits are found generally within specific IT-ecosystem within the IT-landscapes of producing companies, e.g. SAP [44], but not as an overall IT-architecture. Their benefits are hence mostly limited to development by the vendor, but not fully utilisable by producers. Thus, producers still need to either deploy synchronous interfaces between IT-system or predominantly commit to a vendor. EDA does hence mostly distinguish itself from common production IT-architectures, by decoupling the data from systemic functionality and creating an open, centralised data space within the producer's influence. This not only promotes data sovereignty for the producer, but also inverts the communication style towards reactive functionality, which promotes more flexible and manageable distributed components.

4.3 Comparison of architectural requirements and traits of EDA

To evaluate the suitability of event-driven IT-architecture regarding the architectural requirement of Industry 4.0 the identified requirements are compared to the traits of event-driven systems. The features of EDA are evaluated towards each requirement as either *irrelevant*, *relevant* (contributing to/partial fulfilment of requirement) and *significant* (compliance/fulfilment of requirement) and presented in Table 3.

Table 3: Examination of suitability of event-driven IT-architectures for Industry 4.0

	Change			Interconnectivity				Data			Organisation		
	Flexibility	Speed and agility	Complexity management and control	Openness and interoperability	Scalability	Downwards compatibility	IT-Security	Integration	Data consistency	Data-driven-ness	Globalisation and culture	Ergonomics and HMI	Autonomy
Central broker / middleware	4	2	4	4	4	4	0	4	2	4	2	2	0
Distributed system / multiple components	2	2	0	0	4	0	0	4	0	2	4	2	4
Event-driven communication	0	4	0	4	4	4	0	4	2	4	2	0	2
Encapsulation and modularity	4	2	4	2	4	2	0	2	0	0	0	0	4
Loose coupling	4	2	4	4	4	0	2	0	0	2	0	0	4
Publish-subscribe (or similar) principle	0	4	4	2	4	0	0	4	4	4	2	2	4
Asynchronous communication	0	4	4	2	4	0	0	2	0	2	0	0	2
Decision-making at the sink	4	2	2	0	4	0	0	2	0	4	0	0	4

irrelevant 0 relevant 2 significant 4

The **centralised broker** structure of the event-driven architecture effectively decouples systems via a centralised communication platform by separating systemic functionality from exchanged data. This greatly contributes to the *flexibility* and *complexity* of the systemic landscape by breaking (otherwise exponentially increasing) one-to-one interfaces and thus making systems replaceable. The centralised approach to data accessibility via a unified format addresses *openness, downward compatibility, integration* and *data-driven-ness*. The available broker technologies often allow for clustering and replication which introduces *scalability* by design.

The resulting **distributed system** landscape eases the division of functionality into specific domains which again promotes *scalability* (analogous to microservice-architectures [45]) but is also suitable to map a distributed corporate structure in the context of *globalisation*. By distributing systemic functionality into domains, EDA increases overall *autonomy* and hence the overall *integration* by counteracting dominant systems enforcing proprietary frameworks.

The eponymous **event-driven communication** replaces the conservative exchange of (mostly system-specific) commands with the broadcasting of state changes and information yields. This greatly increases *speed and agility*, as system integrations can primarily occur without the adjustment of other systems. The unified language of centrally specified events immensely promotes *openness and interoperability, scalability, downward compatibility and integration*. The reactive nature of events (with attached payload) consumption inherently accounts for the *data-drivenness* of components.

The ability for **encapsulation and modularity** within the system landscape greatly reduces interdependencies, which allows for the exchangeability of systemic functionalities. Hence *flexibility*, *scalability* and *autonomy* are supported. *Complexity management and control* are provided with the ability to maintain the system landscape more easily by purging deprecated functionality or conducting isolated testing.

The **loose coupling** of components is achieved by merging the EDA features above and promotes the overall inter-independency. Independent components can conduct *autonomy* more easily and result in reduced *complexity* of the system landscape regarding managing dependencies. Hence loose coupling offers great *flexibility* and *scalability* while still allowing *openness and interoperability* via a central, common interface.

The **publish-subscribe (or similar) principle** used in the exchange of events and the EDA-nature of **asynchronous communication** provides a lightweight mechanism to consume data without the need to cooperate with the producer. The communication allows both real-time reactions to new data and delayed consumption (without blocking the producer) making it a good contributor towards *speed and agility, scalability* and interface *complexity management*. Additionally, **publish-subscribe** provides a mechanism for a central data truth that is potentially consumable by every component, regardless of knowledge by the publisher, which promotes systemic *integration*, overall *data consistency*, *data-drivenness* and *autonomy*.

The **decision-making at the sink** describes the decentralisation of intelligence towards the endpoint, as the broker by design does/should not execute business logic. This allows the broker to act as a simple distributor of data, unaffected by continuously changing business logic. Thus, the principle incorporates *flexibility* and the components' *data-drivenness* and *autonomy*. Furthermore, the IT-architecture offers better *scalability* when the broker does not need to adapt business logic when scaling it into a cluster of brokers.

EDA inherently does not address *IT-security*, as it focuses on reshaping the format of communication. This by no means does not result in event-driven systems being inherently insecure or hindering the implementation of a secure environment but rather emphasises the need to separately address IT-security measures (as common with other IT-architectures like Rami 4.0 and analogous to Porter and Heppelmann's Capability Model for Smart, Connected Products).

The introduction of event-driven IT-architectures is, by experience, coupled with the need for an active rethinking of established procedures and inter-domain cooperation, which generally complicates the adoption of pro-event-driven *culture* due to laggards and adversaries. The *ergonomics and human interaction* are not supported by EDA inherently but need to be addressed separately by incorporating adequate systemic endpoint solutions, which make use of the event-driven capabilities.

In summary, EDA offers several traits suitable for the implementation of an IT-architecture covering the requirements of Industry 4.0. The not inherently filled demand for organisational architecture and IT-security do not revoke the overall suitability, but need to be addressed separately. The conclusion and the overall applicability of EDA as a solution for Industry 4.0 is discussed in more detail in the following chapter.

5. Conclusion and Outlook

Overall, the investigation identifies a significant fit for event-driven IT-architecture to handle the architectural requirements of Industry 4.0. The shift from systemic ecosystems to an open data platform, which is strategically situated within a company's sphere of power, delivers an excellent fit to fulfil Industry 4.0's requirements of extensive interconnectivity and data-driven decision-making. With an effective separation of connectivity/data and functionality, event-driven systems enable decoupling, modularity and scalability which increases the resilience and sustainable interoperability of the whole system in an ever-evolving landscape of use cases, technologies and changing IT-systems.

Still, issues such as IT-security and the immense shift in culture as well as human interaction need to be addressed separately, because event-driven architectures do not inherently offer a solution for these requirements. The demand for IT-security need be addressed by implementing an active authorisation management and technical solutions like SSL-certificates, ensuring trust in components, on top of existing broker technologies. Depending on the individual data-sensitivity, the implemented solution of an event-driven IT-architecture should be considered regarding the rollout in cloud or on-premise solutions and the structure of broker clusters spanning sensitive domains. The shift in communication patterns, usually not intuitive in the context of systemic interconnection, would need to be addressed with active architecture management and education of stakeholders in the use of event-driven systems. The definition of a standardised stack of tools for interaction with the event-driven system can be key in ensuring HMI.

In conclusion, these results emphasise the occurring trend of procedural transformation of productions into event-driven architectures by extensively incorporating technologies such as Apache Kafka and Solace PubSub+, as well as deployable building blocks in prominent cloud computing services. The overall perceptible trend from monoliths and complex third-party ecosystems towards distributed modular functionality and intelligent endpoints is well supported by such technologies. Crucially, their usage signals an evolving understanding of the data-driven nature on a more fundamental level and the need for a long-lasting and manageable architectural base that enables growth along the future development of digital technologies.

However, the incorporation of event-driven IT-architectures does not represent a fit-for-all solution in the prospect of Industry 4.0. By experience, the self-reliant management of such a data space requires know-how in the design of data schemas and organisation of a corresponding change management. While suitable methods are already publicly available [46,42,43], the correct implementation and continuous pursuit still requires motivation and active confrontation by the producer. Without the goal of pursuing an individual IT-strategy and hence conducting active architecture management, tackling Industry 4.0 with event-driven IT-architectures will, just by itself, not be a beneficial solution.

In prospect, future works on event-driven IT-architectures need to address the incorporation of unfulfilled architectural requirements, namely IT-security and support for organisational matching. Considering an adaption of IT-architectures, the nature of a centralised and contextualised data truth is expected to require the definition of a standardised event (data) model for each component to adhere to, to fully preserve the architectural advantages. For now, adaptors of this architecture are required to define such a model from scratch, which highly increases the effort in implementation and hinders especially small and medium enterprises from fully benefiting from this technological development. At last, organisations need to adapt to manage and develop these kinds of architectures. While software developers already successfully manage projects incorporating event-driven architectures, it is yet to be determined to what extent these procedures help in the corporate organisation of a large-scale IT-architecture across multiple technical domains.

References

[1] BMWK, 2022. Mittelstand Digital - Demonstrationsorte. https://www.mittelstand-digital.de/MD/Navigation/DE/Praxis/Demonstrationsorte/demonstrationsorte.html. Accessed 15 December 2022.

[2] Mayring, P., 2015. Qualitative Inhaltsanalyse: Grundlagen und Techniken, 12., vollständig überarbeitete und aktualisierte Aufl. ed. Beltz, Weinheim, 152 pp.

[3] Laplante, P.A., 2007. What every engineer should know about software engineering. Taylor & Francis distributor, Boca Raton, Fla, London, 311 pp.

[4] Sendler, U. (Ed.), 2016. Industrie 4.0 grenzenlos, [1. Aufl.] ed. Springer Vieweg, Berlin, Heidelberg, 270 pp.

[5] BMWK, 2022. Hintergrund zur Plattform Industrie 4.0: Ziel, Struktur und Geschichte der Plattform. Bundesministerium für Wirtschaft und Klimaschutz. https://www.plattform-i40.de/IP/Navigation/DE/Plattform/Hintergrund/hintergrund.html. Accessed 22 September 2022.

[6] Hirsch-Kreinsen, H., Minssen, H. (Eds.), 2017. Lexikon der Arbeits- und Industriesoziologie: LAIS, 2. Auflage ed. Nomos, edition sigma, Baden-Baden, 421 pp.

[7] Lasi, H., Fettke, P., Kemper, H.-G., Feld, T., Hoffmann, M., 2014. Industrie 4.0. Wirtschaftsinf 56 (4), 261–264.

[8] Anderl, R., Anokhin, O., Arndt, A., 2016. Effiziente Fabrik 4.0 Darmstadt: Industrie 4.0 Implementierung für diemittelständige Industrie, in: Sendler, U. (Ed.), Industrie 4.0 grenzenlos, [1. Aufl.] ed. Springer Vieweg, Berlin, Heidelberg, pp. 121–136.

[9] Minssen, H., 2017. Industrie 4.0, in: Hoose, F., Beckmann, F., Schönauer, A.-L. (Eds.), Fortsetzung folgt. Springer Fachmedien Wiesbaden, Wiesbaden, pp. 117–135.

[10] Spath, D., Ganschar, O., Gerlach, S., Hämmerle, M., Krause, T., Schlund, S., 2013. Produktionsarbeit der Zukunft - Industrie 4.0. Fraunhofer-Verl., Stuttgart, 150 pp.

[11] Hirsch-Kreinsen, H., 2014. Wandel von Produktionsarbeit – „Industrie 4.0“. WSI 67 (6), 421–429.

[12] Eigner, M., 2016. Das Industrial Internet: Engineering Prozesse und IT-Lösungen, in: Sendler, U. (Ed.), Industrie 4.0 grenzenlos, [1. Aufl.] ed. Springer Vieweg, Berlin, Heidelberg, pp. 137–168.

[13] Wehking, K.-H., 2020. Technisches Handbuch Logistik 2: Fördertechnik, Materialfluss, Intralogistik, 1. Auflage 2020 ed. Springer Berlin Heidelberg, Berlin, Heidelberg, Online-Ressource.

[14] Bruns, R., Dunkel, J., 2010. Event-driven architecture: Softwarearchitektur für ereignisgesteuerte Geschäftsprozesse. Springer, Berlin, 241 pp.

[15] Jakubowski, S., 2020. Warum Event Driven Architecture für Ihr Unternehmen sinnvoll ist. https://newcubator.com/blog/warum-event-driven-architecture-fuer-ihr-unternehmen-sinnvoll-ist. Accessed 11 February 2022.

[16] Wipro Digital, 2020. A Guide to Enterprise Event-Driven Architecture. https://wiprodigital.com/2020/11/10/a-guide-to-enterprise-event-driven-architecture/. Accessed 14 January 2022.

[17] Hastbacka, D., Kannisto, P., Vilkko, M., 2018. Data-driven and Event-driven Integration Architecture for Plant-wide Industrial Process Monitoring and Control, 2979–2985.

[18] Matt, D.T., Modrák, V., Zsifkovits, H. (Eds.), 2020. Industry 4.0 for SMEs: Challenges, opportunities and requirements. Springer International Publishing, Cham, 412 pp.

[19] Confluent Inc., 2020. Event-Streaming als Herzstück der Industrie 4.0: Whitepaper, 12 pp. https://assets.confluent.io/m/119f24bff45a5865/original/20201231-WP-Event_Streaming_at_the_Core_of_Industry_4-0-DE.pdf. Accessed 28 January 2022.

[20] English, J., 2019. Event Mesh: Event-driven Architecture (EDA) for the Realtime Enterprise, online, 10 pp. https://solace.com/resources/stream/wp-download-intellyx-eda-for-real-time-enterprise-

nov19?utm_source=Email&utm_medium=Direct&utm_campaign=EDA-Nurture&utm_content=Intellyx-EDA-Paper&mkt_tok=MDcyLUNCSS05MjUAAAGCfiI5xBZdldMPBNgIGuxRDD9sKOol08MCnX0bnaz6Zw8rEsVRThL1qpeA39ADgNNvUtLghxGoTj27yUvAjuK-LHm_ca0NPASoRn1Q0CnluZE. Accessed 9 February 2022.

[21] Sliwa, C., 2003. Event-driven architecture poised for wide adoption. https://www.computerworld.com/article/2570503/event-driven-architecture-poised-for-wide-adoption.html. Accessed 14 January 2022.

[22] Böhm, F., 2021. BMW Group and Confluent: A Fireside Chat. Vortrag im Rahmen der Konferenz Kafka Summit Europe 2021. https://www.confluent.io/events/kafka-summit-europe-2021/bmw-group-and-confluent-a-fireside-chat/.

[23] Confluent, Inc., 2020. How Netflix Uses Kafka for Distributed Streaming. https://www.confluent.io/blog/how-kafka-is-used-by-netflix/. Accessed 4 February 2022.

[24] Confluent, Inc., 2022. Confluent-Kunden: Echtzeit-Event-Streaming für alle Branchen | DE. https://www.confluent.io/de-de/customers/. Accessed 31 January 2022.

[25] Kai Waehner, 2021. Real-World Deployments of Kafka in the Automotive Industry - Kai Waehner. https://www.kai-waehner.de/blog/2021/07/19/kafka-automotive-industry-use-cases-examples-bmw-porsche-tesla-audi-connected-cars-industrial-iot-manufacturing-customer-360-mobility-services/. Accessed 28 January 2022.

[26] Solace, 2022. PubSub+ Customer Success Stories - Solace: Powered by Solace - From startups to the world's largest companies. https://solace.com/company/customers/. Accessed 31 January 2022.

[27] Stark, R., Damerau, T., Lindow, K., 2016. Industrie 4.0 – Digitale Neugestaltung der Produktentstehung und Produktion am Standort Berlin: Herausforderungen und Lösungsansätze für die digitale Transformation und Innovation, in: Sendler, U. (Ed.), Industrie 4.0 grenzenlos, [1. Aufl.] ed. Springer Vieweg, Berlin, Heidelberg, 169-184.

[28] Dumitrescu, R., 2016. Die Chancen für den Standort nutzen, in: Sendler, U. (Ed.), Industrie 4.0 grenzenlos, [1. Aufl.] ed. Springer Vieweg, Berlin, Heidelberg, pp. 201–216.

[29] Michels, J.S., 2016. Industrial Connectivity und Industrial Analytics, Kernbausteine der Fabrik der Zukunft, in: Sendler, U. (Ed.), Industrie 4.0 grenzenlos, [1. Aufl.] ed. Springer Vieweg, Berlin, Heidelberg, pp. 245–270.

[30] Vogel-Heuser, B., Bauernhansl, T., Hompel, M. ten, 2017. Handbuch Industrie 4.0, 2., erw. und bearb. Aufl. ed. Springer Vieweg, Heidelberg, 268 pp.

[31] Huber, A.S., 2016. Das Digital Enterprise nimmt Gestalt an, in: Sendler, U. (Ed.), Industrie 4.0 grenzenlos, [1. Aufl.] ed. Springer Vieweg, Berlin, Heidelberg, pp. 229–243.

[32] Kagermann, H., Lukas, W.-D., Wahlster, W., 2011. Industrie 4.0: Mit dem Internet der Dinge: auf dem Weg zur 4. industriellen Revolution. VDI Nachrichten (13), 2.

[33] Rückert, T., 2016. Das IoT ebnet denWeg zur vernetztenWirtschaft, in: Sendler, U. (Ed.), Industrie 4.0 grenzenlos, [1. Aufl.] ed. Springer Vieweg, Berlin, Heidelberg, pp. 217–228.

[34] Babel, W., 2021. Industrie 4.0, China 2025, IoT. Springer Fachmedien Wiesbaden, Wiesbaden.

[35] Bauer, W., Horváth, P., 2015. Industrie 4.0 - Volkswirtschaftliches Potenzial für Deutschland. CON 27 (8-9), 515–517.

[36] Ganz, C., 2016. Das Internet der Dinge, Dienste und Menschen, in: Sendler, U. (Ed.), Industrie 4.0 grenzenlos, [1. Aufl.] ed. Springer Vieweg, Berlin, Heidelberg, pp. 187–200.

[37] Duggan, D., 2012. Enterprise software architecture and design: Entities, services, and resources. Wiley, Hoboken, N.J., 482 pp.

[38] Jahn, U., 2021. Verteilte Systemarchitektur für mobile Roboter. Dissertation, Bielefeld.

[39] Christudas, 2019. Practical Microservices Architectural Patterns. Apress.

[40] Dunkel, J., Eberhart, A., Fischer, S., Kleiner, C., Koschel, A., 2008. Systemarchitekturen für verteilte Anwendungen: Client-Server, Multi-Tier, SOA, Event-Driven Architectures, P2P, Grid, Web 2.0. Hanser, München, 292 pp.

[41] Jansen, G., Saladas, J., 2021. Advantages of the event-driven architecture pattern: What is event-driven architecture and why use it? IBM. https://developer.ibm.com/articles/advantages-of-an-event-driven-architecture/. Accessed 18 January 2022.

[42] Herrmann, S., 2019. Event Storming - Gemeinsam die Domäne entdecken. https://blog.codecentric.de/2019/08/event-storming-gemeinsam-die-domaene-entdecken/. Accessed 20 September 2022.

[43] Janus, S.-T., 2020. Event-Storming-Modelle testgetrieben implementieren. https://www.informatik-aktuell.de/entwicklung/methoden/event-storming-modelle-testgetrieben-implementieren.html. Accessed 11 February 2022.

[44] Solace, 2022. Solace with SAP - Solace: Event Mesh powered by Solace PubSub+. https://solace.com/sap/. Accessed 31 January 2022.

[45] Richards, M., 2015. Software architecture patterns. O'Reilly Media, [Place of publication not identified], 1 online resource (1 streaming video file (1 hr., 31 min., 30 sec.)).

[46] Hanschke, I., 2016. Enterprise Architecture Management - einfach und effektiv: Ein praktischer Leitfaden für die Einführung von EAM, 2., überarbeitete Auflage ed. Hanser, München, 534 pp.

Sebastian Kremer, M.Sc. (*1994) is head of division Information-Technology-Management and PhD candidate at the FIR e.V. at RWTH Aachen University since 2020. As a senior project manager, Kremer executed research projects in the field of IT-OT-integration towards a digitally connected factory and industry projects for the development of modern IT-architectures for producers and logisticians in Germany.

Leon Konrad, B.Sc. (*1996) is a master student at the RWTH Aachen and Project Worker at the FIR e.V. at RWTH Aachen since 2020. As a scientific assistant, Konrad assisted in the research and development of subscription business models in the manufacturing industry. Additionally, he assisted the start-up SparePartsNow GmbH, which aims to establish a universal digital platform for spare parts in the industry. Since 2022 he is working as a Vendor Manager at SparePartsNow GmbH.

Max-Ferdinand Stroh, M.Sc. (*1991) is head of division Information-Management and PhD candidate at the FIR e.V. at RWTH Aachen University since 2018. As a senior project manager, Stroh executed research projects in the field of cyber-physical systems, smart products and IT-OT-integration towards a digitally connected factory.

Dr.-Ing. Dipl.-Wirt. Ing., Univ.-Prof. Günther Schuh (*1958) is director at the FIR e.V. at RWTH Aachen University. As a directing professor Schuh oversees digitalisation projects at the Institutes IPT, WZL and FIR at the Campus Melaten in Aachen.

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Collaborative Implementation Of Product-Service Systems In Business Ecosystems – Empirical Investigation Of Neutral Third Parties As A Success Factor

Jan Lukas Schmitt[1], David Maximilian Dörr[1], Thomas Bauernhansl[1,2]

[1]*Fraunhofer Institute for Manufacturing Engineering and Automation IPA, Stuttgart, Germany*
[2]*Institute for Industrial Manufacturing and Management IFF, Stuttgart, Germany*

Abstract

The collaborative implementation of product-service systems is a promising field of action for the German mechanical engineering industry. Through the interaction in business ecosystems, mechanical engineering companies integrate complementary competencies and technologies from different actors into customer-centric solutions, which satisfy customer needs to a greater extent. However, collaborative initiatives in business ecosystems often fail in operation or are not implemented at all. The main cause is a lack of cooperation capabilities among the cooperation partners. To solve this issue, this paper investigates how cooperation capabilities can be increased efficiently by interacting with neutral third parties in business ecosystems. Neutral third parties contribute to forming and preserving collaborative initiatives in business ecosystems and reduce transaction costs through their impartiality and specific domain knowledge. Even though the neutral third-party approach is discussed in theory, it has yet been poorly examined in practice. To develop a better understanding regarding the practical fields of application and the requirements for the implementation of the neutral third party approach in the context of mechanical engineering business ecosystems, 29 expert interviews have been conducted. The findings contribute to the transfer of the neutral third-party approach into practice and thus increase the success of a collaborative implementation of product-service systems in business ecosystems.

Keywords

Business Administration; Digitalization / Industry 4.0; Business Ecosystem; Product-Service System

1. Introduction

The collaborative implementation of product-service systems (PSS) is a promising field of action for the German mechanical engineering industry, to enable growth in saturated markets and differentiation in global competition [1]. Through the interaction in business ecosystems, mechanical engineering companies integrate complementary competences and technologies from different actors into customer-centric solutions, which satisfy customer needs to a higher extent [2]. In addition, pooling resources in business ecosystems shares development risks and shortens time-to-market [3].

However, collaborative initiatives in business ecosystems often fail or are not implemented at all [3,4]. This phenomenon originates from conflicts that find their cause in the high technological and relational complexity as well as in extensive transaction costs of these collaborative initiatives [5–7]. The companies involved lack cooperation capabilities to efficiently manage these challenges in the phases of initiation, formation and operation [3,4,8]. Further, companies often do not recognize the missing cooperation capabilities or cannot develop them in a suitable time and cost frame [3,5].

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To solve this issue, this paper investigates how cooperation capabilities can be increased efficiently by interacting with neutral third parties in business ecosystems. This approach is based on the synthesis of the work of LUSH/NAMBISAN (2015) and DE JONG ET AL. (2013) Accordingly, neutral third parties contribute to forming and preserving collaborative initiatives in business ecosystems and reduce transaction costs through their impartiality and specific domain knowledge. [9,10] Although the neutral third-party approach is discussed in theory, it has yet been poorly examined in practice [9]. So far, in the context of the collaborative implementation of PSS in mechanical engineering business ecosystems, practical fields of application and requirements for implementing the neutral third-party approach are unclear [9,11]. To close the described research gaps and thus contribute to the transfer of the approach into practice, expert interviews are conducted, including both qualitative interview techniques and quantitative ratings. Guiding the research process, the following research questions (RQ) are formulated.

RQ1: What are the fields of application for the neutral third-party approach in the context of the collaborative implementation of PSS in mechanical engineering business ecosystems?

RQ2: Which requirements must be considered when implementing the neutral third-party approach in the collaborative implementation of PSS in mechanical engineering business ecosystems?

The second chapter of this paper provides a brief overview of the theoretical foundations of the collaborative implementation of PSS in mechanical engineering business ecosystems, cooperation capabilities, and interaction with neutral third parties. In the third chapter, the research method is explained and justified. The findings of the expert interviews are presented and discussed in the fourth chapter. In the last chapter, a conclusion is drawn concerning the research objective, and finally, a research outlook is given.

2. Theoretical foundations

2.1 Collaborative implementation of PSS

For German mechanical engineering companies, innovations are a key success factor to succeed in global competition [8]. Driven by the penetration of ICT in industry, implementing PSS represent a promising field of action to satisfy customer needs to a greater extent while significantly reducing imitability by competitors [3,12]. A PSS is considered a marketable combination of industrial products and services consisting of intelligent connected physical and digital components [13,14].

As innovation cycles become shorter and the competence requirements increase, a collaborative approach in business ecosystems that enables the integration of complementary competencies and technologies from different actors across industries becomes more and more necessary [8,15]. Business ecosystems are defined as networks consisting of different actors that must collaboratively interact to realize a value proposition in the customer's value chain [15]. In this context, modular combination and pooling are suitable approaches for integrating complementary competencies [16]. At the same time, cooperation forms with a more consensual coordination mechanism and a rather hierarchical coordination mechanism (e.g., by a focal company) are suitable for the collaborative implementation of PSS [15,17]. Government or public sector funding initiatives are not considered.

2.2 Cooperation capabilities

Although the discussion of cooperation capabilities has been rooted in the management and marketing literature since the late 1980s, a wide variety of concepts has emerged to describe the phenomenon of cooperation capabilities. Only KOHTAMÄKI ET AL. integrated the different approaches into one single concept. Accordingly, cooperation capabilities are to be considered in two forms. (1) As strategic or operational capabilities for coordination, structuring, strengthening ties, and learning in cooperations. (2) As a capability for reconfiguring the resources needed to meet cooperation objectives and sensing the need for adaptation. The construct cooperation capabilities constitutes in processes and the competencies required for them. [11] This contribution follows the conceptualization of SCHMITT ET AL. (2022), which extends the previous work of KOHTAMÄKI ET AL. (2017) as described above by considering cooperation capabilities in the cooperation phases of initiation, formation, and operation [18].

Previous studies on cooperation capabilities are primarily empirical-quantitative, so that evidence is available, especially for antecedents (environmental, organizational, and relational conditions) for cooperation capabilities and their effect on cooperation performance [11]. Regarding the effect on cooperation performance, the literature states that there is a positive correlation between cooperation capabilities and collaboration quality as well as cooperation performance [19]. The processes and competencies constituting cooperation capabilities have been receiving less attention in research so far [5,11]. Furthermore, contextual information, such as the objective and framework conditions of cooperations, are rarely taken into account, even though they have a significant impact on collaboration and, thus, on the cooperation capabilities needed [11]. In this context, previous systematic literature reviews on collaborative implementation of PSS in business ecosystems fall short, as the underlying literature only considers segments of the research scope, and priorities regarding cooperation capability needs remain unclear [17,18].

2.3 Interaction with neutral third parties

According to LUSH/NAMBISAN (2015) and DE JONG ET AL. (2013), the cooperation capabilities of partners in business ecosystems can be increased by interacting with neutral third parties. In this context, neutral third parties contribute to forming and preserving collaborative initiatives in business ecosystems and reduce transaction costs through their impartiality and specific domain knowledge. [9,10] The interaction with neutral third parties is considered a service transaction in a market relationship [9,18]. Neutral third parties are characterized as follows. Neutral third parties (1) are not engaged in relationships with cooperation partners that could compromise impartiality, (2) serve the consensual cooperation objectives and should therefore be selected and compensated by all cooperation partners, and (3) have a sufficient reputation as a trusted authority [9].

In the context of collaborative innovation, the roles of neutral third parties have so far only been discussed in theory, leaving the practical fields of application unclear [9,20]. The review of previous literature shows that neutral third parties can influence the initiation and application of structural and relational governance mechanisms and support collaborative innovation activities [9,20,21]. However, it is not understood which actor in the business ecosystem can take on the respective role of the neutral third party and how they fulfill this role [9]. Further, the literature mentions actors only by example (e.g., research institution, industry association, consultancy), without referring to suitable roles [22]. So far, requirements for implementing the neutral third-party approach have only been derived from theory; practical suitability has not yet been studied [18].

3. Research method

To answer research questions RQ1 and RQ2, we chose expert interviews as appropriate research approach, as only fragmented information is available in the literature in the context of collaborative implementation of PSS in mechanical engineering business ecosystems [18]. With the aim of understanding the practical fields of application and requirements for the implementation of the neutral third party approach in the broad scope of consideration, 29 experts from companies of different sizes, industry segments and with varying levels of experience regarding the collaborative implementation of PSS were interviewed in Q3/2022 (Table 1). We interviewed C-level executives, directors in R&D, product management (PM) and business development (BD) as well as project managers with experience in the study context. With a population size of more than 5000 and a confidence level of 90%, the sample size of 29 yields a confidence interval of 85%.

Table 1: Sample composition

Size		Industry Segment		Experience Level*		Role	n=29
<100	7	Plant & Machinery	12	Low	9	C-Level Executive	8
<1000	5	Component Supplier	9	Medium	13	Director R&D	5
<10000	12	Part Supplier	1	High	7	Director PM/BD	10
>10000	5	ICT	7			Project Manager	6

*experience level is based on past and current activities of the company in the context of investigation

For the interviews, we used a semi-structured interview guideline, incorporating both qualitative interview techniques and quantitative ratings. A total of 1287 minutes of interview material was recorded and transcribed. To answer RQ1, interview participants were first asked about the main challenges of collaborative implementation of PSS. Building on these results, fields of application of the neutral third-party approach were explored in terms of addressing the previously identified challenges. In line with the conceptualization of cooperation capabilities, processes underlying the challenges of collaborative implementation of PSS, their relevance, and fields of application of the neutral third-party approach were synthesized through qualitative content analysis based on MAYRING ET AL. (2014) [23]. In addition, a quantitative rating was conducted to rank industry demand for the neutral third-party approach. To answer RQ2, the practical application of the neutral third-party approach was discussed with the experts. Through qualitative content analysis, practical application challenges were identified and consolidated into fields of action. Building on these results, requirements for the practical implementation of the neutral third-party approach were derived.

4. Findings and discussion

4.1 Fields of application for the neutral third-party approach in the context of the collaborative implementation of PSS in mechanical engineering business ecosystems

This chapter examines the practical challenges associated with the collaborative implementation of PSS in mechanical engineering business ecosystems. Building on this, we explore how these challenges can be overcome through interaction with neutral third parties. The practical challenges of collaborative implementation of PSS in business ecosystems and their relative importance are explained using the results of the quantitative study presented in Table 2. In the phases of initiation, formation, and operation, 16 processes were identified that underlie the challenges mentioned by the experts. The results show that challenges are most frequently mentioned in the initiation phase (86%). More than half of the participants state challenges in the formation and operation phases. The processes identified and the associated challenges are presented in detail below.

Table 2: Challenges of collaborative implementation of product-service systems in business ecosystems

Relative frequency of stating challenges in reference to the phase (n=29); rows: Relative frequency of stating challenges in reference to the process

A Initiation	86%	B Formation	62%	C Operation	55%
A1 Vision Creation & Follow-up	59%	B1 Legal & Tech. Configuration	45%	C1 Operating Model Design	34%
A2 Structuring Value Creation	52%	B2 Common Understanding	34%	C2 Stakeholder Management	31%
A3 Partner Persuasion	38%	B3 Negotiation	21%	C3 Conflict Management	24%
A4 Partner Search & Selection	24%	B4 Implementation Planning	17%	C4 Coordination	21%
				C5 Adaption Of Configuration	10%
				C6 Sensing Need For Adaption	7%
				C7 Set Up Collaboration Platform	3%

(A1) Creating a vision for a customer-centric solution that satisfies customer needs to a greater extent is the biggest obstacle to the initiation of collaboration in mechanical engineering ecosystems. When generating ideas, companies tend to think predominantly in terms of the competence areas of their own products or services rather than thinking outside the box putting customer value at the core. Consequently, only subsystems are targeted; holistic optimization of the customer's value creation processes is not achieved. In addition, companies lack the financial and human resources, as well as the risk appetite, to follow up on and launch these visionary initiatives beyond their competence area. (A3) The same challenges arise when convincing partners to participate in collaborative initiatives. (A2) Structuring value creation based on competency needs, market access, and incentivization is the key challenge in building viable business ecosystems. In this context, companies cannot develop an appropriate competency-building strategy (make, buy or collaborate) or position themselves because technology maturity levels and competence providers are often non-transparent, or opportunities and risks in the dynamic competitive environment cannot be anticipated adequately. However, most companies have a mindset problem. They prefer to implement solutions on their own or acquire and show little willingness to compromise when it comes to cooperation. (A4) The acquisition of information for identifying and evaluating potential partners is associated with high transaction costs. At the same time, evaluating the competencies of potential partners is difficult due to a lack of domain knowledge within the company's own organization – especially when it comes to ICT. For this reason, the mechanical engineering industry often works only with partners with a relationship of trust based on a shared history.

(B1) Insufficient understanding of legal frameworks and technical architectures that address the risk profile of the initiative, the appropriate handling of IP, and the flexibility requirements (due to the multiple commercialization opportunities of the company's contributions) inhibit the establishment of collaborations in the formation phase. This uncertainty about how to collaborate also means that potential partners cannot be convinced or that individual companies do not launch collaboration initiatives in the first place. (B2) Another challenge is to create a common understanding of the individual ambitions of the partners, the intended role, the associated benefits, and the common cooperation goal to ensure a win-win situation, especially when partners do not already know each other from previous relationships. This task is sometimes neglected, which leads to false expectations and, thus, conflicts. (B3) In addition, some collaborations do not materialize because the cost and duration of reaching a consensus is too high, or trust is lost during the negotiation of partner contributions and benefits. (B4) Due to the rather loose connections in business ecosystems and the associated lack of clear responsibilities or insufficient resources, the implementation planning is sometimes neglected, resulting in inefficiencies in the operational phase. Also, implementation cost and duration are underestimated. These misjudgments result from a lack of experience concerning the effort involved in the collaborative implementation of PSS.

(C1) In some cases, the cooperation partners do not manage to design an efficient and effective operating model that suitably connects to the core organizations of the partners, so high transaction costs arise and time to market is compromised. (C2) At the same time, stakeholders are not sufficiently informed and involved, resulting in dropping employee motivation as well as low management support and insufficient resource allocation. In addition, conflicts sometimes arise due to different cultural approaches and quality perceptions, especially when the quality of the partners' contributions cannot be adequately assessed due to a lack of domain expertise. (C3) Critical situations arise not only in this context, but also when there is no structure for addressing and resolving conflicts. (C4) The collaborative development and implementation of the customer-centric solution is often not systematic, resulting in waste and slow overall progress. The cooperation partners lack the necessary methodological competence to synchronize the technical and business perspectives as well as the different technological domains. Similar to implementation planning, coordination activities are sometimes neglected due to the rather loose ties in business ecosystems. (C5) Without the continuous adaptation of the cooperation framework to new goals and customer solutions as well as changing partner configurations, conflicts arise as the relationship between partner-individual benefits and contributions gets out of balance. (C6) In addition, recognizing the need for reconfiguration in the dynamic, collaborative environment is challenging due to limited monitoring resources. (C7) Only one of the experts states that the absence of a collaboration platform where partners can share their proprietary tools, technologies, and other resources increases redundancies and slows down development.

In summary, challenges arise throughout all phases—initiation, formation, and operation. Consequently, all phases need to be studied in terms of the applicability of the neutral third-party approach. In line with the findings of the cross-industry studies by LINGENS ET AL. (2022) and PIDUN ET AL. (2020), the most significant challenges for successfully implementing collaborative initiatives in business ecosystems concern the initiation and formation phases [4,24]. Today, most collaborative initiatives in business ecosystems do not establish at all. If the operation phase is reached, collaborative initiatives in business ecosystems are more resilient. Difficulties in the operation phase are rather the slow implementation speeds and high transaction costs for coordinating collaboration.

Building on the processes identified, fields of application for the neutral third-party approach contributing to overcoming the challenges associated with the processes are presented in the form of roles of neutral third parties. Table 3 provides an overview of the roles identified in the expert interviews.

Table 3: Roles of neutral third parties in the context of the collaborative implementation of product-service systems in business ecosystems

Phase	**A Initiation**		**B Formation**		**C Operation**	n=29
Role	Visionary	A1-A4	Facilitator	B1-B3	Cooperation Mgmt. Support	C1-C4
	Sparring Partner	A1-A4	Benefit Assessor	B2	Orchestrator	C1-C4
	Technology Expert	A2, A4			Mediator	C3
	Ecosystem Maker	A2				
		Processes (Challenges) Adressed				

In the initiation phase, the **visionary** takes the initiative to create a vision for a customer-centric solution that satisfies customer needs to a greater extent, identifies suitable cooperation partners, and convinces the respective management of the initiative. In this way, the visionary undertakes the creation of a vision that goes beyond the competence areas of the respective products or services and follows up on the vision until the respective management is convinced. So far, it is unclear which actor can take on the role of the visionary, i.e., which actor has a deep understanding of the customer problem, the awareness of and access to complementary partners, as well as the required standing to convince respective management. At the same time, it is unclear how the actor is incentivized since he takes the initiative and is not initially commissioned for his service. The **sparring partner** addresses the same processes as the visionary but takes a supporting role. Therefore, the initiative and the drive must come from the company itself. The sparring partner supports the creation of the vision with impulses (e.g., from research), the search for suitable partners through its network and ensures a common language when convincing the respective management. Actors that can already take on this role today are, for example, research institutions or technology transfer centers. Furthermore, the **technology expert** supports the development of an appropriate competency-building strategy (make, buy or collaborate) through their specific domain knowledge. Activities include the selection of suitable technologies, the assessment of technology maturity level, the search for and evaluation of potential competence providers, and the support of companies in the sustainable development of in-house competencies. Lastly, the **ecosystem maker** (e.g., standardization organizations or industry associations) provides the platform for the definition of standards, thus promoting the establishment of ecosystems as scalable marketing opportunities arise.

In the formation phase, the **facilitator** contributes to the formation of the collaborative initiative through mediation as well as an explanation of appropriate technical and legal frameworks for collaboration. Stressing the essential elements of the agreement and providing appropriate frameworks reduces the partners' uncertainty or fear of being deceived. Moderation and mediation contribute to effective consensus building by avoiding stalemate situations, enabling appropriate communication between the parties, and preventing the emergence of distrust in negotiations. The **benefit assessor** (e.g., management consultancy) supports the decision of the management or the shareholders by objectively evaluating the benefits of the collaborative initiative through developing a business plan for the respective companies.

In the operation phase, the **cooperation management support** assists partner monitoring and coordination, thus increasing implementation speed and reducing transaction costs. In doing so, the neutral third party ensures a systematic approach and contributes its methodological expertise and experience to the planning and synchronization of activities as well as to the design of the organizational model. In addition, it reduces friction in collaboration through mediation between cultures and stakeholders, e.g., through common language, as well as by identifying, addressing, and resolving conflicts early on based on impartial information about objective partner behavior and subjective partner satisfaction. The **orchestrator** has equivalent tasks to the cooperation management support but takes primary responsibility for them and is not just in the supporting role. Against this role, it is argued that in the collaborative implementation of PSS, the actor with the greatest relative benefit should be the orchestrator, as this actor has the greatest incentive for success. The **mediator** (e.g., legal advisor) is called in when conflicts arise with the task of resolving them out of court and avoiding stalemate situations.

In total, nine potential fields of application of the neutral third-party approach in the context of the collaborative implementation of PSS in mechanical engineering business ecosystems were identified. Compared to the neutral third-party roles in existing literature, we identified three new roles—visionary, ecosystem maker, and benefit assessor. At the same time, experts did not mention the following four potentially suitable roles described in literature—(1) trust transfer to parties that lack a history of prior relationship, (2) provide trilateral governance if transaction is not worth drawing an extensive contract for, (3) reputation management and blocking exit for deviant parties, (4) timely and minimally-destructive relationship termination [9].

Overall, the relevance of the neutral third-party approach for increasing the collaboration quality and the cooperation performance is rated medium or better by about two-thirds of the interview participants (Table 4). In rating the relevance as none, very low or low, it was argued that other factors were more important. At the same time, it can be assumed that the ranking is due to the fact that the approach is not yet established in practice and therefore lacks references.

Table 4: Relevance of neutral third-party interaction for increasing collaboration quality and cooperation performance

Relative frequency of rating					n=29
None	**Very Low**	**Low**	**Medium**	**High**	**Very High**
10%	7%	17%	34%	24%	7%

4.2 Requirements for the practical implementation of the neutral third party approach in the context of the collaborative implementation of PSS in mechanical engineering business ecosystems

This chapter presents the fields of action identified, discussing the practical application of the neutral third-party approach with the experts. Building on the results, we derive requirements to transfer the approach into practice or make it more accessible to practice. Figure 1 shows that the most frequently stated field of action is solution awareness (72%), followed by value transparency (62%). Problem awareness (38%), search and selection process (21%), as well as competency evaluation (21%), are mentioned less frequently.

Solution awareness: So far, companies have individual ideas for fields of application for the neutral third-party approach. However, they lack a complete overview of suitable fields of application, operationalizable role profiles (competence profiles, tasks, interaction type and intensity, transaction governance), and suitable actors that efficiently and effectively address the challenges of collaborative implementation of PSS. In connection with this, it is not possible to identify suitable actors who qualify as neutral third parties, as concrete role profiles for actor evaluation are not available.

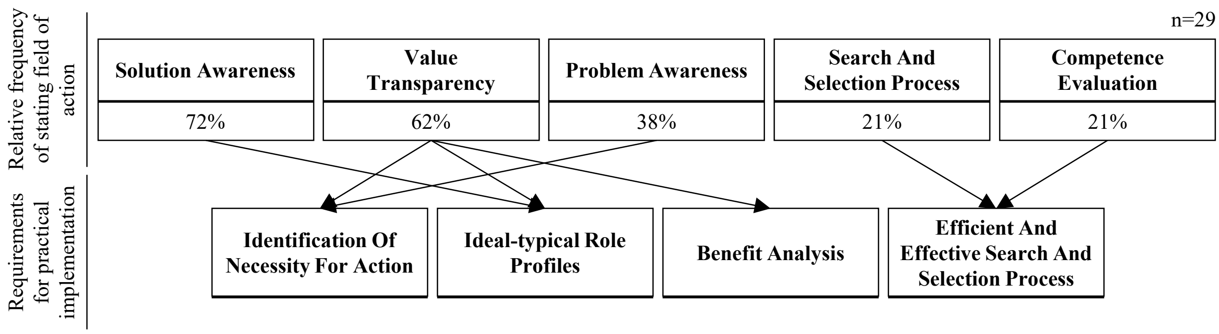

Figure 1: Requirements for the practical implementation of the neutral third party approach in the context of the collaborative implementation of PSS in mechanical engineering business ecosystems

Value transparency: Companies cannot assess in which cases it is reasonable to work with neutral third parties and in which cases it is not. This is because the value of interacting with neutral third parties is non-transparent because there is a lack of sufficient understanding of the problem to be solved and the solution provided. If the added value cannot be made transparent, reservations such as "we don't need any help; we can do it ourselves" cannot be overcome.

Problem awareness: Companies fail to recognize collaboration challenges in time or cannot assess the necessity for action because they often lack experience regarding the collaborative implementation of PSS.

Search and selection process: If the effort to find and contract neutral third parties is too high, the approach will not be used. In this context, it is unclear what an efficient process looks like that is accepted by all cooperation partners so that the credibility of the neutral third party is not compromised.

Competence Evaluation: The evaluation of the competence of the neutral third party prior to the delivery of knowledge-intensive services with a high degree of individualization and customer integration is difficult, which usually makes trust the deciding factor. Nevertheless, risks must be limited as far as possible.

In summary, five fields of action were identified during the expert interviews, confirming the results of the literature synthesis by SCHMITT ET AL. (2022) in the context of the collaborative implementation of PSS in mechanical engineering business ecosystems and extending it by identifying the highest relevance of the fields of action "solution awareness" and "value transparency" [18]. Building on these results, four requirements for the practical implementation are derived.

Identification of necessity for action: Support in identifying collaboration challenges and assessing the cooperation partner's capabilities to manage these challenges.

Ideal-typical role profiles: Operationalizable role profiles (competence profiles, tasks, interaction type and intensity, transaction governance) meeting the need for effectiveness and efficiency. Ideal types serve as a basis for evaluating current actors in terms of suitability for the respective neutral third-party role and, as an ideal type, serve as an orientation for existing as well as emerging actors seeking a neutral third-party role.

Benefit analysis: Method for evaluating interaction with neutral third parties in the context of the demand holder to enable an informed make or buy decision as well as to contribute to the persuasion of the demand holder of the neutral third party approach.

Efficient and effective search and selection process: Efficient and effective process accepted by all cooperation partners so that the credibility of the neutral third party is not compromised, including methodical guidance for evaluating the competence of neutral third parties in the selection process.

5. Conclusion and outlook

This paper aims to develop a better understanding of the fields of application and the requirements for the practical implementation of the neutral third-party approach in the context of the collaborative implementation of PSS in mechanical engineering business ecosystems. Accordingly, it contributes to the transfer of the neutral third-party approach into practice and thus increases the success of collaborative initiatives in business ecosystems. This paper adds to existing research in three ways. First, the expert interviews show that challenges to the successful implementation of PSS in mechanical engineering business ecosystems arise throughout all phases—initiation, formation, and operation. However, the most significant challenges relate to the initiation and formation phases. Second, based on the challenges stated, nine potential fields of application for the neutral third-party approach were identified. That is three new fields of application compared to the existing literature. Third, discussing the practical implementation of the neutral third-party approach with the experts, four requirements for the practical implementation are derived.

This investigation has a number of limitations opening up promising avenues for further research. The findings of this investigation are subject to the single respondent bias. In addition, since there is no clear indication of the composition of the population, it is questionable whether the sample's composition is representative. Also, since the study is a point-in-time recording, the focus of the challenges may shift with the further emergence of collaborative implementation of PSS in business ecosystems. To address these deficits and strengthen the generalizability of the results, we suggest further qualitative and quantitative studies in the future. Since this study identified three new roles for neutral third parties using an inductive approach, we suggest a deductive approach to review them and potentially identify further ones. Finally, requirements for the practical implementation of the neutral third-party approach were derived based on the view of the cooperation partners. In order to secure a win-win situation for cooperation partners and neutral third parties, potential neutral third parties should be consulted in further investigations.

References

[1] Illner, B., Lässig, R., 2019. Making Money on Digital in Mechanical Engineering: Guidelines for successful monetization of digital goods and services, 32 pp. https://www.bcg.com/publications/2019/ making-money-digital-mechanical-engineering. Accessed 19 October 2022.

[2] Möller, K.K., Halinen, A., 1999. Business Relationships and Networks. Industrial Marketing Management 28 (5), 413–427.

[3] Seiter, M., Autenrieth, P., Haas, J., Heering, F., 2020. Innovationen und Kooperationen in zukünftigen Wertschöpfungsnetzwerken, 87 pp. https://impuls-stiftung.de/studien. Accessed 19 October 2022.

[4] Pidun, U., Reeves, M., Schüssler, M., 2020. Why do most business ecosystems fail?, 10 pp. https://www.bcg.com/publications/2020/why-do-most-business-ecosystems-fail. Accessed 19 October 2022.

[5] Humbeck, P., Goss, F., Bauernhansl, T., 2019. Value Creation Through Product-Service Systems in Business Ecosystems - Identification of Key Challenges for Mechanical Engineering Companies, in: 2019 IEEE International Conference on Industrial Engineering and Engineering Management, Macao, China. IEEE, Piscataway, NJ, pp. 1354–1358.

[6] Kohtamäki, M., Parida, V., Oghazi, P., Gebauer, H., Baines, T., 2019. Digital servitization business models in ecosystems: A theory of the firm. Journal of Business Research 104, 380–392.

[7] Tjemkes, B., Vos, P., Burgers, K., 2018. Strategic alliance management, 2nd ed. Routledge Taylor & Francis, London, New York, 424 pp.

[8] Antons, D., Piening, E., Salge, T.-O., 2018. Führung und Innovation in Zeiten der Digitalisierung, 46 pp. https://www.vdma.org/organisation-kultur. Accessed 19 October 2022.

[9] Jong, G. de, Klein Woolthuis, R., Nooteboom, B., Faems, D., 2013. The role of third parties in strategic alliance governance, in: T.K. Das (Ed.), Dynamics in strategic alliances. Information Age Publishing, Charlotte, NC, pp. 55–72.

[10] Lusch, R.F., Nambisan, S., 2015. Service-Innovation: A Service Dominant Logic Perspective. MIS Quarterly 39 (1), 155–176.

[11] Kohtamäki, M., Rabetino, R., Möller, K., 2017. Alliance capabilities: A systematic review and future research directions. Industrial Marketing Management 68, 188–201.
[12] Oliva, R., Kallenberg, R., 2003. Managing the transition from products to services. International Journal of Service Industry Management 14 (2), 160–172.
[13] Drossel, W.-G., Ihlenfeldt, S., Langer, T., Dumitrescu, R., 2018. Cyber-Physische Systeme, in: Neugebauer, R. (Ed.), Digitalisierung. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 197–222.
[14] Tomiyama, T., Lutters, E., Stark, R., Abramovici, M., 2019. Development capabilities for smart products. CIRP Annals 68 (2), 727–750.
[15] Adner, R., 2017. Ecosystem as Structure. Journal of Management 43 (1), 39–58.
[16] Hagenhoff, S., 2008. Innovationsmanagement für Kooperationen, 1st ed. Göttingen University Press, Göttingen, 369 pp.
[17] Kolagar, M., Parida, V., Sjödin, D., 2022. Ecosystem transformation for digital servitization: A systematic review, integrative framework, and future research agenda. Journal of Business Research 146, 176–200.
[18] Schmitt, J.L., Doerr, D., Heidelbach, J., Bauernhansl, T., 2022. Produkt-Service-Systeme kollaborativ umsetzen: Neutrale Drittparteien als Erfolgsfaktor. Werkstattstechnik 112 (11,12).
[19] Kupke, S., 2009. Allianzfähigkeit von Unternehmen: Konzept und Fallstudie, 1st ed. Gabler, Wiesbaden, 533 pp.
[20] Rupek, T., 2021. Establishing Governance Structures for Analytics-Driven Interorganizational Data Sharing Networks – Designing a Framework Based on a Qualitative Study, in: Lernen, Wissen, Daten, Analysen.
[21] Obstfeld, D., 2005. Social Networks, the Tertius Iungens Orientation, and Involvement in Innovation. Administrative Science Quarterly 50 (1), 100–130.
[22] Russo-Spena, T., Tregua, M., Bifulco, F., 2017. Searching through the jungle of innovation conceptualisations. Journal of Service Theory Practice 27 (5), 977–1005.
[23] Mayring, P., Fenzl, T., 2014. Qualitative Inhaltsanalyse, in: Baur, N., Blasius, J. (Eds.), Handbuch Methoden der empirischen Sozialforschung. Springer VS, Wiesbaden, pp. 543–556.
[24] Lingens, B., Seeholzer, V., Gassmann, O., 2022. The architecture of innovation: how firms configure different types of complementarities in emerging ecosystems. Industry and Innovation, 1–32.

Biography

Jan Lukas Schmitt (*1995) is a research associate at the Fraunhofer Institute for Manufacturing Engineering and Automation IPA. He studied mechanical engineering at the RWTH Aachen University. His research focuses on business models, predominantly in the context of business ecosystems.

David Maximilian Doerr (*1989) is a research associate at the Fraunhofer Institute for Manufacturing Engineering and Automation IPA. He studied industrial engineering at the RWTH Aachen University. Since 2017 he is coordinator for business models at the Fraunhofer IPA. Since 2019 he has been working in the Corporate Strategy and Development Department and is Deputy Manager of the Fraunhofer Project Centre for Smart Manufacturing in Shanghai.

Prof. Dr.-Ing. Thomas Bauernhansl has been director of the Fraunhofer Institute for Manufacturing Engineering and Automation IPA in Stuttgart since September 2011 and is director of the Institute for Industrial Manufacturing and Operation IFF at the University of Stuttgart.

Bauernhansl studied mechanical engineering at the RWTH Aachen University. After receiving his doctorate with distinction, he was employed by the Freudenberg company from 2003, most recently as director of the Technology Center at Freudenberg Sealing Technologies. His focus was on location planning, factory planning, production relocation, technology management and lean production.

Thomas Bauernhansl is involved in numerous advisory boards and executive committees in industry, associations, research and politics. He is the author and editor of numerous books on topics such as transformability in production, Industry 4.0 and management in production.

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Framework For Context-Sensitive Dashboards Enabling Decision Support On Production Shop Floor

Karl Lossie[1], Niklas Birk[1], Sagiban Sivasubramaniam[1], Robert H. Schmitt[1,2]
[1]Fraunhofer Institute for Production Technology IPT, Aachen, Germany
[2]Laboratory for Machine Tools and Production Engineering WZL of RWTH Aachen University, Aachen, Germany

Abstract

The advancing digitalization of production means that a large amount of data and information is being collected. Used correctly, these represent a significant competitive advantage. Decision support systems (DSS) can help to provide employees with the right information at the right time. Context-sensitive dashboards in the sense of decision support have the potential to provide employees on the shop floor with information according to their needs. Within the scope of this work, a framework for the determination of the context-sensitive information needs of the staff on the shop floor was developed. The goal was to reduce the development and adaptation effort of a context-sensitive application by classifying activities with similar information needs in advance. According to the methodology, the information needs of the employees are first analyzed and activities are summarized in terms of their general information needs. Subsequently, information needs are weighted in order to prioritize them with regard to the processing and selection of information. The context-sensitive dashboard was implemented using a user-centric approach to achieve a high level of user acceptance. Finally, the developed prototype, including architecture and design, was tested and evaluated by experts. Three scenarios were compared in which experts were asked to assess the information requirements for employees in production. These results were compared with the results of the framework. The comparison showed that for two of the three scenarios, the weighting determined in the framework matched the experts' assessments to a high degree. These general scenarios show that it is possible to generate context-sensitive dashboards based on demand using the developed framework. If the activities become more specific, it became apparent that further developments of the framework are necessary to cover the corresponding information needs. For this purpose, an iterative application to further scenarios and subsequent implementation in the framework seems to be purposeful.

Keywords

Context-Sensitive; Decision Support; Dashboard; Production Shop Floor; Framework

1. Introduction

The advancing digitalization of production means that a large amount of data and information is being collected. Used properly, these represent a significant competitive advantage. Decision support systems (DSS) can help to provide employees with the right information at the right time. Context-sensitive dashboards in the sense of decision support have the potential to provide employees on the shop floor with information according to their needs.

First, we will discuss current developments for support on the production shopfloor. Based on this, we propose a framework that was developed for determining the context-sensitive information needs of staff on

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the shop floor. The goal was to reduce the development and adaptation effort of a context-sensitive application by pre-classifying activities with similar information needs. According to the methodology, the information needs of the employees are first analyzed and activities are summarized in terms of their general information needs. Subsequently, the information needs are weighted to prioritize them with regard to the processing and selection of information. Afterwards, the context-sensitive dashboard was implemented using a user-centric approach to achieve a high level of user acceptance. Finally, the developed prototype, including architecture and design, was tested and evaluated by experts, validating the framework and concluding this paper.

2. Recent Developments for Support on Production Shop Floor

2.1 Decision Support Systems

In a modern production environment, people, machines and products are networked via the internet and exchange information with each other. This is where DSS come in. Because the increased flexibility and dynamics in production mean that production processes need to be adaptable, DSS can enable that the right information is available to operators at the right time and in the right place. [1]

The aim of such systems is to enable decision-makers to make decisions of the highest possible quality by collecting, processing, analyzing and providing information and data. To this end, large volumes of data can be processed automatically and visualized clearly for the user. Frequently, DSS do not offer the user just one solution, but compare several alternatives with regard to their advantages and disadvantages. [2] The advantage of an DSS that integrates humans into the decision-making process is particularly apparent in the presence of uncertainty and when no clear patterns in decision-making are apparent. In this case, human intelligence is superior to computers. [3]

Common DSS used in almost every modern production facility include Manufacturing Execution Systems (MES) and Enterprise Resource Planning (ERP) systems. With the help of Manufacturing Execution Systems (MES), production processes can be planned and controlled and the material and information flow of production can be mapped. In contrast to MES, enterprise resource planning (ERP) systems operate at a lower level of detail over the medium and longer term. These systems are used to manage operational resources such as production equipment, personnel and capital. [4–6]

Both ERP and MES are limited in their flexibility and data-driven process optimization for direct use as DSS on the shop floor [7]. For this reason, there are many different DSS designed to support specific activities and processes on the shop floor. Through smaller and more powerful devices connected via the Internet, ergonomics and the number of integrated functionalities is increasing.

2.2 Dashbords

On the shop floor, DSS are often used in conjunction with dashboards. These are divided into three different types: strategic, tactical and operational. Strategic dashboards can be used to monitor the company's progress towards strategic goals, whereas tactical dashboards are used to monitor progress and trends for all of an organization's strategic initiatives. Because this work focuses on operational dashboards they will be explained in more detail. Operational dashboards are dashboards used to monitor enterprise processes, activities, and complex events. Generally, the user interface provides daily or weekly updates or near real-time charts and reports that illustrate the status of business and production processes. By using dashboards on a regular basis, problems can be identified early and actions can be taken. Because of their practical nature, they are not used at higher levels of the organization, but where the processes and activities take place. Like tactical dashboards, the narrow scope of operational dashboards requires detailed information with strong analytical capabilities. In light of a dashboard's limited screen space and high level of specialization, operational dashboards in particular must be tailored to the needs of their target users. [8,7,9]

2.3 Context-Sensitive Systems

The generally accepted definition of context by DEY [10] is extended by ROSENBERGER et al. [11] to improve its applicability with respect to the industrial domain. The term context refers to any information that can be used to characterize an entity, its state, or its environmental situation, if the information is considered relevant for the interaction between user and application. An entity can be a person, a place, or a tangible object or intangible state, including the user and the application itself. [12,13] Context-sensitive systems are rarely used in industrial applications. Due to the increasing proliferation of mobile devices and wearables, systems with location recognition are increasingly used. [14,15] According to ALEXOPOULOUS et al. [16], successful architectures for context-aware applications in production should have the following common characteristics:

1. multi-tier architectural approach that encapsulates features and functionalities.
2. event-driven approach, due to the multiplicity of IoT-enabled devices
3. context sensitivity should be supported by technologies such as ontologies and semantics.

ROSENBERGER et al. [11] developed a process model for the development of context-sensitive systems for industrial applications. A cross-phase user-centered approach for context determination is presented, which combines tasks of the process definition and context determination phases. This is used as an orientation for later implementation in this thesis. A comprehensive overview of the use and research status of context-sensitive systems can be found in PERERA et al. and HONG et al. [17,18].

3. Framework for Development of Context-Sensitive Dashboards

ROSENBERGER et al. propose a general process model to develop context-sensitive systems [11]. It divides the analysis and design phase of context-aware systems into three stages:

1. Activity determination: identification of activities to be supported by context-aware functionalities.
2. Process definition: Determination of how the system should react to the occurrence of a context.
3. Context determination

Based on the general procedure for the development of context-sensitive systems presented above, a suitable procedure for this work is developed below. One of the main reasons for the high development effort of context-sensitive applications according to the framework from ROSENBERGER et al. is the individual consideration of individual activities. As described, production scenarios on the shop floor are becoming more dynamic, complex and subject to constant adaptation. On the one hand, this means that an increasing number of activities must be considered and analyzed individually. On the other hand, the increasing dynamics of production means that new activities occur that were not taken into account during the development of the original application. To update the application, the entire process model must be run through for the new activities.

A major goal of this work is to reduce the effort required to create a context-sensitive application and thereby increase the benefit-to-expense ratio. To achieve this goal, a new process model is developed, shown in Figure 1. This model takes the approach of reducing the number of activities to be analyzed by grouping individual activities into classes that have the greatest possible degree of overlap in terms of system response and contexts.

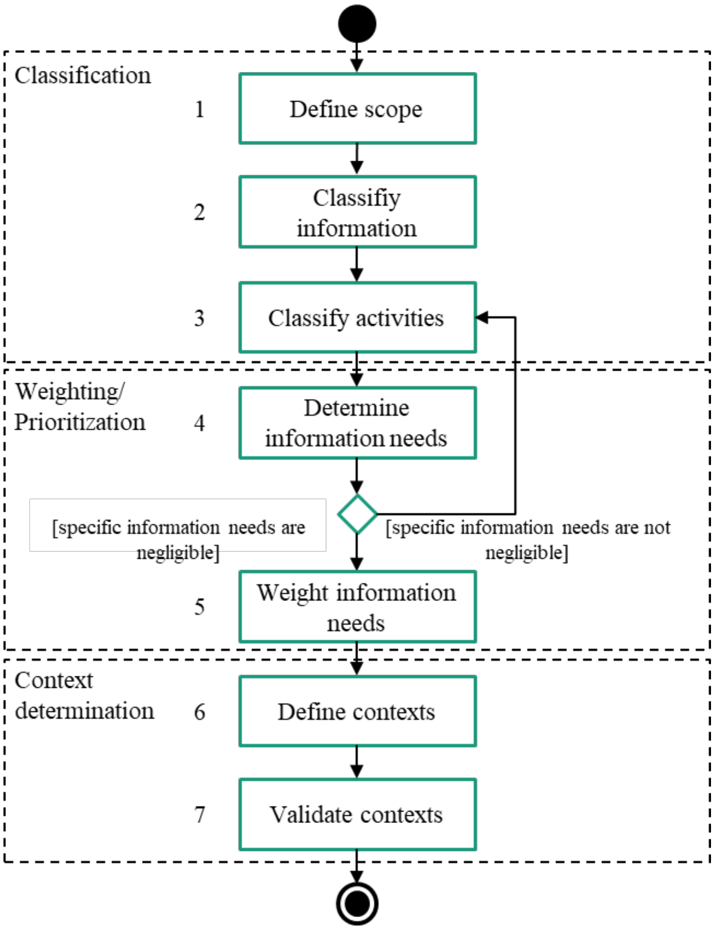

Figure 1: Framework for developing context-sensitive dashboards

After the definition of the scope (step 1), the information that is of interest to the shop floor personnel is classified (step 2). Subsequently, the activities occurring within the definition area are identified. These activities are analyzed and classified (step 3) with regard to their system response. In the case of the DSS acting passively here, the system response corresponds to the change in the displayed information or the information requirement of the personnel for the execution of the activity. In the following step, it is checked whether the selected classification is suitable for further development (step 4). This is the case if the intersection of the common information needs of the respective class is sufficiently large or the share of the activity-specific information needs is negligibly small. If this criterion is not met, the classification approach must be adjusted (step 3). This is followed by the weighting or prioritization of the relevance of the information needs (step 5). Relevance in this context means the significance of the information requirement for the shop floor personnel. On the one hand, the effect or the influence of the information, on the other hand, the probability of occurrence of the information need in dependence on the specific activity is considered. Finally, the contexts are assigned to the activity classes based on categories and validated (step 6 and 7).

4. Applying the Framework to the Production Shop Floor

After presenting the general framework for the development of context-sensitve dashboards, it will now be operationalized to the production shop floor. For this, the steps referenced in Figure 2, which need operationalization will be described in detail. In the case of appliyng the framework to the shop floor the infromation needs from step 4 coincide with the classified information from step 2. The steps 4 and 7 (determine information needs / validate contexts) are therefore excluded from the next subchapters.

4.1 Definition of Scope

As shown in Figure 1, the first step is the definition of scope. The production shop floor will be the frame of reference for the application of the framework. In the following subchapters, a distinction is made between the direct areas (fabrication and assembly) and the indirect areas (logistics, maintenance and quality assurance). Also, production planning and control will be included as a separate area. Shop floor personnel refers to all persons who perform activities in these areas.

According to the classification of dashboards described earlier, this work reffers to an operational dashboard. In this context, it is a passive DSS that clearly provides information for process monitoring and control. The individual needs of the user are to be fulfilled by real-time information to enable faster and high-quality decision-making.

4.2 Classification of Information

The second step according to the framework is the classification of information. As shown in Table 1, the general categories for information needs (context, performance, knowledge and communication) can be subdivided into more specific categories. Specific information from MES, ERP, and other data sources can be assigned to these categories in the implementation of the DSS.

Table 1: Classification of information needs on the shop floor adapted from [19]

General information needs	#	Specific information needs
Context	1	Alarms, warnings, notices
	2	Order information
	3	Information about completed/planned orders
	4	Information about previous/future process steps
	5	Environment information
	6	Contact information of responsible persons
Performance	7	Company related KPI
	8	Production line related KPI
	9	Process-related KPI
	10	Personnel-related KPI
Knowledge	11	Detailed, interactive work steps/instructions
	12	Safety/health instructions
	13	Resource information
	14	Process improvement
	15	Documentation
Communication	16	synchronous
	17	asynchronous

4.3 Classification of Activities

In the following, the various areas of the shop floor are examined in more detail and a suitable classification approach is sought for all the activities occurring there (cf. step 3 in Figure 1). For each of the six different areas, a classification approach is identified that can be used to group the activities into subcategories. These subcategories should be selected in such a way that they have as large an intersection as possible in terms of their information requirements, or that the amount of activity-specific information is negligibly small. Figure 2 shows an overview of the different activities on the shop floor and their respective classification approach.

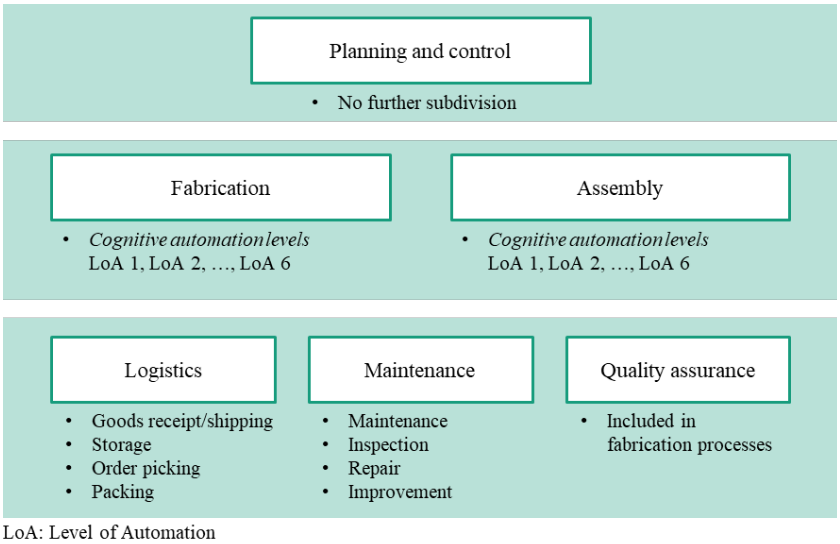

Figure 2: Classification of shop floor activities

A suitable classification approach for fabrication and assembly activities can be the classification by different degrees of automation after [20]. The Level of Automation (LoA) within production is defined as the division of physical and cognitive tasks between humans and technology into a spectrum ranging from fully manual to fully automated. Each of these tasks can then be classified into seven levels, from fully manual control to fully automated. Both the degree of physical and cognitive assistance can thus be assessed on a common scale. In general, the need for information for shop floor personnel decreases with higher levels of automation. For the other shop floor activities, the classification can be seen in Figure 2.

4.4 Weighting of information needs

To enable the system to process and select which information is to be displayed prioritized in the specific case, a weighting of the various information needs is carried out for this purpose (cf. step 5 Figure 1). For each specific information need (criterion), a weighting factor (weight) w_j is determined. This factor is usually set up to be between 0 and 1 on a cardinal scale.

$$\sum_{j=1}^{n} w_j = 1 \tag{1}$$

n = number of criteria

The weights can take on different functions, depending on the decision procedure. In this paper, the most common interpretation of the weighting factor is the relative importance of one criterion over the others. Since these weights are assigned subjectively, it is important to show the decision process towards them as transparently as possible. One goal is therefore to ensure that the weighting made is comprehensible and, can be adjusted without great effort. [21]

Many methods for determining the weights can be found in the literature. The procedure used here is based on the Failure Mode and Effects Analysis (FMEA) [22,23]. Based on this methodology, the effect of specific information requirements on the shop floor is estimated. To make this assessment and weighting more consistent and comprehensible, the following four fundamental criteria are introduced:

1. Occupational safety
2. Product Quality
3. Adherence to delivery dates
4. Productivity

These fundamental criteria cover the key risks on the shop floor and are weighted relative to each other. The calculation of the weight g_i of the respective specific information requirement results as follows:

$$g_i = \sum_{j=1}^{n} k_j * x_j \quad (2)$$

n = number of fundamental criteria

k_j = weight of the fundamental criterion

x_j = importance of error effect

Regarding the importance of the error effect x_j, weights from 1 (no impairment) to 10 (dangerous/illegal) are assigned. In the context of information needs, this weighting signifies how relevant specific information is to avoid errors or complying with the fundamental criteria. The probability of occurrence plays a role in the subsequent step, which is determined for the various defined activity classes of the respective specific information needs. This is done in the form of an argumentative approach, which enables a general estimation of the frequencies or probability of occurrence (equivalent to FMEA) of the information requirement. Since this assignment is carried out at a rather high level of abstraction and subjectively, a deficit of the classification approach arises at this point. For this reason, the weighting was designed in such a way that it is also possible to change certain weighting parameters retrospectively and to adapt them individually to the shop floor. In addition, due to the high degree of abstraction, specific activities may have information needs that deviate from their class, which cannot be covered by the classification scheme. To compensate for this deficit, a personalization function can be provided in the later application. Finally, the weights of the specific information needs are determined based on the effect of the information needs and the occurrence probabilities. Here, the weight of the specific information need is $w_{i,j}$:

$$w_{i,j} = g_i + P(I)_{i,j} * \frac{1}{\sum_{i=1}^{n} g_i * P(I)_{i,j}} \quad (3)$$

g_i = effect of the information need

$P(I)_{i,j}$ = probability of occurrence of the specific information need

Index i refers to the class of information need (e.g., order information, information about completed/scheduled orders, etc.), index j refers to the activity class (e.g., LoA 1, LoA 2, etc.). The second part of the formula includes the normalization of the absolute values, which results in the sum of all weights corresponding to an activity class 1.

4.5 Definition of Context

In this paper, the scheme of ROSENBERGER et al. is used, to classify context [11]. To better represent the industrial environment, the core categories *user, environment and system* are extended in this case by the specific categories information retrieval and pattern recognition. The relevant contexts for this work are depicted in Figure 3.

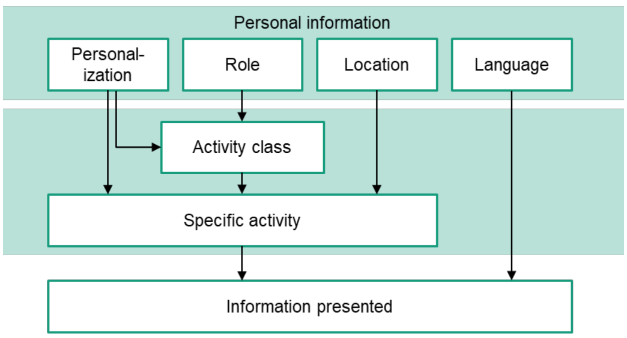

Figure 3: Context model for shop floor personnel

5. Prototype and Validation

With the developed framework, the specific information needs and weights were assessed. Additionally, a prototype dashboard was developed, using the underlying assumptions. For the validation, three different exemplary scenarios were considered in which experts for production assessed the information requirements. For this purpose, the various available information was to be sorted into a ranking order with regard to its relevance for the specific scenario. In each case, 17 application-specific pieces of information were listed for each scenario, which were to be ranked in terms of their relevance for the activity to be performed (prioritization from 1 to 17): 1 Information on dimensions and tolerances of the workpiece; 2 Information about follow-up order; 3 Information about previous production steps of the workpiece; 4 Note: Check filling level of cooling liquid; 5 Humidity of the environment; 6 Contact information of the person(s) responsible for the machine; 7 Averaged scrap rate of the entire production; 8 Overall equipment effectiveness OEE; 9 Average cycle time of the process; 10 Personnel-related number of completed production orders; 11 Detailed work instructions for the production of the workpiece; 12 Safety instructions: Wear safety goggles and gloves; 13 Set speed of the milling head; 14 Suggestion for process improvement: Second step of the instructions is misleading; 15 User manual of the milling machine; 16 Real-time support via video chat with production manager; 17 Text message from production manager about machine inspection the following day. Subsequently, this assessment was averaged and compared with the determined weights (see Figure 4).

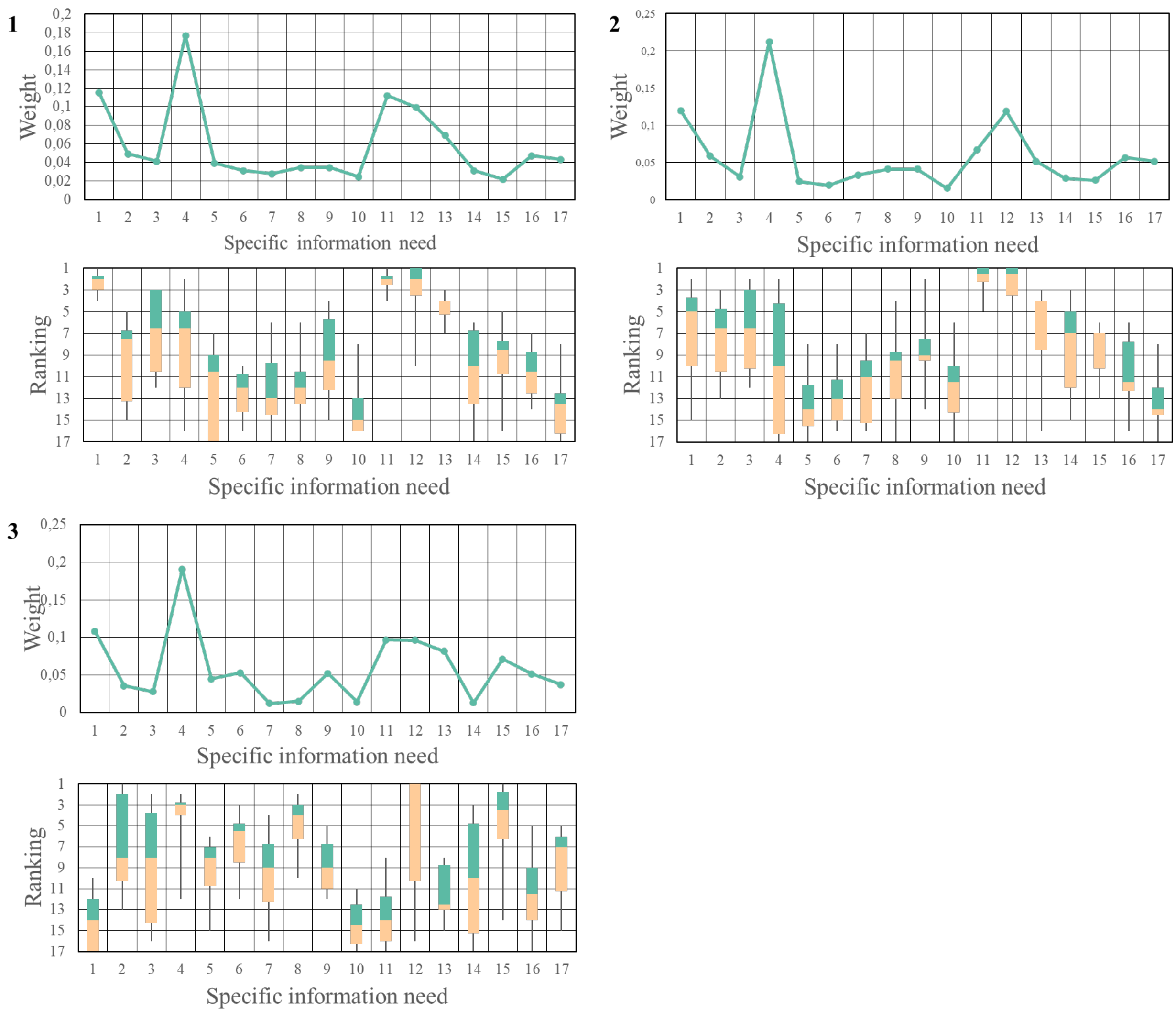

Figure 4: 1: Validation results for scenario 1,2 and 3 (corresponding bold numbers), model output for weighted infromation needs on top, results from expert questionaire on the bottom (boxplots, number of participants n = 8)

Scenario 1 involves a manufacturing activity on a milling machine in which no automation technology has been installed. Thus, the technology does not challenge the execution of the user's actions, nor does it take over parts of the control of the process (LoA 3). In Scenario 2, the milling machine has been upgraded and now has sensor and control technology that allows the process to be checked and corrected (LoA 6). In the third scenario, a maintenance activity is performed on the milling machine.

The comparison of the results of the first two scenarios has shown that the weighting of the framework and the assessment of the production experts coincide to a high degree. Only a few specific information requirements differ significantly. This raises the question of whether the experts' assessment produces better results than the argumentative approach.

The consideration of a maintenance activity has shown the limitations of the framework. Once activities become too specific, the generalized classification approach followed in the paper cannot cover all specific information needs. However, this shortcoming could be compensated by a personalization feature and iterative improvement through user feedback in the later application.

6. Conclusion and Outlook

This paper proposed a framework for the development of context-sensitive dashboards. It has been implemented as a prototype and validated through expert interviews. The comparison showed that for two of the three scenarios, the weighting determined in the framework matched the experts' assessments to a high degree. It must be said though, that the number of experts for validation was very limited (eight). By increasing the audience for validating the framework, the results shold be further analyzed. These general scenarios show that it is possible to generate context-sensitive dashboards based on demand using the developed framework. If the activities become more specific, it became apparent that further developments of the framework are necessary to cover the corresponding information needs. For this purpose, an iterative application to further scenarios and subsequent implementation in the framework seems to be purposeful.

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References

[1] Syberfeldt, A., Holm, M., Danielsson, O., Wang, L., Brewster, R.L., 2016. Support Systems on the Industrial Shop-floors of the Future – Operators' Perspective on Augmented Reality. Procedia CIRP 44, 108–113.

[2] Arnold, D., Isermann, H., Kuhn, A., Tempelmeier, H., Furmans, K. (Eds.), 2008. Handbuch Logistik. Springer Berlin Heidelberg, Berlin, Heidelberg.

[3] Felsberger, A., Oberegger, B., Reiner, G., 2016. A Review of Decision Support Systems for Manufacturing Systems, in: SAMI@ iKNOW, p. 8.

[4] Kletti, J., 2015. MES - Manufacturing Execution System. Springer Berlin Heidelberg, Berlin, Heidelberg, 298 pp.

[5] VDI Verein Deutscher Ingenieure e.V., 2016. Fertigungsmanagementsysteme: (Manufacturing Execution Systems – MES), 78 pp.

[6] VDMA, 2018. VDMA 66412-40 MES im Umfeld von Industrie 4.0. Beuth Verlag GmbH, Berlin, 24 pp.

[7] Gröger, C., Stach, C., Mitschang, B., Westkämper, E., 2016. A mobile dashboard for analytics-based information provisioning on the shop floor. International Journal of Computer Integrated Manufacturing 29 (12), 1335–1354.

[8] Eckerson, W.W., 2011. Performance dashboards: Measuring, monitoring, and managing your business, 2nd ed. ed. Wiley, New York, xvii, 318.

[9] Rasmussen, N.H., Bansal, M., Chen, C.Y., 2009. Business dashboards: a visual catalog for design and deployment. John Wiley & Sons.

[10] Dey, A.K., 2001. Understanding and Using Context. Personal and Ubiquitous Computing 5 (1), 4–7.

[11] Rosenberger, P., Gerhard, D., Rosenberger, P., 2018 - 2018. Context-Aware System Analysis: Introduction of a Process Model for Industrial Applications, in: Proceedings of the 20th International Conference on Enterprise Information Systems. 20th International Conference on Enterprise Information Systems, Funchal, Madeira, Portugal. 21.03.2018 - 24.03.2018. SCITEPRESS - Science and Technology Publications, pp. 368–375.

[12] Nadoveza, D., Kiritsis, D., 2013. Concept for Context-Aware Manufacturing Dashboard Applications. IFAC Proceedings Volumes 46 (9), 204–209.

[13] Nunes, D., Boavida, F., Silva, J.S., 2017. A practical introduction to human-in-the-loop cyber-physical systems, First edition ed. Wiley IEEE Press, Hoboken, NJ, 307 pp.

[14] Baldauf, M., Dustdar, S., Rosenberg, F., 2007. A survey on context-aware systems. International Journal of Ad Hoc and Ubiquitous Computing 2 (4), 263–277.

[15] Makris, P., Skoutas, D.N., Skianis, C., 2013. A Survey on Context-Aware Mobile and Wireless Networking: On Networking and Computing Environments' Integration. IEEE Commun. Surv. Tutorials 15 (1), 362–386.

[16] Alexopoulos, K., Sipsas, K., Xanthakis, E., Makris, S., Mourtzis, D., 2018. An industrial Internet of things based platform for context-aware information services in manufacturing. International Journal of Computer Integrated Manufacturing 31 (11), 1111–1123.

[17] Hong, J., Suh, E., Kim, S.-J., 2009. Context-aware systems: A literature review and classification. Expert Systems with Applications 36 (4), 8509–8522.

[18] Perera, C., Zaslavsky, A., Christen, P., Georgakopoulos, D., 2014. Context Aware Computing for The Internet of Things: A Survey. IEEE Commun. Surv. Tutorials 16 (1), 414–454.

[19] Gröger, C., Hillmann, M., Hahn, F., Mitschang, B., Westkämper, E., 2013. The Operational Process Dashboard for Manufacturing. Procedia CIRP 7, 205–210.

[20] Frohm, J., Lindström, V., Winroth, M., Stahre, J., 2008. Levels of Automation in Manufacturing. Ergonomia - International Journal of Ergonomics and Human Factors 30, 181–207.

[21] Eisenführ, Franz and Weber, Martin, 2003. Rationales Entscheiden. Springer-Verlag, Berlin, Heidelberg, 423 pp.

[22] Farny, D., 2011. Versicherungsbetriebslehre. VVW GmbH.

[23] Romeike, F., Hager, P., 2020. Erfolgsfaktor Risiko-Management 4.0. Springer Fachmedien Wiesbaden, Wiesbaden, 657 pp.

Biography

Karl Lossie (*1992) studied mechanical engineering at TU Dresden, Germany. Since 2018, has works as a Research Associate at Fraunhofer Institute for Production Technology (IPT). His focus lies in the field dicision support in production.

Niklas Birk (*1994) studied mechanical engineering at RWTH Aachen University. He worked as a student assistant and master's student at Fraunhofer Institute for Production Technology (IPT) from 2018 to 2021.

Sagiban Sivasubramaniam (*1997) studies mechanical engineering at RWTH Aachen University. Since 2021, he works as a student assistant at Fraunhofer Institute for Production Technology (IPT).

Robert H. Schmitt (*1961) has been professor of Chair of Metrology and Quality Management and Member of the Board of Directors at Laboratory for Machine Tools and Production Engineering WZL of RWTH Aachen since 2004. He is also Member of the Board of Directors at Fraunhofer Institute of Production Technology (IPT).

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Flexibility-Driven Planning Of Flow-Based Mixed-Model Assembly Structures

Nils Föhlisch[1], Peter Burggräf[1,2], Tobias Adlon[1], Christopher Kapella[1]

[1]*Laboratory for Machine Tools and Production Engineering (WZL), RWTH Aachen University, Campus Boulevard 30, 52074 Aachen, Germany*

[2]*Chair of International Production Engineering and Management (IPEM), University of Siegen, Paul-Bonatz-Straße 9-11, 57076 Siegen, Germany*

Abstract

Trends such as mass customization, changing customer preferences and resulting output fluctuations increasingly challenge the production industry. Mixed-model assembly lines are affected by the rising product variety, which ultimately leads to ascending cycle time spreads and efficiency losses. Matrix assembly addresses these challenges by decoupling workstations and dissolving cycle time constraints while maintaining the flow. Both matrix and line assembly are flow-based assembly structures characterized by assembly objects moving along the stations. In assembly system planning, competing assembly structures are developed and the one best meeting the use case's requirements is selected for realization. During assessing requirements and selecting the superior assembly structure, the systematic consideration of flexibility is often not ensured within the planning approach. Therefore, a preferred assembly structure may not have the flexibility required for a use case. The systematic and data-driven assessment of required and provided flexibility in assembly system planning is necessary.

This paper presents an assessment model that matches a use case's requirements with the flexibility of flow-based assembly structures based on production program and process data. On the one hand, requirements are defined by flexibility criteria that evaluate representative product mixes and process time heterogeneity. On the other hand, provided flexibility of flow-based assembly structures is assessed in a level-based classification. A method for comparing the requirements and the classification's levels to prioritize assembly structures for application in a case is developed. The flexibility requirements and assembly structure of an exemplary use case are determined and discussed under the planning project's insights to evaluate the developed model. This work contributes to the objective and data-driven selection of assembly structures by utilizing use case-specific data available during the phase of structural planning to meet flexibility requirements and ensure their consideration along the assembly planning process.

Keywords

Flexibility Assessment; Assembly System Planning; Matrix Assembly; Line Assembly; Flow-based Assembly; Flexibility Requirements

1. Introduction

Due to the increasing individualization, products are tailored precisely to customer needs. Companies use Mixed-Model Assembly Lines (MMAL) to manage the resulting product variety in production and to reduce investment risk [1]. These are used to manufacture a variety of products within one assembly system without the need for retooling [2]. Within the system, a uniform cycle time must be maintained, which is available for executing the processes in each station. Increasing product variety and the associated growth in station-related process time heterogeneity result in rising cycle compensation times, which lead to efficiency losses

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[3]. Even though significant measures are conducted to reduce cycle time spreads, MMAL are reaching the limits of their economic viability [4, 5]. Matrix assembly systems are an approach to simultaneously increase flexibility and efficiency of variant-rich assembly [4]. These combine the advantages of job-shop assembly regarding flexibility and of flow-line assembly regarding efficiency by dissolving the cycle time constraint and decoupling workstations. A flexible flow arises, wherein assembly objects take an individual path through the system [6], which is only limited by the product-specific priority sequence graph [7]. In this context, flexibility describes a system's ability to reversibly adapt its processes to changing conditions within short time [8, 9]. Matrix and line assembly are summarized under flow-based assembly structures, which are characterized by moving assembly objects that pass through working stations according to the flow principle.

So far, the industrial application of matrix assembly has been limited, although the concept is broadly discussed and tested in prototypes in practice. Companies' lack of experience in the use and planning of matrix assembly systems and high planning complexity are possible reasons for the slow introduction [10]. Since matrix assembly emerged, companies increasingly face the question during assembly planning whether matrix assembly is better suited to their challenges than line assembly. Conventional assembly planning procedures mainly consist of four phases [11]. First, the planning task with its requirements and boundary conditions is defined. On this basis, one or multiple competing assembly structures are developed and examined in the concept phase of structural planning. The evaluation is based on a comparison under consideration of the requirements and objectives. The appropriate structure is selected and then concretized in the detailed planning. The result of the detailed planning is implemented in the system realization [12].

Within the requirement specification in the first phase, flexibility is often considered a subordinate factor and quantification of related objectives is difficult. In the absence of quantitatively specified flexibility requirements, matrix assembly structures cannot be objectively evaluated alongside those of line assembly, as it is flexibility that is a key driver of the adoption of a matrix assembly. Therefore, prior to capacity determination and performance simulation, a data-driven procedure is required to evaluate and select the appropriate assembly structures, considering flexibility of flow-based assembly. This paper presents an assessment model that analyzes process time and product mix data of a use case regarding flexibility requirements in order to prioritize flow-based assembly structure alternatives with respect to the best fulfillment. Hence, the research question of this paper is: *"How can flexibility requirements from process time and product mix data be assessed and matched with flow-based assembly structures for prioritization?"*

2. Literature Review

The presented approaches are part of the findings of a structured literature review conducted according to VOM BROCKE ET AL. [13]. Many approaches in literature address criteria for flexibility in certain domains [14-17] and VAN DE GINSTE ET AL. [18] undertake a review focusing on the definition of flexibility as well as corresponding criteria in assembly. The authors analyze scientific articles, from which the 15 most used criteria are extracted. The various criteria result primarily from each company defining flexibility for itself, making manufacturing flexibility challenging to summarize. The most frequently cited criteria are volume, routing, mix, machine and process flexibility. However, the presented criteria are partly similar, respectively redundant and build on each other. It remains unclear which flexibility criteria form a redundant-free set and comprehensively specify the requirements for an assembly structure during system planning.

Several approaches elaborate structural relationships among the criteria and provide hierarchical organizations [17-19]. KOSTE AND MALHOTRA [19] propose a set of criteria for analyzing manufacturing flexibility and propose a hierarchy consisting of five successive tiers. These include the individual resource, shopfloor, plant, functional and strategic business unit tier. The lower tiers partly serve as enablers of the upper ones. It is required to determine which tier respectively criteria are most appropriate and form a redundant-free, comprehensive set for the specification of the requirements while planning an assembly structure. Furthermore, it needs to be detailed how criteria are quantitatively assessed for structural planning.

Several approaches for the criteria-based assessment of flexibility can be identified in the relevant literature [20-23]. ROGALSKI [22] provides an approach for evaluating quantity, product mix and expansion flexibility at different observation levels. The relevant limits of quantity flexibility are represented by the break-even point and the maximum capacity. Product mix flexibility describes the scope for adapting the production program and is calculated from the profit maximum based on the optimum production program and its average, product-specific deviation. To determine expansion flexibility, the break-even points of the various expansion alternatives and a defined target capacity are used. However, the three criteria considered do not cover all aspects relevant for structural planning, e.g. the introduction of new products. In addition, cost- or capacity-based approaches cannot be used for decision support while selecting the appropriate assembly structure, since cost rates and capacities are not known in the early planning phase of structure planning.

SCHUH ET AL. [23] develop a key figure model for the evaluation of flexibility with regard to changes in output, variant mix and products. The basis of the evaluation is the hierarchical modeling of the production system by means of classes for work centers, lines, etc. provided by the key figure model. These contain the attributes required for the modeling and the functions for the flexibility calculation on the considered level. The requirements for the production system are described by means of user-defined reference scenarios. On this basis, the flexibilities are calculated by the functions per workstation and, building on this, for the higher levels. By means of the resulting quantitative key figures, different systems can be compared. However, for the application of indicator models like the presented, the assembly structure for modeling by means of classes must already be designed in detail. Thus, the procedure starts after the concept-defining phase of structure planning. Furthermore, only interlinked assembly structures in the form of workstations, segments etc. connected in parallel or in series can be modeled, and matrix configurations are excluded.

From the review results, it can be concluded that existing cost and capacity-based approaches for flexibility assessment cannot be used for assembly structure planning since the required data is not available in this early planning stage. Additionally, approaches that require modeling a system's structure are insufficient, since the structure is still unknown during assembly structure planning and modeling all potential structures is inefficient. Therefore, this paper aims to develop an assessment model that compares a use case's requirements with the flexibility of flow-based assembly structures based on data available in the early stages of assembly planning. In this way, it contributes to the efficient and data-based evaluation, selection and planning of flow-based assembly structures from both a research and a practical perspective.

3. Flexibility Assessment Model

The flexibility assessment model is developed based on the literature review findings and under continuous reflection with a panel of assembly planning experts consisting of consortium partners of the research project *AIMFREE*. The user of the model specifies the flexibility requirements based on the defined criteria set using production program and process time data. The requirements are then assessed and compared with provided flexibility of flow-based assembly structures in a classification. The appropriate assembly structure alternatives for the analyzed use case are prioritized and design recommendations are derived.

The experts confirmed that from the hierarchy of KOSTE AND MALHOTRA, the relevant criteria for the specification of requirements for the assembly structure are on the plant tier. Additionally, from the available data during the early planning stages, production program and process time data have been identified as beneficial for quantifying flexibility requirements using these criteria. Table 1 shows the data sets that are required for the specification of the flexibility requirements. Reference scenarios and their relations are included, each describing representative sequences of production programs for short-term and long-term change to model requirements over multiple periods.

Table 1: Flexibility criteria for the specification of requirements

Criteria \ Data sets	Process time data of models and variants	Process time data of new products	Product mix scenarios	Short- term change of product mix	Long-term change of product mix	Short-term quantity scenarios	Long-term quantity scenarios
Product flexibility	**X**						
New product flexibility	**X**	**X**					
General product mix flexibility	**X**		**X**				
Short-term product mix flexibility	**X**		**X**	**X**			
Long-term product mix flexibility	**X**		**X**		**X**		
Volume flexibility						**X**	
Expansion flexibility							**X**

On the basis of the criteria and related data, the requirements and provided flexibility of assembly structure alternatives are compared. The alternatives that span the solution space of structure planning are provided in the classification for flow-based assembly structures in Table 2. The rows of the classification represent flexibility levels, each reflecting assembly structure alternatives. The levels are arranged according to increasing provided flexibility from the first level (low flexibility) to the highest (maximum flexibility). The columns of the classification contain the design dimensions of flow-based assembly structures, which comprise the essential components for structure planning. The cells contain characteristics that are assigned to the dimension of the column and are used in the level corresponding to the row. Thus, a level respectively an assembly structure alternative is composed of the combination of characteristics in a row.

Table 2: Classification of flow-based assembly structures

Levels	Design dimensions: Dimensionality of object routes	Synchronization principle of time	Mobility of the production resources
1	One-dimensional (Line)	Uniform cycle time	Stationary
2			Moving
3		Average cycle time	Stationary
4			Moving
5	Two-dimensional (Matrix)		Stationary
6			Moving
7		Expected operation time	Stationary
8			Moving
9		Reaction to assembly progress	Stationary
10			Moving
11		Expected operation time and reaction to assembly progress	Stationary
12			Moving

The data are evaluated using statistical methods to determine the flexibility requirements. The analysis focuses on assessing the heterogeneity of the underlying data as a measure for the required flexibility. Accordingly, the more heterogeneous the values in the data, the higher the flexibility requirements of the use case. For this purpose, the normalized process time difference is considered for product and new product flexibility. For general, short-term and long-term product mix flexibility, the global mean value is determined for each criterion on a cross-process basis, as well as the local mean value, the standard deviation and the minimum and maximum values on a process-specific basis. For volume and expansion flexibility, regression analyses are used for the development of the requirements over several periods. Discrete scales of the provided flexibility are defined with the experts for each design dimension of the classification as a function of the statistical key figures. Each graduation of the scales describes the provided flexibility of a dimension's characteristics. Thus, narrowly defined graduations are assigned to the characteristics with low provided flexibility and broadly defined are assigned to those with high. On this basis, the characteristics are prioritized separately for each dimension. For this purpose, the necessary flexibility resulting from the specified requirements is compared with the provided flexibility defined by the decision rules in form of the functions. The generated prioritizations for each dimension are then aggregated into recommended assembly structures. In the following the assessment of the requirements and the comparison with flexibility of assembly structure alternatives is shown in detail for each criterion.

Product flexibility examines the flexibility requirements that arises due to the process time heterogeneity between the product models. All models in the assembly system are compared with each other so that for each comparison between two, the relative difference of the individual process steps is calculated according to equation (1).

$$Dif_{i,j,p}^{Mod} = \frac{|Z_{i,p}^{Mod} - Z_{j,p}^{Mod}|}{max(Z_{i,p}^{Mod};Z_{j,p}^{Mod})} \; ; \; i \neq j \tag{1}$$

$Dif_{i,j,p}^{Mod}$	Relative process time difference between model i ϵ M and j ϵ M in process step p ϵ P
$Z_{i,p}^{Mod}$	Process time of model i ϵ M in process step p ϵ P
$Z_{j,p}^{Mod}$	Process time of model j ϵ M in process step p ϵ P
M	Models in the assembly system
P	Process steps of the assembly system

A matrix is generated by applying equation (1) to all model comparisons and process steps. While the columns contain the process steps, the rows contain each comparison between two models. The larger the values in the matrix are, the more significant is the process time heterogeneity and therefore the flexibility requirement. Intervals are defined based on the values to determine the necessary degree of flexibility. On the other side, provided flexibility of the characteristics of each dimension in the classification is defined by thresholds resulting from the functions. This means that the more flexible a characteristic is, the larger are the corresponding thresholds. The characteristics and the linked thresholds are encoded to enable automated processing. Those codes are integer values representing the respective characteristic's degree of flexibility. Therefore, the first level's characteristic is linked to the lowest integer value and top the level's to the highest one. The codes are then used to classify each matrix element reflecting the heterogeneity of the related process times. The elements are converted according to the intervals and assigned to one code. For each comparison between two models, i.e., each row of the matrix, the percentages of assignments to the codes are determined. Thereby each defined code holds a percentage regarding the considered model comparison. The percentages are accumulated, starting with the lowest degree of flexibility to the highest. Once the accumulated percentage exceeds a predefined threshold, the corresponding code respectively degree of flexibility is assigned to the model comparison. That leads to one degree of flexibility per model comparison and row. Based on that, the value of all model comparisons and therefore, the required degree of flexibility within the product flexibility is derived.

The analysis of new product flexibility is conducted in analogy to product flexibility. However, within this criterion, the expected process steps of new products are compared with those of existing products. It is assumed that new products in an assembly system basically share some of the properties of existing products and can be compared regarding identical, deviating, additional and omitted process steps. For this purpose, a similarity analysis is conducted. If there are few changes in process steps necessary to assemble the new product and if the process time heterogeneity is sufficiently low, the resulting flexibility requirement is minimal and vice versa. The latter condition is checked using a defined threshold.

Product mix flexibility analyzes process time heterogeneity of representative general, short- and long-term product mixes. Within general product mix flexibility, process time heterogeneity within each representative product mix is examined. Process time mean values and standard deviations of each process step and within each product mix are calculated. Using those parameters, scatter ranges representing the required flexibility are derived. The upper and lower bounds of the scatter ranges are calculated according to equation (2).

$$s_{psi,p}^{high/low} = MV_{psi,p} \pm \sigma_{psi,p} \tag{2}$$

$s_{psi,p}^{high/low}$	Upper/lower scatter range bound of process step p ϵ P in product mix scenario psi ϵ PS
$MV_{psi,p}$	Mean value of process step p ϵ P in product mix scenario psi ϵ PS
$\sigma_{psi,p}$	Standard deviation of process step p ϵ P in product mix scenario psi ϵ PS
PS	Representative product mix scenarios of the assembly system

The larger the ranges and the more these spread around the cross-mix mean value $MV_{psi,p}$, the greater the process time heterogeneity and therefore, the flexibility requirements. Analog to product flexibility, thresholds are formed within the product mix flexibility to assign the scatter ranges to the assembly structure alternatives' characteristics and their codes respectively. The thresholds are calculated as function of the cross-mix mean value and standard deviation. To evaluate the scatter ranges, they are compared with the thresholds of the intervals according to equations (3) and (4).

$$s_{psi,p}^{high} \leq G_c^{high} \tag{3}$$

$$s_{psi,p}^{low} \geq G_c^{low} \tag{4}$$

$G_c^{high/low}$	Upper/lower threshold of characteristic c ϵ C
C	Characteristics of the assembly structure alternatives

Equations (3) and (4) are checked for all characteristics, starting with lowest flexibility continuing to highest. A characteristic and the corresponding code are assigned once both inequations are fulfilled. Similar to product flexibility, a matrix is derived, which contains the assigned concepts in the form of their encoded values. The rows constitute the process steps while the columns comprise the representative product mixes. Each defined code holds a percentage regarding the considered mix comparison. The percentages are accumulated, starting with the lowest degree of flexibility to the highest analog to product flexibility. Once the accumulated percentage exceeds a predefined threshold, the corresponding code respectively degree of flexibility is assigned to the mix comparison. Based on that, the value of all mix comparisons and therefore, the required degree of flexibility within the general product mix flexibility is derived.

Short- and long-term product mix flexibility examine process time heterogeneity considering the change between mix scenarios. On the one hand side, short-term product mix flexibility focuses on the short-term change from one production program to another, for example within a daily or weekly period. Long-term product mix flexibility considers trend changes in the program over the long time horizon, such as within years, and therefore considers two or more mixes in a row representing a trend. The criteria compare different representative product mixes analyzing the changes in location and size of the scatter ranges of mean value and standard deviation in each process step. Therefore, the differences of the process specific mean values and standard deviations are calculated using equations (5) and (6). To classify the determined values, intervals are defined and linked to the characteristics in the classification. Similar to the abovementioned procedure, the determined values are assigned to the intervals. This results in matrices from which the flexibility requirements and the respective characteristics are derived.

$$\Delta MV_{psi,psj,p}^{short/long} = \frac{|MV_{psi,p} - MV_{psj,p}|}{\max(MV_{psi,p}; MV_{psj,p})} \tag{5}$$

$$\Delta \sigma_{psi,psj,p}^{short/long} = \frac{|\sigma_{psi,p} - \sigma_{psj,p}|}{\max(\sigma_{psi,p}; \sigma_{psj,p})} \tag{6}$$

$\Delta MV_{psi,psj,p}^{short/long}$	Difference between mean values of process step p in product mix scenarios psi and psj ϵ PS
$\Delta \sigma_{psi,psj,p}^{short/long}$	Difference between standard deviation of process step p in product mix scenario psi and psj ϵ PS

Volume and expansion flexibility are analyzed under consideration of output quantities since a system's scalability is decisive. Several short- and long-term quantity scenarios can be taken into account to consider different market developments and corresponding flexibility requirements. While volume flexibility considers the ability to alter the output quantities in the short-term, expansion flexibility takes long-term variations into account. Using the output quantities and relations indicated in the input data, short-term and long-term scaling coefficients are generated using linear regression analysis. These coefficients are assigned to predefined intervals which correspond to characteristics in the classification and were identified analyzing use case data sets including experts' experience. Depending on the use case, several output quantities can reflect different scenarios and therefore, several short- and long-term scaling coefficients. These are equally applied in determining the flexibility requirements of volume respectively expansion flexibility.

As mentioned above, the characteristics of the assembly structures in the classification are associated with codes that reflect their degrees of flexibility. These codes are utilized within each flexibility criterion in order to prioritize the characteristics and thereby derive the criteria specific design recommendation. Thus, a common reference is provided to aggregate the results and derive the overall design recommendation on the basis of the criteria weighting. The characteristics prioritized in this way for the three dimensions form the recommended assembly structures respectively levels in the classification.

4. Critical Reflection

The assessment model has been embedded in a software application for use in industry projects and for evaluation with the expert panel of the research project *AIMFREE*. The software requires entering the input data of the considered use case. Based on that, the application automatically calculates and determines the flexibility requirements. From this, design recommendations for the assembly structure are derived. The assessment model has been applied to several use cases utilizing related data sets for evaluation and improvement purposes.

In order to critically reflect and illustrate the application of the presented model in a practical context, the flexibility assessment and derivation of the design recommendation is exemplified by a use case that was carried out to verify the assessment model. The participating assembly planning experts knew neither the use case under consideration nor its implementation in reality and are therefore not biased. The use case of the aggregate manufacturer is characterized by many variants with partly high cycle compensation times, a highly seasonal order volume and a required annual output of 3,000 pieces. Concerning the mix of the two main models, a short-term change from 80/20 % to 20/80 % was defined as a requirement. In the following, the results of the application and the evaluation with the expert panel are presented focusing on the significant product and general product mix flexibility. The results of the assessment in Figure 1 and 2 show that the system consists of two segments characterized by different required flexibility. The left part of each figure refers to the first segment, whereas the right part refers to the second segment.

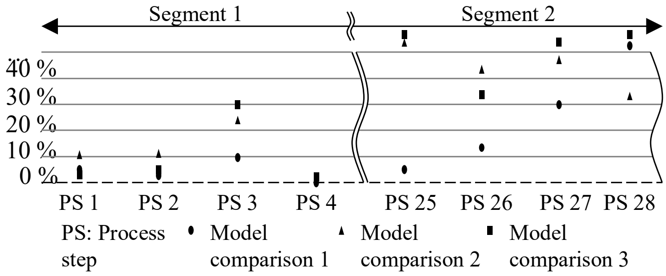

Figure 1: Results for the assessment of product flexibility

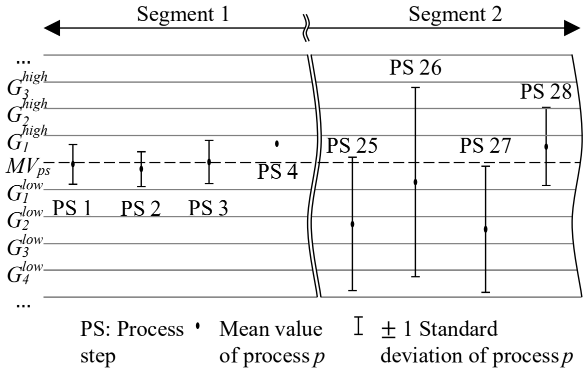

Figure 2: Results for the assessment of general product mix flexibility

Figure 1 highlights that in the second segment, the heterogeneity between the models is much more distinctive than in the first one. Therefore, a one-dimensional assembly system with an average cycle time and mobile production resources results as a criteria-specific design recommendation for the first segment. For the second segment, highly flexible structure alternatives result as criteria-specific design recommendation from the high required flexibility. A similar result is achieved for general product mix flexibility in Figure 2. The figure shows that the scatter ranges in the first segment are significantly smaller than those in the second one. In addition to that, the scatter ranges are close to the cross-scenario mean value in the first segment, while the second ones are less centred and accordingly more heterogeneous. The aforementioned thresholds have been established in Figure 2 in the form of horizontal lines representing the comparison of required and provided flexibility. Due to that, for the first segment, a one-dimensional assembly system with uniform cycle time and mobile production resources results as a criteria-specific design recommendation. For the second segment, a two-dimensional control-based assembly system with mobile production resources follows as a criteria-specific design recommendation.

Before the application of the assessment model, the expert panel manually analyzed the requirements and data of the use case coming to the conclusion that segmenting the assembly system into two sequential sub-systems is promising as those strongly differ in terms of required flexibility. The experts considered a clocked assembly line appropriate for the first segment and a flexible respectively matrix assembly structure for the second one. This consideration was kept secret while applying the assessment model to the use case to later compare the results. In summary, the application of the assessment model delivered a similar design recommendation as the assembly planning experts but additionally provided a rationale using the assessment results. By doing so, the segmentation point between the segments was confirmed.

During the application of the assessment model for evaluation, it became evident to the supervising experts that especially the quantitative assessment of the flexibility requirements proved to be of significant help for structure planning. The objective connection between available production planning data and the derived recommendation strongly supported transparency of the prioritization of alternatives and related decision-making. The comments of the experts proved that utilizing the assessment model focuses the discussion on the most relevant aspects for planning an assembly structure. The model delivers appropriate as well as valuable recommendations efficiently since for generating a similar recommendation result, only a fraction of the time compared to the manual approach of the experts was required.

5. Conclusion and Outlook

Given increasing cycle time spreads and efficiency losses, assembly planners face the challenges of developing alternatives to conventional line assembly that enable flexible and at the same time efficient production. The decoupling of workstations and dissolving the cycle time constraint within matrix assembly systems has the potential to overcome these challenges. Thus, the presented work focuses on developing an assessment model for the requirement-led planning of flow-based assembly structures. The model enables the planner to determine the use case-specific flexibility requirements based on data and efficiently prioritize respectively select the appropriate assembly structures for further consideration in the further planning stages of capacity planning and performance simulation. An interdisciplinary panel of experts accompanied the model development and evaluation underlining the benefits of the practical application in industry use cases. The evaluation confirmed the advantageousness of the assessment model in comparison to existing and manual approaches underlining the gain in efficiency and transparency when it comes to the data-driven specification of flexibility criteria and determination of the appropriate assembly structures. During the reflection, further research questions and potential extensions were identified. Additional research is beneficial in the sensitivity analysis of the parameters and interval values included in the model. Moreover, the integration of the model into a fully comprehensive assembly planning procedure is advantageous.

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References

[1] Hottenrott, A., Grunow, M., 2019. Flexible layouts for the mixed-model assembly of heterogeneous vehicles. OR Spectrum 41 (4), 943–979.

[2] Gaal, A., Hofer, K., Ryback, T., Lingitz, L., Sihn, W., 2020. An agent-based approach to planning and controlling adaptable cell-oriented assembly systems. Procedia CIRP 93, 1158–1163.

[3] Mayer, S., Höhme, N., Gankin, D., Endisch, C., 2019. Adaptive Production Control in a Modular Assembly System - Towards an Agent-based Approach, 2019 IEEE 17th International Conference on Industrial Informatics (INDIN), Helsinki, Finland, 22.07.2019 - 25.07.2019, 45–52.

[4] Greschke, P., Schönemann, M., Thiede, S., Herrmann, C., 2014. Matrix Structures for High Volumes and Flexibility in Production Systems. Procedia CIRP 17, 160–165.

[5] Liu, C., Li, W., Lian, J., Yin, Y., 2012. Reconfiguration of assembly systems: From conveyor assembly to serus. Journal of Manufacturing Systems 31 (3). 312–325

[6] Burggräf, P., Dannapfel, M., Adlon, T., Kahmann, H., Schukat, E., Keens, J., 2020. Capability-based assembly design: An approach for planning an agile assembly system in automotive industry. Procedia CIRP 93, 1206–1211.

[7] Hüttemann, G., 2021. Model-based a priori analysis of line-less mobile assembly systems. Doctoral thesis, RWTH Aachen University.

[8] Kern, W., Lämmermann, H., Bauernhansl, T., 2017. An Integrated Logistics Concept for a Modular Assembly System. Procedia Manufacturing 11, 957–964.

[9] Wiendahl, H.-P., ElMaraghy, H., Nyhuis, P., Zäh, M., Wiendahl, H.-H., Duffie, N., Brieke, M., 2007. Changeable Manufacturing - Classification, Design and Operation. CIRP Annals 56 (2), 783–809.

[10] Göppert, A., Schukat, E., Burggräf, P., Schmitt, R. H., 2021. Agile Hybrid Assembly Systems: Bridging the Gap Between Line and Matrix Configurations, in: Weißgraeber, P., Heieck, F., Ackermann, C. (Eds.), Advances in Automotive Production Technology, 3–11.

[11] Bäumers, Y., 2017. Wirtschaftlicher Detaillierungsgrad der Montageablaufplanung. Doctoral thesis, RWTH Aachen University.

[12] Slama, S., 2004. Effizienzsteigerung in der Montage durch marktorientierte Montagestrukturen und erweiterte Mitarbeiterkompetenz. Bamberg, Meisenbach.

[13] Vom Brocke, J., Simons, A., Niehaves, B., Riemer, K., 2009. Reconstructing the Giant - On the Importance of Rigour in Documenting the Literature Search Process, in: Proceedings of the 17th European Conference on Information Systems, 3226–3238.

[14] Sethi, A. K., Sethi, S. P., 1990. Flexibility in Manufacturing: A Survey. The International Journal of Flexible Manufacturing Systems (2), 289–328.

[15] Perez Perez, M., Serrano Bedia, A. M., Concepcion Lopez Fernandez, M., 2016. A review of manufacturing flexibility: systematising the concept. International Journal of Production Research (54), 3133–3148.

[16] Beach, R., Muhlemann, A.P., Price, D. H. R., Paterson, A., Sharp, J. A., 2000. A review of manufacturing flexibility. European Journal of Operational Research (122), 41–57.

[17] Bochmann, L. S., 2018. Entwicklung und Bewertung eines flexiblen und dezentral gesteuerten Fertigungssystems für variantenreiche Produkte. Doctoral thesis, ETH Zürich.

[18] Van De Ginste, L., Goos, J., Schamp, M., Cleays, A., Hoedt, S., Bauters, K., Biondi, A., Aghezzaf, E., Cottyn, J., 2019. Defining Flexibility of Assembly Workstations Through the Underlying Dimensions and Impacting Drivers. International Conference on Production Research Manufacturing Innovation: Cyber Physical Manufacturing (25), 975–977.

[19] Koste, L. L., Malhotra, M. K., 1999. A theoretical framework for analyzing the dimensions of manufacturing flexibility. Journal of Operations Management (18), 75–93.

[20] Klemke, T., Mersmann, T., Wagner, C., Goßmann, D., Hyhuis, P., 2011. Bewertung und Gestaltung der Wandlungsfähigkeit von Produktionssystemen. ZWF (106), Carl Hanser Verlag München, 922–927.

[21] Harari, N.S., Fundin, A., Carlsson, A.-L., 2020. A Participatory Research Approach for studying the Design Process of Flexible Assembly Systems. CIRP Conference of on Manufacturing Systems (53), 1043–1048.

[22] Rogalski, S., Ovtcharova, J., 2009. Flexibilitätsbewertung von Produktionssystemen. ZWF (104), Carl Hanser Verlag München, 64–70.

[23] Schuh, G.; Gulden, A.; Wemhöner, N.; Kampker, A., 2004. Bewertung der Flexibilität von Produktionssystemen - Kennzahlen zur Bewertung der Stückzahl-, Varianten- und Produktänderungsflexibilität auf Linienebene, In: wt Werkstatttechnik online, 94 (6), 299–304.

Biography

Nils Föhlisch (*1992) is research associate at the Department of Factory Planning at the Laboratory for Machine Tools and Production Engineering WZL of RWTH Aachen University since 2019.

Prof. Dr.-Ing. Peter Burggräf (*1980) is scientific head of the Department of Factory Planning at the Laboratory for Machine Tools and Production Engineering WZL of RWTH Aachen University and has been head of the Institute of International Production Engineering and Management at the University of Siegen since 2017.

Tobias Adlon (*1989) is chief engineer of the Department of Factory Planning at the Laboratory for Machine Tools and Production Engineering WZL of RWTH Aachen University since 2020.

Christopher Kapella (*1995) was a master thesis student and student research assistant at the Laboratory for Machine Tools and Production Engineering WZL of RWTH Aachen University.

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Concept For Data-Based Sales And Resource Planning For Re-Assembly In The Automotive Industry

Günther Schuh[1,2], Seth Schmitz[1], Marco Schopen[1], Henning Neumann[1]
[1]*Laboratory for Machine Tools and Production Engineering (WZL) of RWTH Aachen University, Aachen, Germany*
[2]*Fraunhofer Institute for Production Technology IPT, Aachen, Germany*

Abstract

In linear economy, the growing wealth in the world is linked to a growing resource consumption and greenhouse gas emission. This results in a shortage of primary resources, environmental destruction through resource extraction, and global warming. A high productivity of the manufacturing industry, overcapacities and a decrease in the value of existing products intensify this situation. Circular economy offers resource-efficient value addition by multiple utilization of resources. One challenge in this form of value creation is the duration of reconditioning processes and the lack of product innovation in reconditioned products. To bring products back to the market as quickly as possible, the method of Re-Assembly is introduced and focused in this paper. Re-Assembly can be defined as reconditioning old products into new or higher-valued products, by assembling new or remanufactured parts and components after disassembly. However, manufacturing companies face difficulties in industrialization of such methods. In practice, one of the biggest challenges is the mid- and long-term planning of the reconditioning process. Due to uncertainties in the quality and quantity of the returning end-of-life products the resulting reconditioning process is challenging to predict in terms of process time and production costs. To encounter this, this paper presents a concept for sales and resource planning in the context of Re-Assembly. In the first step the uncertainties for the long term production planning and the resulting data requirements are identified. Based on this, a concept for sales and resource planning is presented. The approach is based on the Internet of Production reference framework and includes data from the whole product lifecycle. As the area of application, the automotive industry is chosen as it is the largest manufacturing industry in Germany and already leading in the recording of usage data of their products.

Keywords

Production Planning; Sales Planning; Circular Economy; Re-Assembly; Internet of Production

1. Introduction

Since the beginning of industrialization, raw materials have been consumed to produce products that are disposed at the end of their life. Among other things, this causes environmental pollution and biodiversity loss. In addition to these threatening aspects, this linear economy leads to many social problems such as land displacement and forced relocation of the population. [1] The circular economy seeks to counter the challenges of linear economy and bring the economic system into a cycle by decoupling economic growth from finite resources and returning used products to the user cycle. It also aims to use renewable energy, minimize toxic chemicals, and eliminate produced waste. [2] In order to reuse products that have already been disposed, strategies have been developed that can be summarized in a so-called *9R Framework*. This framework includes strategies such as reuse, remanufacturing and recycling. One of the central strategies is remanufacturing, which is characterized by an extended value creation opportunity and at the same time is

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more resource-efficient than recycling [3,4]. For the automotive industry, remanufacturing offers the possibility of attractive product differentiation in an already competitive and saturated market. Several Original Equipment Manufacturers (OEM) are already using the remanufacturing method to recondition spare parts and offer them as an alternative to newly produced spare parts [2]. Completely remanufactured vehicles have not been offered in large quantities yet. This is due to challenges associated with the transition to the circular economy and remanufacturing-specific uncertainties. Remanufacturing is characterized by various uncertainties, for example in the quality and availability of the cores as well as the processes needed for the reconditioning, that complicates the resource planning in particular [5]. Also the sales planning is facing new challenges for example product cannibalization, which means the drop in sales of a product that results from the introduction of a remanufactured product from the same company, brand or product line [6].

To enable the remanufacturing of complete vehicles, a new type of remanufacturing the Re-Assembly is introduced in this paper. In the following chapter related literature from the sales and resource planning in remanufacturing is presented and research gaps are identified. Chapter 4 presents the concept for a databased and integrated sales and resource planning for the remanufacturing industry using the reference architecture of the Internet of Production (IoP).

2. Theoretical Background

In the circular economy technological processes are differentiated in the R-Strategies such as recycling or remanufacturing. A broad variety of definitions for these strategies ranging from four to nine different methods is given in the literature. KIRCHHERR ET AL. give an overview of different definitions of these strategies and the circular economy [3]. The strategies differentiate in their circularity as well as in the possible innovation of the reconditioned product. Circularity is defined by a set of circularity indicators. A higher circularity means a lower resource consumption and more benefits for the environment. Contrary to the higher circularity, the possible innovation in the reconditioned product is lower with a higher circularity. For example the possible innovation reached by a new product made of recycled material is higher than the possible innovation in repairing a used product [7].

Remanufacturing is a key strategy in this context. An industrial remanufacturing process is used to recondition old parts, so-called cores, to as-new or upgraded condition. This involves the steps of inspection, disassembly, reconditioning, Re-Assembly and final testing. [8] The process allows to add new innovations to products during the remanufacturing process. Challenges for this strategy are the time that products are taken off the market for the reconditioning processes and an increasing complexity of the process with more complex products. To reduce the complexity and the off-market-time the method of Re-Assembly is proposed. The Re-Assembly process consists of the disassembly of modules of the product and the assembly of either new, remanufactured or upgraded modules. Extracted old modules can either be reconditioned in a separate process by the same manufacturer (e.g. an OEM in the automotive industry) or a supplier for the module. The product itself is send back to the market with the changed modules without the delay of the reconditioning process. Also the Re-Assembly processes allows to upgrade the product with new innovations which were developed after the first sale of the product. This enables the manufacturer to increase the value of the product. To enable and accelerate this strategy of the circular economy a precise planning is needed which is discussed in this paper.

The sales planning describes the process of planning how many products of a specific product type will be sold in a defined time period. This information is used in the resource planning to validate if the production is capable of producing the products from the sales planning. Especially in the area of remanufacturing these methods need to be integrated with the core-acquisition. Core acquisition is defined as the active management of core sourcing, to achieve a better balance between return of cores and demand for remanufacturing. [6]

3. Related Work

This chapter presents recent work and concepts of sales and resource planning in the field of remanufacturing and refurbishment as the closest R-strategies to the new concept of Re-Assembly.

WALTHER gives an overview of the sales and production planning for products and components. The process is divided into the three components *product reconditioning*, *component reconditioning*, and *disposal*. An integrated model is used to describe the interactions between the components and is exemplarily applied to a vending machine manufacturer. The model does not integrate the demand of the reconditioned product nor upgrades or other technological innovation. [6]

NADAR ET AL. develop a dynamic model to describe the sales planning problem of a company with combined sales of new and remanufactured products. Demand in the model is described by a modified Bass Diffusion Process. The authors concluded, that depending on the sales scenario a partial fulfilment of the demand can lead to a profit optimization even though, there are no constraints for new-item manufacturing. The model does not integrate the possibility to update products or products with a longer lifespan such as cars. [9]

MATSUMOTO AND IKEDA assess the quality of demand forecasting by time series analysis in remanufacturing and propose a forecasting method including expert knowledge. The developed method is mainly for independent remanufacturers with incomplete information regarding the sales numbers of new products. As a result the authors distinguish between three different curves based on their trend behaviour and propose a forecasting method for each of these categories. To distinguish between these types of curves the authors recommend the involvement of human experts. The developed method does neither include the number of available cores nor the difference in quality of remanufactured or upgraded parts. [10]

MUTHA ET AL. present a core acquisition strategy for independent remanufacturers to optimize their costs during core acquisition. In their work they model two difference scenarios, one scenarios includes the acquisition of bulk of cores with a random quality and therefore a random cost for the remanufacturing process. The other scenario includes the acquisition of cores with a certain quality level but a higher price. Using the model, the authors propose a strategy to buy cores with an uncertain quality in the first period to minimize the acquisition cost under uncertain demand and change to a reactive acquisition of higher quality cores from the second period on. [11]

YANG ET AL. develop different methods to optimize the core-acquisition-process under incomplete information regarding the core quality. The paper is motivated by the missing historical data of the available cores in the market. The quality level is therefore often explained by discrete quality levels for the products and forecasted using nominal or asymptotic distributions. The authors develop two linear models to minimize the cost of bad quality cores. Even though the models work in the proposed way, the authors conclude, that the main part of the costs can just be minimized by using a multisource information fusion method to receive a more realistic distribution of the core quality to close the gap between the estimated and real quality distribution. [12]

The presented approaches from the literature each include solutions for a specific area in resource and sales planning using analytical methods and data from the past. An exception is YANG ET AL who propose the usage of multisource information. This approach is just used in the specific application and does not take into account the integrated planning of sales and resources which is needed for remanufacturing [6]. Therefore an approach to combine the usage of multisource real-time data in the integrated planning is missing.

4. Concept for databased sales and resource planning for Re-Assembly in the automotive industry

The following chapter is presenting a concept for databased and integrated sales and resource planning which minimizes the impact of the uncertainties from Re-Assembly. To lower the information uncertainty in sales and resource planning databased methods have been proven to be a solution.

The IoP reference architecture can be used to combine different data sources and IT-systems from various domains and lifecycle phases. The IoP is divided into three cycles of the products lifecycle: development-cycle, production-cycle and user-cycle [13]. Due to its capability to aggregate data from the usage phase of a product as well as from the production IT-systems it is ideally suited to support the decision making process in a circular economy. A major part in the IoP are Digital Shadows, which consist of data provision, analysis methods and information requirements. The different levels of the digital shadow can be seen in Figure 1. Goal of the digital shadow is to provide information needed for a decision in the production environment by aggregating and analysing data from multiple data sources. [14]

Especially the production planning and control (PPC) in the automotive remanufacturing is challenging due to uncertain information. [5] To overcome these challenges the uncertainties need to be identified and analysed. For this case an identification process is used. From the uncertainties the data needs for the planning method are derived. The concept can be seen in Figure 1. After introducing the process for uncertainty identification, the following chapter describes the three main components of the digital shadow in detail.

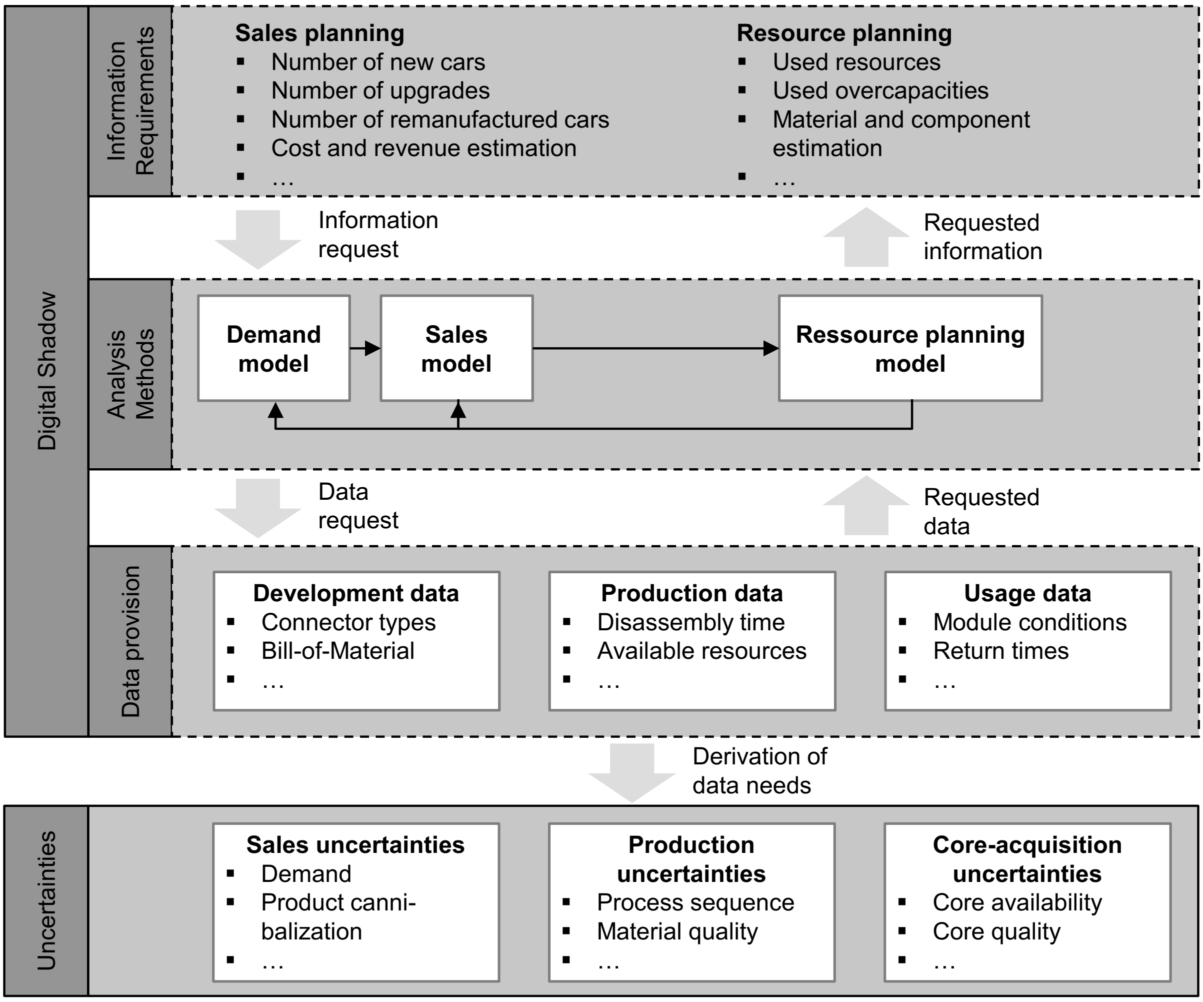

Figure 1: Concept of the digital shadow for sales and resource planning in Re-Assembly

4.1 Identification of uncertainties in Re-Assembly

The identification process is shown in Figure 2. In the first step of the method uncertainties are identified using a literature review in common scientific research databases. The titles and abstracts of the found literature are screened, filtered and the relevant literature is analysed.

Figure 2: Method for the identification of uncertainties

The second step consists of interviews with experts from industry regarding uncertainties in their remanufacturing and service system. These interviews can be conducted by using expert-workshops to receive information about uncertainties from the practical day to day work in the remanufacturing industry.

The third step is the categorization of the identified uncertainties in the main areas of the sales and resource planning in the remanufacturing industry. In the linear economy this planning is done in the close exchange between the sales and production department. Due to integrated planning of the core acquisition this category is also added to the categorization [15]. Next to this three categories the external uncertainties following the PESTEL (political, economic, social, technological, ecological and legal) criteria [16] are also added to the framework to include fundamental external uncertainties. Figure 3 gives an overview of the framework.

During the categorization of the identified uncertainties the framework is further detailed to ensure a better understanding of the uncertainties. The sales category was split up into the categories *quantitative* and *qualitative*. The quantitative uncertainties include the demand of remanufactured products [17] and the reduction of the total cost of ownership for the customer [5]. Qualitative uncertainties are for example the customers perception of the quality of remanufactured products [18]. Core Acquisition is split up into the four categories *quality*, *quantity*, *cost* and *time* of the cores. These categories are also proposed by WEI ET AL. [15]. The production uncertainties can be divided into elementary factors of production [19] and the different steps of a remanufacturing process following for example OKORIE ET AL. [20] to identify critical process steps.

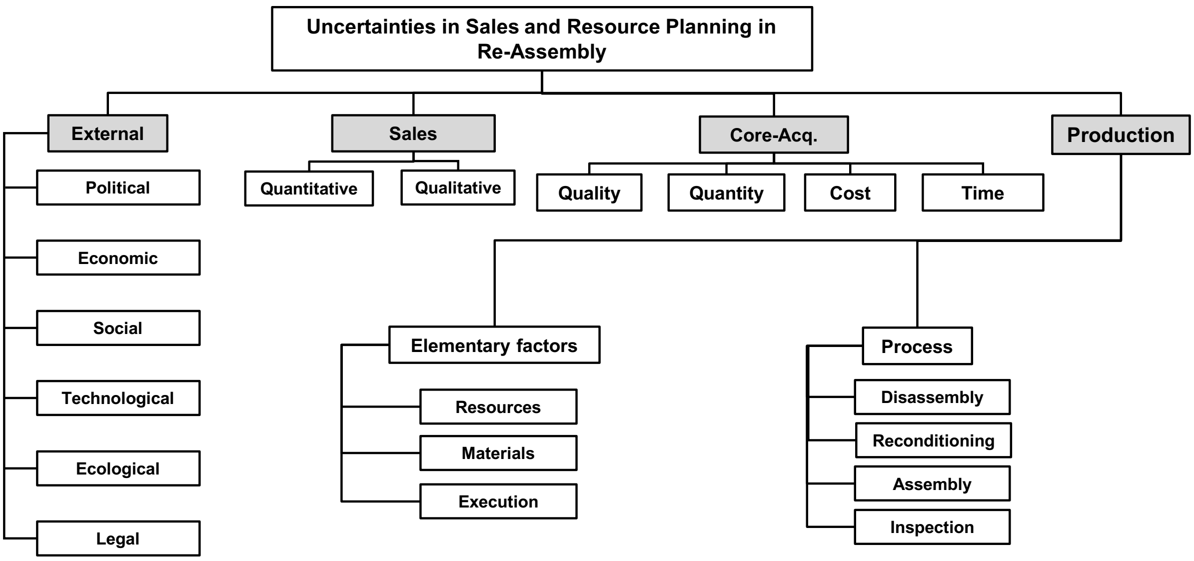

Figure 3: Detailed framework for the categorization of uncertainties in Re-Assembly

4.2 Data provision in the digital shadow

In accordance with the reference architecture of the IoP, the data provision is based on data from the development, production and user-cycle of the vehicles. To identify the data requirements for the use case the uncertainties identified as described in chapter 4.1 as well as the data requirements for a sales and resource planning in the linear economy can be used. Using the categories described in chapter 4.1 the relevant uncertainties for the sales planning can be taken from the sales and core acquisition branch. Therefore not all uncertainties need to be inspected. However the identified data from this step needs to be modelled in a data model to give an overview of the elements and their relations [14]. It is noticeable, that much of the data used is produced in the user-cycle and might be provided by the aftersales department or external market research-agencies. The planning will be done in discrete time periods which can for example be defined as one month or one quarter.

The data needs for the resource planning can be derived analogue to the sales planning from the uncertainties identified in the categories of production and core acquisition. The core acquisition is also needed in this step to make sure the resource demand can be identified based on the availability and condition of the core. The data from the production and the capacities can either be extracted from the Manufacturing Execution System (MES) or the Enterprise Resource Planning (ERP) System and is assigned to the production cycle. Data regarding the condition of the cores can be extracted from a storage connected to the controller area network (CAN-Bus) or independent sensors in the vehicle. The used data might range from the mileage of the car to specific vibration data from the drive train.

4.3 Analysis methods

The first step in the analysis level of the digital shadow is the data pre-processing to structure and aggregate the data from the data provision in a way they can be used by the analysis models [14]. This pre-processing step can also be used to bring the data in a storage where different stakeholders from the circular economy can access them. An example for such a data structure is the digital product data pass as proposed by the European Union [21]. Further, the pre-processed data is used by the different models which interact with each other for the combined planning of sales and resource planning. The models and their interaction is shown in Figure 4.

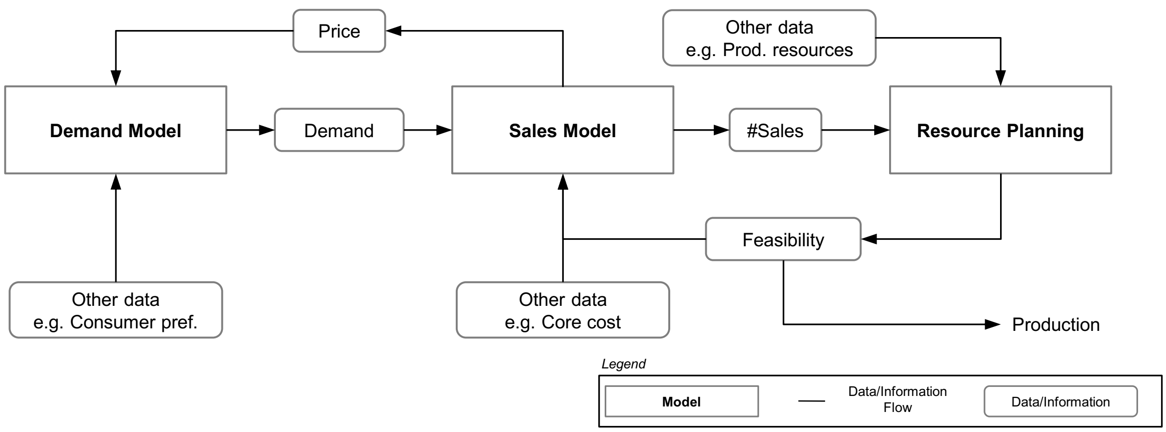

Figure 4: Models of the analysis method

In order to create the sales plan, it is first necessary to determine the demand for vehicles in the market. This estimation can take place, for example, via the customer behaviour on the market and the possible vehicles offered. A demand model that can be assigned to the category of consumer behaviour, but also takes aspects from the other categories, is the overall market model according to [22]. Especially the discrete choice model is included in the overall market model. The model is characterized by the fact that both the demand for individual vehicle models and the demand for different segments can be determined using a product space to describe the vehicles. This product room of the model can be extended with Re-Assembly specific properties such as technical upgrades and number of previous owners.

The demand specified by the demand model serves as the basic input for the sales model, which is intended to formulate profit-optimized sales for a vehicle model and the associated remanufacturing variant. Thus, the inherent factors of remanufacturing must be taken into account. While product cannibalization is already addressed in the demand model, sales planning should reduce uncertainties regarding core availability. Uncertainties in the case include the timing and volume of core returns as well as the quality of the returning cores. The sales model aims to optimize vehicle sales for profit over several periods. Therefore, the model has a dependency on the time dimension. For a consistent overall planning, the observation frame is adopted from the overall market model. Thereby, all vehicles to be sold are sold at the end of a period and produced or refurbished in the same period. Planning over several periods means that optimization can also take into account the sale of new vehicles for holding cores in subsequent periods.

To validate the feasibility of the proposed sales program from the sales model a resource planning model is needed. This model optimizes the production resource usage under the restrictions given by the production capacities. The resource planning need to be done under uncertainty in the duration and sequence of process steps as identified in chapter 4.1. Such models which can handle uncertainty in resource planning are already established for the optimization of production programs in the linear economy with uncertainties in the demand [23]. These models must be extended and tested to include the specific properties of Re-Assembly. If the model determines that the proposed production program is not feasible even with capacity expansion, alternative sales programs must be identified and validated by adjusting the sales planning conditions.

4.4 Information requirements

The information requirements for the sales and resource planning in Re-Assembly include the information requirements from the linear planning as described in [24]. Next to this information also Re-Assembly specific information is needed. This information includes, for example, the number and type of upgrades to be performed and the sale of remanufactured vehicles. Another important information that is needed in the planning is the number of cores in the different quality levels which need to be procured to realize the sales plan even with uncertainties in the quality level of the cores.

5. Summary and outlook

The implementation of a circular economy is necessary for economic, ecological and social reasons. In the implementation of the paradigm, Re-Assembly offers an innovative approach to minimize the reconditioning times of complex products and thus maximize the time products are used during their lifetime. However, the methodology encounters a number of uncertainties that hinder the planning and implementation.

In this work, the uncertainties for Re-Assembly were systematically identified and assigned to the individual planning and implementation steps using a classification method. Based on the identified uncertainties, a concept for data-based sales- and resource-planning was presented. This concept is based on the structure of a digital shadow in the reference architecture of the IoP. The core of the concept is represented by three interfering models for demand-, sales- and resource-planning, which are used to cover the information requirements.

In further research, the components of the digital shadow need to be detailed and tested on real data. For this purpose, it is also suitable to use data from the long-established supplier market for automotive components, since remanufacturing as a superordinate strategy of Re-Assembly has been widespread in this market for a long time.

Acknowledgement

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References

[1] Umweltbundesamt, 2021. Ressourcennutzung und ihre Folgen. https://www.umweltbundesamt.de/themen/abfall-ressourcen/ressourcennutzung-ihre-folgen. Accessed 30 May 2022.

[2] MacArthur Foundation, 2013. Towards the Circular Economy: Economic and business rationale for an accelerated transition. Accessed 15 August 2022.

[3] Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the circular economy: An analysis of 114 definitions. Resources, Conservation and Recycling 127, 221–232.

[4] Potting, J., Hekkert, M., Worrell, M., Hanemaaijer, A., 2016. Circular Economy: Measuring innovation in the product chain. PBL Netherlands Environmental Assessment Agency, Den Haag.

[5] Kamper, A., Triebs, J., Hollah, A., Lienemann, C., 2019. Remanufacturing of electric vehicles: Challenges in production planning and control. Procedia Manufacturing 33, 280–287.

[6] Walther, G., Spengler, T.S. (Eds.), 2010. Nachhaltige Wertschöpfungsnetzwerke: Überbetriebliche Planung und Steuerung von Stoffströmen entlang des Produktlebenszyklus. Zugl. Braunschweig, Techn. Univ., Habil.-Schr., 2009, 1. Aufl. ed. Gabler, Wiesbaden, 304 pp.

[7] Potting, J., Hekkert, M., Worrell, E., Hanemaaijer, A., 2017. Circular economy: Measuring innovation in the product chain.

[8] Lange, U., 2017. Ressourceneffizienz durch Remanufacturing- Industrielle Aufarbeitung von Altteilen: Kurzanalyse. VDI ZRE Publikationen (18).

[9] Nadar, E., Kaya, B.E., Güler, K., 2020. New-Product Diffusion in Closed-Loop Supply Chains. M&SOM 23 (6), 1413–1430.

[10] Matsumoto, M., Ikeda, A., 2015. Examination of demand forecasting by time series analysis for auto parts remanufacturing. Jnl Remanufactur 5 (1), 1–20.

[11] Mutha, A., Bansal, S., Guide, V.D.R., 2016. Managing Demand Uncertainty through Core Acquisition in Remanufacturing. Prod Oper Manag 25 (8), 1449–1464.

[12] Yang, C.-H., Ma, X., Talluri, S., Ivanov, D., 2022. Optimal Core Acquisition and Remanufacturing Decisions With Discrete Core Quality Grades. IEEE Trans. Eng. Manage., 1–20.

[13] Schuh, G., Prote, J.-P., Gützlaff, A., Thomas, K., Sauermann, F., Rodemann, N., 2019. Internet of Production: Rethinking production management, in: Wulfsberg, J.P. (Ed.), Production at the Leading Edge of Technology. Proceedings of the 9th Congress of the German Academic Association for Production Technology (WGP), September 30th - October 2nd, Hamburg 2019. Springer Berlin / Heidelberg, Berlin, Heidelberg, pp. 533–542.

[14] Schuh, G., Gützlaff, A., Schmidhuber, M., Maibaum, J., 2021. Development of Digital Shadows for Production Control. Hannover : publish-Ing, 10 pp.

[15] Wei, S., Tang, O., Sundin, E., 2015. Core (product) Acquisition Management for remanufacturing: a review. Jnl Remanufactur 5 (1).

[16] Issa, T., Chang, V., Issa, T., 2010. Sustainable Business Strategies and PESTEL Framework. GSTF International Journal on Computing 1 (1), 73–80.

[17] Angkiriwang, R., Pujawan, I.N., Santosa, B., 2014. Managing uncertainty through supply chain flexibility: reactive vs. proactive approaches. Production & Manufacturing Research 2 (1), 50–70.

[18] Östlin, J., 2008. On Remanufacturing Systems: Analysing and Managing Materal Flows and Remanufacturing Processes.

[19] Gutenberg, E., 1983. Grundlagen der Betriebswirtschaftslehre: Die Produktion, 24., unveränd. Aufl. ed. Springer, Berlin, Heidelberg, 521 pp.

[20] Okorie, O., Salonitis, K., Charnley, F. Remanufacturing and refurbishment in the age of Industry 4.0: an integrated research agenda, in: , Sustainable Manufacturing, pp. 87–107.

[21] Jahnz, A., Gospodinova, S., Stoycheva, D., Miccoli, F., 2022. Green Deal: New proposals to make sustainable products the norm and boost Europe's resource independence, Brussels, 4 pp.

[22] Eggert, W., 2003. Nachfragemodellierung und-prognose zur Unterstutzung der langfristigen Absatzplanung am Beispiel der deutschen Automobilindustrie, Karlsruhe.

[23] Herrmann, F., 2022. Lineare Optimierung unter Unsicherheit: Eine Einführung, 1st ed. 2022 ed. Springer Fachmedien Wiesbaden; Imprint Springer Gabler, Wiesbaden, 305 pp.

[24] Schuh, G., 2012. Produktionsplanung und -steuerung 1: Grundlagen der PPS, 4th ed. Springer Verlag.

Biography

Günther Schuh (*1958) holds the Chair of Production Systems at the Laboratory for Machine Tools and Production Engineering WZL at RWTH Aachen University, is a member of the board of directors of the Fraunhofer Institute for Production Technology IPT and director of the Research Institute for Rationalization (FIR) at the RWTH Aachen.

Seth Schmitz (*1991) studied Business Administration and Engineering specializing in Mechanical Engineering at the RWTH Aachen University and Tsinghua University. He is Head of the Production Management Department at the Laboratory for Machine Tools and Production Engineering WZL at RWTH Aachen University.

Marco Schopen (*1993) studied Business Administration and Industrial Engineering at University of applied Sciences Aachen. He is Team Lead Process Management in the Production Management department at the Laboratory for Machine Tools and Production Engineering WZL at RWTH Aachen University.

Henning Neumann (*1996) is research assistant at Laboratory for Machine Tools and Production Engineering (WZL) of RWTH Aachen University in the Process Management group of the Production Management department since 2020. He studied industrial engineering with a specialization in mechanical engineering at RWTH Aachen University.

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Critical Conditions For Factory Ramp-Up Planning In SMEs

Maria Thomassen[1], Lars Skjelstad[1]
[1]*SINTEF Digital, Trondheim, Norway*

Abstract

Companies experiencing rapid sales growth need to ramp-up operations and production facilities to meet the increased customer demand. Exporting small and medium sized companies (SMEs) offering new technology in new markets often have to deal with high uncertainty and risk and the ramp up plan needs to be continuously adjusted to changing sales forecasts. Factory planning is a complex task, and includes a wide range of critical decisions. The literature is mainly dominated by research seeking to develop theoretical models and methods for planning support. There is limited empirical research addressing issues related to the actual planning process. Existing methods are mainly developed based on general theoretical terms without taking specific conditions into account. Further research is therefore needed to better adapt current models and methods to specific contexts. This study seeks to bring further understanding of critical conditions for the planning process, by exploring the conditions of the planning process in a real-life context of an SME. The findings are expected to contribute to improved insights to the factory ramp-up planning process in SMEs and better understanding of critical factors that need to be considered.

Keywords

Planning context; Factory planning; SME; Production ramp-up; Case study

1. Introduction

Factory planning is a critical process for companies experiencing sales growth and increasing production volumes. Due to dynamic world market conditions, manufacturing companies that participate in global trade often face challenges when making decisions related to factory expansion and production ramp-up. Factory planning may be a complex task, especially for fast growing small and medium sized enterprises (SMEs), which often have limited financial resources and competence. This is because factory planning often involves a wide range of critical decisions, where multiple factors need to be considered making the decision process complex [1]. Market uncertainty, related to the timing and rate of sales growth for instance, may add to the complexity of the planning situation.

A significant amount of models and frameworks providing decision support in factory planning are available in existing literature, see literature reviews by [2], [3] and [4]. Structured and systematic approaches are proposed as well as sophisticated methods that are adjusted to specific decisions, e.g. investment in capacity expansion [5]. The factory planning literature is mainly dominated by research seeking to develop theoretical models and methods for planning support. There is limited research addressing issues related to the planning process and empirical studies. Further research is therefore needed to better adapt current models and methods to specific contexts [1]. Also, researchers especially call for further case study investigations in a variety of situations for a better understanding of application of models in industry [5].

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The importance of context for the factory planning process and adoption of planning methods and models is widely recognized in current literature. For example, Glock and Grosse [3] emphasize the need to take specific characteristics of ramp up situations into consideration, including factors such as interruptions, uncertainty, defects, learning and demand growth. Traditional factory planning approaches are further criticized for providing limited support in terms of process adaptability and flexibility, which is required to handle changes during planning projects, nor consider specific requirements of factory planning projects [6]. More dynamic approaches such as condition based factory planning (CBFP) are developed to meet the need for more flexible and adaptable planning processes [7]. Factory planning in an SME context is considered to be especially challenging, since these companies do not typically follow a standardised factory planning procedure but rather a pragmatic, unstructured approach [8].

Even though the importance of context and external conditions are recognized in previous research, studies addressing factory planning issues rarely take contextual factors into account. Therefore, this study seeks to bring further understanding of critical conditions of factory planning, by highlighting detailed insights from a real-life SME context.

2. Methodology

The study is based on an explorative case study research design with one case company [9]. The manufacturing company develops and produces technological equipment with one specific industry sector as the main target, and with a wide range of additional application opportunities in other industry segments. Machines primarily serve a global market and are exported to customers all over the world. The company has about 130 employees and it represents a typical Norwegian SME in several ways. Yet, the high part of export sales combined with large degree of market uncertainty, due to the novelty of their machine combined with a wide range of possibilities in various markets and segments, constitutes a specific feature of this company. The company's planning situation is characterized by high uncertainty regarding the developments of markets and sales volumes, rapidly changing conditions, and high financial risk. Investments in new technology development over the past ten years combined with an increased focus on sustainability and reducing greenhouse gas emissions in the main target sector, have led to a rapidly increasing demand. This has implied a need to plan for increased production volumes in the factory.

The study is part of two research projects where the company collaborates with an external research institute. The research addresses major issues related to the development of production activities and the factory in view of the specific export growth situation of the company. A team with external researchers and company representatives have held workshops and meetings to discuss issues and solutions related to the company's production and factory planning.

A literature search is carried out to identify relevant previous works within factory planning and production ramp-up planning. Rather than providing a comprehensive and in-depth literature review on the topic, this literature search seeks to provide a brief overview of relevant works. The search approach is based on the guidelines by Thomé et al. [10]. Literature is identified through searches in Google Scholar and Scopus, using relevant keywords including "factory planning", "ramp-up planning", "SME", "planning process", "conditions", "factors", and so on. The relevance of identified papers was determined based on their abstracts. The literature search also included forward and backward searches.

Since previous research of factory planning has mainly been concentrated on providing systematic and structured models and approaches, and studies investigating the planning process and critical conditions are lacking, an explorative approach is adopted in this study. It means that empirical data from the case company are used to add a rich and detailed picture of critical conditions.

3. Theoretical background

A challenge of factory planning is to design production systems that, on one hand, last for decades but, on the other hand, are adaptable to changing requirements of the dynamic market environment [7]. Also, important questions for process, resources and layout design can often not be answered systematically due to uncertain information and changes in requirements. Since factories have to be designed to adapt to changing, situation specific requirements, factory planning needs to combine the initial factory design and continuous reorganisation of the production system [7].

A factory planning reference model has been developed by Hawer et al. [1] based upon a set of planning tasks. Typical tasks include defining the manufacturing program and manufacturing system structuring, selection and determining quantity of manufacturing equipment, determining space requirements (rough and detailed), material flow analysis (between blocks and detailed), building and facility design, rough planning of block layout, technology planning, ideal and real layout planning (detailed). Each planning task together with input and output data constitutes a module. The reference model aims to give general guidance and a starting point to gain awareness about how the planning tasks in a project depend on each other and should be adapted to each company's specific settings in order to be applied by users.

Facility layout planning, which is considered one of the most important design decisions, involves the process of physically arranging all the production factors that make up the production system [2]. The layout planning problem encompasses two process related criteria; the planning approach and phase [2]. Layout planning approaches can be defined as either static or dynamic depending on the variability of the material flow intensity during the planning horizon. Also, layout planning phases include the layout as a whole (block layout) which represents the phase when departments are arranged in buildings by considering if one relevant objective is met, while in the detailed layout phase elements making up the production system in the physical space inside each department are arranged.

Schuh et al [7] criticise traditional sequential planning approaches for failing to support factory planning projects in practice as they overlook the interactions and dynamics in the planning project as well as the stakeholder subjectivity. In addition, unconsidered interactions, conflicting motives and inflexible project structure lead to time-consuming, expensive and late adaptations. Insufficient synchronisation and coordination may also imply local optimisation and deviations from the overall objectives. In order to deal with these issues, the authors [7] propose the condition based factory planning. This is a modular, parallel approach that can be reconfigured according to the specific conditions of the planning project and company.

4. Empirical findings

This chapter presents critical conditions of the factory planning process that are identified in the case company. An overview of conditions is shown in Table 1, followed by a further description of conditions.

Table 1: Overview of case findings

Condition	Description based on examples from the case company
Market information reliability	Limited reliability of available market information and expected demand growth rate
	Uncertainty in sales and growth forecasts
Interdependencies between planning tasks	Several tasks related to for example production capacity, product variety and factory construction, depend upon other running planning tasks
	Multiple tasks are carried out in parallel, rather than in a sequential order
Access to necessary resources and expertise	Limited availability of dedicated resources with specific factory planning expertise
	Team of employees from various functions representing a mix of skills and competences
	Involvement of the management team and external researchers
	Gain strong and wide support in the organization

Balance of multiple objectives	Decisions are based on combined objectives, influenced by changing conditions and uncertainties related to e.g. markets, customer behaviour and product development Iterative approach where solution options are developed and evaluated by several iterations Alignment of rough overall plans with more detailed ones
Definition of project structure	Frequent changes of external conditions Continuous development process to find the best alternative Handling multiple updates of assumptions, forecasts, and plans
Knowledge and data on current production	Decisions on capacity expansion need to be taken based on uncertain production process information Uncertainty regarding lead times and quality in current processes Limited availability to detailed production process data and limited application of quantitative models and methods in planning
Decision-making culture	Ability of management and employees to deal with uncertainty and risk in markets and technology development Decisions based on limited information and rough analyses
Ramp-up in line with sales growth	Step-by-step approach to match stepwise production capacity expansion with anticipated sales growth Phase in of new technology while running normal production Significant investments in new technology may imply excess capacity
Planning of new investments	Decisions on major investments in new production technology and in infrastructure based on highly uncertain market information and demand forecasts Prioritizing investments that contribute to capacity expansion Investments combined with performance improvements Balancing short-term planning and long-term commitment of new investments

The company has identified significant market opportunities, both across multiple market locations, with worldwide customers and sales activities, and multiple industries e.g. agriculture and waste sectors. Due to its limited resources to provide detailed analyses and insights into market opportunities, the **reliability of market information** is considered to be low. Uncertainty in growth scenarios and sales forecasts is a specifically critical condition, that affects the entire planning process.

The company's factory planning process involves several **interdependent planning tasks** that run simultaneously, including for instance determining space requirements, material flow analysis, physical building and facility design, rough planning of block layout, technology planning, and so on. The planning process mainly concerns up-scaling existing capacities in the factory and extending the existing building, in parallel with running operations. Also, the ramp-up on a short-term involves the production of the same machines that are produced in the factory today, while on a longer term the product range may be extended. A dynamic planning approach, facilitating multiple tasks, is needed to ensure alignment of plans for future production capacity, product variety and the development of production facilities.

Due to limited resources, the company has difficulties in allocating **specific internal planning resources and expertise** to ramp-up planning tasks. A dedicated multidisciplinary team with employees representing various relevant skills and competences related to manufacturing and assembly processes, testing, inventory and logistics, production development and technology, and so on, is defined to carry out planning tasks in a joint manner. For the company, it is important that the process has broad support in the organization, involving employees representing multiple functions and facilitate a democratic process taking several perspectives into consideration and support solutions and decisions. The management team of the company is also involved in discussions and decision-making together with the planning team. A team of researchers have been involved, providing support to the factory planning team by adopting a systematic approach and evaluating relevant options.

The planning tasks seek to find optimal solutions where several **planning objectives are balanced**. The planning situation is influenced by uncertainty and frequent changes related to product development, customer behaviour, markets and so on. Thus, planning involves several iterations of developing and evaluating possible solutions. Also, tasks involve the alignment of overall rough plans and detailed planning, as well as adjustment of plans to changing conditions.

The factory planning project is mainly structured as an integrated continuous development process, involving a wide range of relevant considerations. The planning tasks are coordinated in the planning team and evolves in line with changing conditions. Tasks are not defined or planned in a typical **project structure** with a project plan including activities and a timeline with milestones, and so on. The chosen approach allows flexibility and continuous adjustments, taking into consideration frequent changes in underlying assumptions such as sales forecasts and production volumes, due to major uncertainty and frequently changing conditions.

With limited **knowledge of production process performance***,* such as lead time and quality performance, the company is forced to make planning decisions based on incomplete information on their own operations. Detailed data on operational performance is also limited. Qualitative planning methods are thus primarily applied, while quantitative methods are used only to a limited extent to support the company's planning process.

The new machines that the company has developed constitute a radical innovation. This implies that the market introduction of the machines is related to major uncertainty. With an environment characterized with high uncertainty related to market adoption and technology development, the organization has developed a flexible **decision-making culture**. This means that in decision-making, employees are used deal with uncertainty and risk, adapting to changing conditions and make decisions based upon imperfect information and rough analyses.

The factory planning process in the company encompasses major investments in facilities and infrastructure, as well as in specific manufacturing technology and equipment and material handling systems, to ensure necessary capacity expansion. It is important for the company that the capacity **ramp-up plan is in line with sales forecasts**. The necessary capacity expansion is thus planned to be carried out in steps, where investment plans and production capacity plans are frequently aligned with up-to-date sales forecasts. When replacing old equipment, expansion plans consider the introduction of new equipment without disruptions in operations. To ensure sufficient long-term capacity, the company also needs to plan investments that may imply excess capacity on short-term.

Decisions regarding major investments in new production technology and in infrastructure need to be taken based on highly uncertain market information and demand forecasts. With limited funding, the company plans to make several major investments e.g. in the factory building and in manufacturing technology and equipment. The **planning of new investments** constitutes an essential part of the company's factory planning process, where priority is given to investments that directly contribute to capacity expansion. An example is the expansion of the existing factory building to include new offices for the administration. The investment in new offices has lower priority than the investment in the new production hall that is expected to contribute to increase capacity in final assembly, testing and shipping. In order to ensure financial pay-off of investments in production facilities and buildings, which are not expected to have a direct effect on performance, the company also seeks to combine new investments in capacity expansion with improvements in operations. Overall, the company meets challenges related to that the long-term commitment of several investments in necessary production facilities and technologies leads to reduced planning flexibility on a short term. Therefore, the company seeks to ensure high flexibility also in their long-term investments. An example is the construction of a new factory building, which constitutes a major investment. The building is constructed so that it can be easily adapted to various types of operations, as space needs may change in the future, with changing locations of departments and functions.

5. Discussion and conclusion

This study highlights a set of critical conditions for factory ramp-up planning in an SME setting. Findings suggest that companies have various needs of decision support in terms of systematic methods and advanced tools. This supports previous research emphasizing the need for condition-based approaches. In terms of applicability of sophisticated decision support, SMEs typically have limited resources. While SMEs may experience high complexity in their factory planning processes, a typical challenge among SMEs is related to limited access to data and quantitative facts that are important input in decision-making. The applicability of existing advanced models and methods available in literature in SMEs may thus be questioned. There are major opportunities to enable data driven decision support and promote further advancement of current planning methods by utilizing digital technologies, such as sensors, RFID and Internet of things.

The study contributes with detailed empirical insights into critical conditions for the planning process, emphasising the importance of contextual settings. Being based upon one single case of an SME with a high degree of export to multiple market segments with major uncertainty, findings are expected to be particularly relevant for exporting SMEs, targeting multiple markets. However, since the single case in several ways represent a typical SME, findings are also expected to be relevant for SMEs in more general terms.

Suggested further research includes studies addressing how the planning context influences the adoption of tools and methods as decision support in factory planning. The conditions identified in this study can serve as a starting point investigating empirical contexts and planning processes in real life settings, comparing various contexts, by adopting a multiple case study approach. The findings may also be valuable for practitioners in manufacturing SMEs, e.g. production managers, that aim to further understand and develop their factory ramp-up planning processes.

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References

[1] Hawer, S., Sager, B., Braun, H., Reinhart, G., 2017. An adaptable model for the factory planning process: Analyzing data based interdependencies. Procedia CIRP 62, 117–122.

[2] Pérez-Gosende, P., Mula, J., Díaz-Madroñero, M., 2021. Facility layout planning. An extended literature review. International Journal of Production Research 59 (12), 3777–3816.

[3] Glock, C. H., Grosse, E. H., 2015. Decision support models for production ramp-up: a systematic literature review. International Journal of Production Research 53 (21), 6637–6651.

[4] Surbier, L., Alpan, G., Blanco, E. 2014. A comparative study on production ramp-up: state-of-the-art and new challenges. Production Planning & Control 25 (15), 1264–1286.

[5] Julka, N., Baines, T., Tjahjono, B., Lendermann, P., Vitanov, V., 2007. A review of multi-factor capacity expansion models for manufacturing plants: Searching for a holistic decision aid. International Journal of Production Economics 106 (2), 607–621.

[6] Büscher, C., Voet, H., Meisen, T., Krunke, M., Kreisköther, K., Kampker, A., Schilberg, D., Jeschke, S., 2014. Improving factory planning by analyzing process dependencies. Procedia CIRP 17, 38–43.

[7] Schuh, G., Kampker, A., Wesch-Potente, C., 2011. Condition based factory planning. Production Engineering, 5 (1), 89–94.

[8] Burggräf, P., Dannapfel, M., Schneidermann, D., Ebade Esfahani, M., 2022. Network-based factory planning for small and medium-sized enterprises. Production Planning & Control, 33 (12), 1173-1181.

[9] Yin, R. K., 2009. Case study research: Design and methods, vol. 5, SAGE.

[10] Thomé, A. M. T., Scavarda, L. F., & Scavarda, A. J., 2016. Conducting systematic literature review in operations management. Production Planning & Control, 27 (5), 408-420.

Biography

Maria Thomassen is a senior research scientist at SINTEF Digital in Oslo, Norway, with long experience from applied research projects in research fields mainly including operations and production management, logistics and supply chain management, involving industry collaboration. Thomassen holds a PhD from the Norwegian University of Science and Technology in Trondheim.

Lars Skjelstad is a senior research scientist at SINTEF Digital in Trondheim, Norway. He has long experience with applied research activities within production and logistics management, and mass customization with companies in different industries. Skjelstad holds a PhD from the Norwegian University of Science and Technology in Trondheim.

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Customer Perspective On The Purchase and Use Of Sustainable And Innovative Furniture In A Co-Creation Process

Franziska Zielenbach[1], Tobias Schröer[1], Volker Stich[1]
[1]*Institute for Industrial Management (FIR) at RWTH Aachen, Aachen, Germany*

Abstract

For developing a European industrial cooperation and involvement in the furniture industry, the international research project INEDIT conducted a survey for furniture customers. By finding out the needs and wishes of the customer regarding innovative products and the production process the project will establish a new way for designing and producing furniture. Within INEDIT a platform is built on which customized, technologically innovative and sustainable furniture can be created and produced in a co-creation process. The furniture industry should thus become significantly more flexible, transparent and sustainable. Following the "do-it-together" approach, a business ecosystem will be generated which creates added value not only for customers but also for designers, suppliers and manufacturing companies. In order to involve the customer even more actively in the design process and the production, the platform will provide access to a mix of digital and physical services and is linked to all other stakeholders in the value chain. To match the platform and the process to the needs, wishes and demands of the customer an anonymous survey with 300 participants was developed and conducted. By analyzing the survey, important factors were found for buying and for using furniture considering new technological inventions (e.g. 3D-printing or smart objects), sustainability of the products and the production process. Furthermore, the potential customer-group and their usage of the do-it-together process and additional activities can be tightened.

Keywords

Co-Creation; Do-it-together; Sustainable Furniture; Smart Furniture; Customer Perspective

1. Introduction – The need of the customer perspective

The overall target of the research project INEDIT is to establish a new way for designing and producing furniture by including several European countries and stakeholders. Therefore, a platform is built on which customized, sustainable and technologically innovative furniture can be created and produced in a co-creation process, following the “do-it-together” approach. To ensure a productive and rentable performance of the platform, the customer perspective is a highly relevant aspect. As the customers must purchase and use the end-products it is important to know and to understand their wishes and needs. Additionally, the platform wants to actively integrate the customers in the design process and the production, and therefore the platform will provide access to a mix of digital and physical services and is linked to all other stakeholders in the value chain. To meet the needs, wishes and demands of the customer to the product, the process and the technologies an anonymous survey with 300 participants is developed. The target of the survey is to show the willingness for buying and for using furniture considering new technological inventions, sustainability of products, sustainability of the production and the usage of the do-it-together process.

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2. Methodological Approach

In order to understand the customer's perspective more precisely and to obtain the required answers, the methodology of hypothesis testing is applied. This is a method of testing an assertion by measuring data from a sample. To do this, the first step is to create hypotheses that can be proven or disproven by statistical data. These hypotheses were developed based on an expert workshop within the INEDIT project and are sharpened in this paper with a literature research. By setting up a quantitative survey, the results can be processed afterwards with the tool Excel and the criteria can be made measurable. Thus, a one-sides or a two-sides test can be done. Hypothesis are accepted if the majority (> 50 %) of participants made the assumed specification and rejected if 50 % or less than 50 % made the assumed specification.

In the following, the hypotheses are first defined, afterwards the execution of the study is described and then the results are examined using the measurable data. This leads to the acceptance or the rejection of the hypotheses.

3. Current Research and derivation of Hypothesis

To meet the expectations of the end user of the INEDIT platform it is necessary to understand him and to get to know who the customer is. The advantages of the internet are used by people with a wide age range, nevertheless, young people are more likely to be open to new aspects than older people. Older people are more skeptical and inexperienced, especially when it comes to shopping. Similarly, due to the materials, manufacturing methods, quality, customization, etc., the products will not be able to compete with mass production in terms of price. Thus, the potential customers of the INEDIT Platform will be young and affluent. [1, 2, 3, 4] This leads to the first hypothesis.

H1: Potential customers of the INEDIT platform are young and affluent.

In times of mass production, the same furniture styles can be found in many homes. Therefore, the trend of customizing the existing furniture is becoming more and more desirable and popular. At the same time, the influence of social media, especially among young people, is becoming increasingly important. 90 to 95% of the decisions we make in the store are determined by impulses, emotions and habits. In online media, visual elements play the biggest role. Furniture should represent the character of the buyer. In this context, the otherwise important factors in the furniture purchase move into the background. [5, 6, 7] Therefore, the next hypothesis is:

H2: Potential customers are individuals that buy furniture for design reasons.

The term sustainability is based on three main pillars, namely environmental, social and economical sustainability. However, in many cases there is no differentiation between the three terms and most people only think of environmental sustainability upon hearing the term. There is a difference of perception of the terms, especially for consumers. [8, 9] Therefore, the proposed hypothesis is:

H3: End users place a higher priority on environmental than social sustainability.

In recent decades, the interest and the associated relevance of sustainability has grown steadily. In almost all industries, this aspect is becoming increasingly important for the customer and thus also for the manufacturer. Customers are willing to pay for this additional effort in the manufacturing process. The willingness to pay for sustainable furniture is therefore higher than for conventional furniture. [10, 11, 12, 13] The next hypothesis follows from this:

H4: The willingness to pay is higher for sustainable furniture then for conventional furniture.

The technology of 3D printing is not a recent innovation due to a missing availability. Therefore, many individual customers have not had the chance to experience it and are therefore unsure about its use and function. Considering furniture is a high investment piece that is supposed to last for a long time and is big in size, customers want to be sure of quality and longevity. For someone who has not experienced 3D printing it is difficult to create confidence in the technology. [10, 11, 12] From this, hypothesis 5 follows:

H5: End users who are interested in 3D printing in general are more willing to buy 3D printed furniture.

An important factor in determining the price of a piece of furniture is the type and quality of materials used. The customer has prices in mind for different materials and their manufacturing methods. With 3D printing, most people associate plastic as the base material, which suggests a lower price. Therefore, the willingness to pay for 3D printed furniture is lower than for conventional furniture. [14, 15, 16] This leads to the next hypothesis:

H6: The willingness to pay is lower for 3D printed furniture than for conventional furniture.

Modern technologies support the customer during the purchase process. In the furniture industry, augmented reality, especially virtual reality, is becoming increasingly important. The customer can view his piece of furniture even before it is manufactured and place it in the desired environment. Combined with good service, this enables the customer to have a successful buying experience. But social interaction is also relevant for those involved in manufacturing. Knowing past interactions helps in discovering and building alliances with companies with whom there has been a transaction history and collaborative relationship. Joint action is thus facilitated for all involved parts. [17, 18, 19] The next hypothesis follows from this:

H7: Driving factors for the participation in the INEDIT platform are social interaction and the use of technologies (VR/XR).

Smart home technologies have created a great support for the everyday life. Everyday problems are simplified or even eliminated as a result. Another benefit is the saving of energy. Whether through intelligent heating behavior, automatic light control or energy-saving end devices, the consumer saves energy and thus money. [20, 21, 22] It follows:

H8: Consumers interested in smart home technologies are looking for support in daily routines and energy savings.

Technology and smartification are slowly but surely entering the private space and more customers start to digitize their homes. However, this development is quite slow and the smart home offerings are limited. Looking at furniture, there is currently not much in the market, therefore it is difficult to assess the situation. [23] The proposition is:

H9: Consumers who are interested in smart home technology are willing to pay more for smart furniture.

4. Framework and execution of the survey

This research consists of one end user-oriented study. Within the main study the perceptions of the end users and therefore potential customers of the INEDIT platform are examined. At the beginning of the survey the participants had to characterize themselves as furniture buyer and their willingness to pay for different kinds of furniture. This was followed by questions regarding the willingness to participate in the design process on a platform and core functionalities. Then the questionnaire focused on the characteristics and functionalities of the furniture to be designed. First by questions about sustainability, followed by questions regarding the smartification of products and last by questions regarding 3D printing. For each characteristic the willingness to pay was also considered in comparison to conventional furniture. At the end of the study, the participants were asked to give information concerning their demographics. That is age, gender, monthly net income (household) and origin.

The study was distributed online via the questionnaire tool LimeSurvey and the platform Fanvoice. The advantage of an online survey is that more people from different backgrounds can be reached within a short amount of time. It cannot be ensured that the participants answer honestly and that they complete the survey. A snowball effect within the INEDIT project team was used to reach more people. Initially, the link to the survey was posted on the research partners' websites and sent out to the respective networks. Concerning the sample, there are no limitations. Furthermore, there was no selection concerning age, gender, education level, income or origin. By distributing the survey online, it is possible that the origin of the participants differs widely. Furthermore, the survey was available in three European languages (German, English and French) to diminish possible language barriers. An online survey may limit the age differentiation of the participants.

5. Evaluation and Results

Over the course of 130 days, a total of 304 people (N=304) complete the study: 45.72 % (n=139) identify as female, 39.15 % (n=119) identify as male, 1 person identifies as other (0.33 %) and 45 participants decided not to disclose their gender (14.8 %). The biggest group is in the age range of 30 and 50 years old (n=117, 38.49 %). 24.67 % of the participants are under the age of 30 (n=75) and 22.37 % are over the age of 50 years old (n=68). 14.47 % of the participants (n=44) did not indicate an age range. The majority of participants is coming from the European Union (78.29 %, n=238), where France (45,1 %, n=137) and Germany (25 %, n=76) are dominating. 2 participants are coming from the United Kingdom (0.66 %) and 3 participants from Africa (0.99 %). Again, 61 participants (20.06 %) did not disclose their country of origin. Lastly, the monthly net household income was quite evenly distributed. 12.17 % of the participants (n=37) have less than 1,500 €, 24.67 % (n=75) have between 1,500 € and 3,000 €, 12.5 % (n=38) have between 3,001 € and 4,000 €, 16.21 % (n=49) have between 4,001 € and 6,000 €, 9.21 % (n=28) have between 6,001 € and 8,000 € and 5.59 % (n=17) over 8,000 € per month to spend. 19.74 % of the participants (n=60) decided not to disclose their monthly net household income.

To analyze **hypothesis 1**, whether potential end users of the platform are young and affluent, the age range and monthly net household income was analyzed for participants that indicated a readiness to use the platform. The analysis included 215 participants out of N=304, because some participants decided not to disclose age nor income. Figure 1 shows the distribution of age and income for potential customers. As shown in the figures above, 31,16 % of the potential end users are below 30 years old, which can be interpreted as young. With regards to affluence, nearly half of the potential end users (48.37 %) have a monthly net household income of less than 3,000 €. The hypothesis 1 has two conditions and is accepted if the majority of end users is in the age range of 20-30 years and their monthly net income is more than 3000 €. The two-sided significance test shows that the hypothesis has to be rejected regarding the age group but can be closely accepted regarding the income.

The following hypotheses are also accepted or rejected according to the same methodology The repeated mention of this will be omitted.

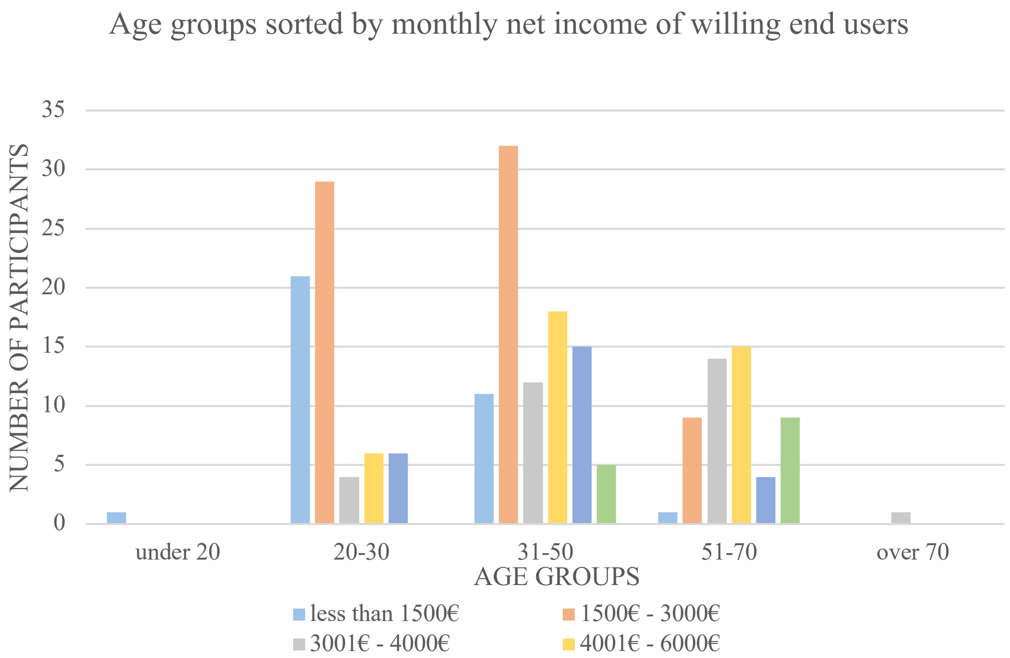

Figure 1: Age groups of potential customers divided in different monthly net income clusters.

For the **second hypothesis,** whether potential end users of the platform are individuals that buy furniture for design reasons, the self-characterization of the participants was used as indicator. Participants could give more than one reason for buying furniture. 50.5 % of the participants indicated design choices as reason to buy furniture, however 59.13 % gave as the reasons that they had to, because of broken furniture or moving. By dividing the groups further, the result is that only 52 participants (17.25 %) buy furniture solely for design reasons and 126 participants (41.86 %), because of damaged furniture or relocations. Therefore the data indicates a rejection of hypothesis 2, because the main motivator to buy furniture is because items are broken or new items are needed for new living spaces, instead of design reasons.

The **third hypothesis** focuses on sustainability and what end users understand as sustainable. To analyze this, two dummy variables are created to differentiate between environmental and social sustainability. The following answer options indicate environmental sustainability: Preservation of natural resources, No pollution and harm of natural habitats, Using only recycled materials, Using only recyclable materials, No waste of resources during the production, Low carbon footprint and Small transport distances for resources and furniture. Social sustainability consists of Fair priced workers within the value creation, Profit for local communities, Health of the workers within the value creation and Fair distribution of profits within the value creation. Participants could give more than one answer what means sustainability to them. Without excluding any of the other answer options, 94.29 % of the participants (N=280) understand sustainability with regards to environmental aspects. 73.57 % of the participants also consider social elements of sustainability. The two most important factors out of eleven possibilities are the preservation of natural resources, e.g. only using wood from reforested forests, (216 of 280) and fair pay for workers in the value chain (172 of 280). By excluding the construct of social sustainability 62 participants (22.14 %) only consider environmental aspects of sustainability. That is relatively high in comparison to excluding environmental aspects, which leaves 4 participants (1.43 %). The data indicates that hypothesis 3 can be accepted, that for end users' environmental sustainability has a higher priority than social.

For the **fourth hypothesis,** the willingness to pay for sustainable furniture is considered. Participants were asked to indicate a percentage range that they would be willing to pay more. Figure 2 shows the data. A large majority of participants (74.61 %, n=191) are willing to pay up to 25 % more for sustainable than for conventional furniture. 45 participants (17.58 %) are even willing to pay more than 25 % more. Only a small number of participants (7.81 %, n=20) are not willing to pay more for sustainable furniture than for conventional. Therefore, this hypothesis can be accepted.

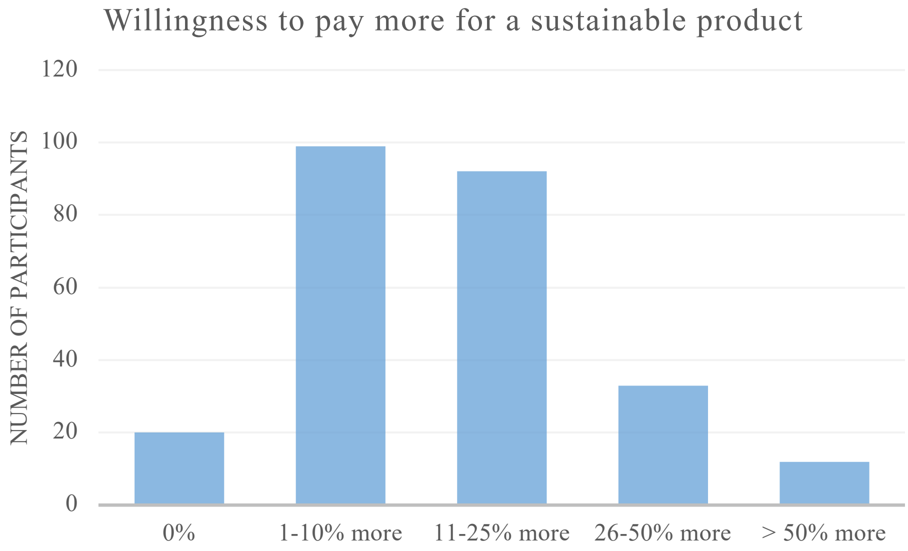

Figure 2: Participants willingness to pay more for sustainable furniture.

Hypothesis 5 focuses on 3D printing and for this, it is analyzed whether end users (N=275) who are interested in 3D printing in general are more likely to buy 3D printed furniture. 70.18 % of the participants (n=193) are interested in the technology of 3D printing and 168 participants (61.09 %) are interested and willing to buy 3D printed furniture. Only 8.72 % of interested end users are not willing to buy 3D printed furniture. These numbers are compared then to end users that are not interested in 3D printing in general, however are interested in buying 3D printed furniture. These are only 6.55 % participants (n=18). Therefore, the hypothesis can be accepted, because end users, who are interested in 3D printing in general are more willing to buy 3D printed furniture.

For **hypothesis 6,** the willingness to pay for 3D printed furniture is analyzed. The assumption is that end users have a lower willingness to pay for 3D printed furniture. The data (N=212) shows that 40.09 % (n=85) of the respondents are willing to pay less for 3D printed furniture than for conventional. However, more than half of the participants (53.30 %, n=113) are willing to pay the same for 3D printed furniture as for conventional. Considering these results, it can be concluded that hypothesis 6 has to be rejected.

To analyze **hypothesis 7**, driving factors for the participation in the INEDIT platform are considered. For this question, participants could give multiple answers as to what is important to them in order to participate in the platform. 146 participants (50.69 %) named social interaction and use of technologies, among others, as driving factors for the participation in the platform. However, 68,06 % of the participants (n=196) named other factors as the motivators for participation. By excluding participants, who named other factors, and only taking those, who are driven by social interactions and use of technology, in consideration, 70 participants (24.31 %) are left. Though the same can be done for participants that regard other factors as more important and excluding those, who are driven by social interactions and use of technology. 120 participants (41.67 %) regard other factors as the main drivers behind participation in the platform. Therefore, hypothesis 7 can be rejected.

For **hypothesis 8**, the end users interested in smart home technology and especially the field of application is analyzed. End users with a general interest in smart home technologies are considered and which features are of special interest to them. Figure 3 shows the results. Again, participants were able to give multiple answers and therefore a more detailed analysis is needed. 197 participants (64.80 %, N=304) are interested in smart home technology in general. Out of these 189 participants (62.17 %) are interested in support in daily routines and energy savings. However, due to the multiple answers 132 participants are also interested in other fields of application (43.41 %). By excluding the different end user groups, the results are a bit clearer. 21.38 % of all participants (n=65), who are interested in smart home technologies in general, are only looking for objects that help with daily routines and energy savings. However, only 2.63 % of participants (n=8) are only looking for other areas of application. Therefore, hypothesis 8 can be accepted.

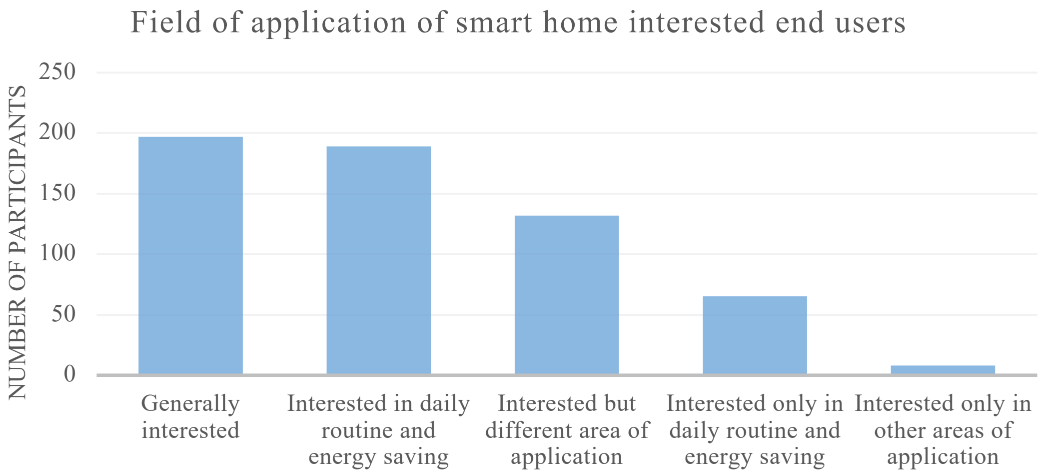

Figure 3: In smart home interested end users and their areas of application.

Hypothesis 9 considers, whether end users, who are interested in smart home technology in general are willing to pay more for smart furniture. Figure 14 shows the results. 43.65 % of the participants (n=86), who are interested in smart home technologies state that their willingness to pay depends on the value that is created through the smart feature. Another 43.14 % (n=85) are willing to between 10 and 30 percent more for a smart product. In comparison, only 14 participants (20.29 %), who are not interested in smart home technologies, are willing to pay 10 to 30 percent more and for 21 participants (30.44 %) it depends on the value created. Therefore, hypothesis 9 can be accepted.

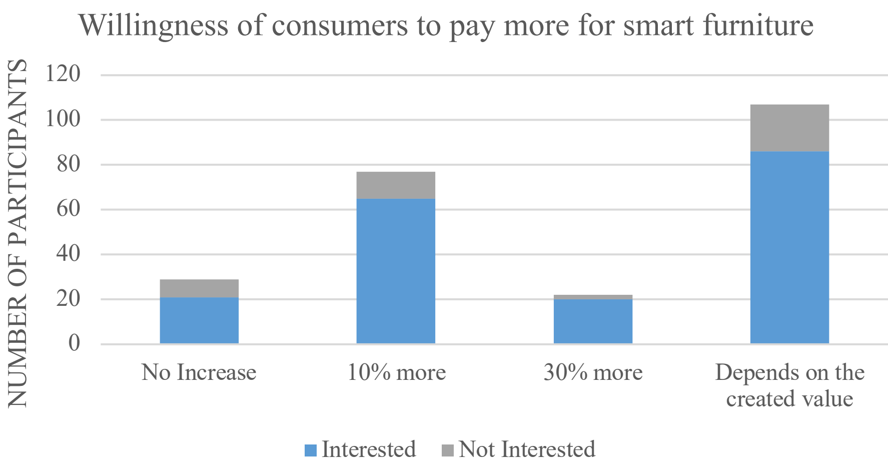

Figure 4: Willingness of smart home interested end users to pay more for smart furniture

6. Limitations, Conclusion and Outlook

There are a few limitations to this study. First, it was only conducted online which means that potential customers, who are not willing to participate in an online survey were excluded from the sample. Second, even though more than 300 people participated in the study, this is only a small sample size regarding the population of the European Union. Additionally, 70,1 % of the participants are living in Germany or France what can lead to a distortion as it does not represent the European Union in a completely equal way.

The survey's objective is to investigate the perspective of the end user of the INEDIT platform. Assumptions are made prior to the survey to investigate customer's reasoning for buying furniture in general, but also their perceptions and expectations of sustainability, smartification and 3D printing in the furniture sector.

The insights from the survey can have a valuable impact to the INEDIT platform. First, the potential customer base is quite diverse regarding age and income. There is not one dominating age or income group, which shows that the platform appeal to anyone. Furthermore, the survey results show that there is a considerable interest in sustainable furniture. Potential customers are also willing to pay more for it. This can be used to address potential manufacturers to register on the platform and offer their services. Second, the community aspect of the platform does not seem to be a driving factor behind the participation on the platform. Further research must be undertaken to find out whether this is true for all platform users (buyers, designers, and manufacturers) or just for one of the stakeholder groups. This leads to the design aspect. It seems that furniture design is also not one of the reasons for using the platform. Therefore, the design process should be as simple as possible to appeal to the end users. Third, there is a good chance that if the knowledge about 3D printing in general is increasing, that the interest in 3D printed furniture and therefore the demand of it will grow as well. Manufacturers should explore this technology to be prepared for the future.

Furthermore, particular statistical methods are not yet applied. To make a deeper validation of the hypothesis further procedures can be performed in the follow-up.

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References

[1] Schlosser, Ann E., Sharon Shavitt, and Alaina Kanfer, 1999. Survey of Internet users' attitudes toward Internet advertising. Journal of interactive marketing, 38.

[2] Duggan, Maeve, and Aaron Smith. Cell internet use 2013 2013, 8.

[3] Kobul, M.K., 2022. Socioeconomic status influences Turkish digital natives' internet use habitus, in: Kobul, M.K. (Ed.), Behaviour & Information Technology, pp. 1–19.

[4] Kappeler, K., Festic, N., Latzer, M., 2020. Who Remains Offline and Why? Growing Social Stratification of Internet Use in the Highly Digitized Swiss Society. SSRN Journal, 8.

[5] VIikari, V. Consumer Preferences for Secondhand Furniture, 17.

[6] Frizziero, L. E. O. N. A. R. D. O., et al. Stylistic design engineering (SDE) for an innovative green vehicle following QFD and TRIZ applications, in: , Stylistic design engineering SDE, p. 816.

[7] Summers, G., 2001. Upholstered furniture meets virtual reality. Upholstery Design Management, 28–31.

[8] Goodland, Robert, and Herman Daly, 1996. Environmental sustainability: universal and non-negotiable. Ecological applications, 1002–1017.

[9] Catlin, J.R., Luchs, M.G., Phipps, M., 2017. Consumer Perceptions of the Social Vs. Environmental Dimensions of Sustainability. J Consum Policy 40 (3), 245–277.

[10] Modica, P.D., Altinay, L., Farmaki, A., Gursoy, D., Zenga, M., 2020. Consumer perceptions towards sustainable supply chain practices in the hospitality industry. Current Issues in Tourism 23 (3), 358–375.

[11] Shahsavar, Tina, Vladimír Kubeš, and Dušan Baran. Willingness to pay for eco-friendly furniture based on demographic factors. Journal of Cleaner Production 2020 (250).

[12] Wei, Shuqin, Tyson Ang, and Vivien E. Jancenelle, 2018. Willingness to pay more for green products: The interplay of consumer characteristics and customer participation. Journal of Retailing and Consumer Services (45), 230–238.

[13] Papadopoulos, Ioannis, et al, 2014. Building the green-smart way: Exploring conditions for green and smart furniture manufacturing for people in the third age, in: Papadopoulos, Ioannis, et al (Ed.), 7th Annual Conference of the EuroMed Academy of Business, p. 1417.

[14] Pacheco, V.M. Manufacture of Furniture under Demand with Low Environmental Impact Through 3D Printing of Recycled Plastic 6.

[15] Bravi, Laura, Federica Murmura, and Gilberto Santos, 2017. Attitudes and behaviours of Italian 3D prosumer in the Era of Additive Manufacturing. Procédia Manufacturing (13), 980–986.

[16] Svoboda, J., Tauber, J., & Zach, M., 2019. 3D Print application in furniture manufacturing. Proceedings of the Digitalisation and Circular Economy: Forestry and Forestry Based Industry Implications, 12th WoodEMA Annual International Scientific Conference on Digitalisation and Circular Economy: Forestry and Forestry Based Industry Implications, 131–140.

[17] Oh, Hyunjoo, So-Yeon Yoon, and Chi-Ren Shyu, 2008. How can virtual reality reshape furniture retailing? Clothing and Textiles Research Journal (26.2), 143–163.

[18] Yin, X., Wang, H., Xia, Q., Gu, Q., 2019. How Social Interaction Affects Purchase Intention in Social Commerce: A Cultural Perspective. Sustainability 11 (8), 2423.

[19] Ren, Minglun, Lei Ren, and Hemant Jain. Manufacturing service composition model based on synergy effect: a social network analysis approach. Applied Soft Computing (70), 288–300.

[20] Turjamaa, R., Pehkonen, A., Kangasniemi, M., 2019. How smart homes are used to support older people: An integrative review. International journal of older people nursing 14 (4), 1-15.

[21] Wilson, G., Pereyda, C., Raghunath, N., de la Cruz, G., Goel, S., Nesaei, S., … & Cook, D. J, 2019. Robot-enabled support of daily activities in smart home environments. Cognitive Systems Research (54), 258–272.

[22] Ford, R., Pritoni, M., Sanguinetti, A., & Karlin, B, 2017. Categories and functionality of smart home technology for energy management. Building and environment (123), 543–554.

[23] Saputra, Farhan, and M. Ridho Mahaputra, 2022. Relationship of Purchase Interest, Price and Purchase Decisions to IMEI Policy (Literature Review Study). Journal of Law, Politic and Humanities, 66–75.

Biography

Franziska Zielenbach (*1992) is a research associate in the research group production management at the Institute of Industrial Management (FIR) at RWTH Aachen. In between of her Bachelor studies in Design- and Project Management and her Master studies in Industrial Engineering she worked for two years in the Business Process Management in the automotive sector.

Tobias Schröer, M. Sc. (*1991) studied Business and Engineering at the TU Clausthal. Since 2016, he has been working as a research assistant at the Institute for Industrial Management (FIR) at RWTH Aachen and is head of the Production Management department since 2020.

Prof. Dr.-Ing. Volker Stich (*1954) has been CEO of the Institute for Industrial Management (FIR) at the RWTH Aachen University since 1997. Prof. Dr.-Ing. Volker Stich worked for 10 years for the St. Gobain Automotive Group and led the management of European plant logistics. In addition, he was responsible for the worldwide coordination of future vehicle development projects.

4th Conference on Production Systems and Logistics

A Review of Process Innovations in the Cell Finishing of Lithium-Ion Batteries in Large-Scale Production

Jan Felix Plumeyer[1], Nils Menebröker[2], Henning Clever[1], Lukas Kokozinski[2], Saskia Wessel[2], Heiner Hans Heimes[1], Achim Kampker[1,2]

[1]*Production Engineering of E-Mobility Components (PEM), RWTH Aachen University, Aachen, Germany*
[2]*Fraunhofer Research Institution for Battery Cell Production (FFB), Münster, Germany*

Abstract

The European Union's ambitious climate targets will make climate-friendly storage technologies essential. More than any other, this decade could be marked by battery technology, especially the lithium-ion battery (LIB). In addition, various trends in mobility and consumer electronics are spurring the cross-industry use of this secondary storage device. As a result, the need for additional production capacities is rising, and the need for vertical integration of the value chain of LIB in Europe. In current forecasts, Europe has a considerable deficit between battery cell demand and production capacities. The deficit highlights the need for additional capacities and effort to develop new production systems. Furthermore, production technologies remain challenging, as high reject rates are expected initially, and a reduction of costs at the battery cell level is mandatory. Formation and aging as part of the cell finishing are the production steps with the highest processing time and space requirements. The formation can take up to 24 hours, and the subsequent aging between 8 to 36 days. It thus represents the biggest bottleneck. In large-scale production, various process innovations are being worked on, depending on the degree of automation. However, a systematic study of the impact of these process innovations is hardly ever carried out. Various approaches are conceivable here: Innovative formation protocols, optimized plant technology, flexible goods carrier systems and other process-related innovations. This paper provides researchers and industry experts with meaningful insights into the status quo and future developments in the cell finishing of battery cells through a comprehensive research approach. These trends will be presented and systematically evaluated to identify the most significant levers to reduce costs and time. It reviews process innovations in cell finishing to approach this research gap and aims to answer how these innovations will benefit and shape the large-scale production of lithium-ion battery cells.

Keywords

Lithium-Ion Battery Cell Production, Cell Finishing, Cell Conditioning, Formation, Soaking, 2nd Filling, Aging, Process Innovations, Large Scale Production

1. Introduction

Lithium-ion batteries are one of the key technologies for the transition from fossil fuels to renewable energies and thus have an outstanding significance on the way to a world free of pollutant emissions and for the mitigation of climate change. [1] Their ability to store electrical energy almost without a loss will make it possible to switch electrical energy production to renewable sources in the long term. Due to their technical properties as electrical energy storage devices, lithium-ion batteries have a wide range of applications. They are, for example, the most frequently used energy storage device in mobile electronic devices. [2]

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Technological progress and announcements by Original Equipment Manufacturers (OEMs) about a fully electrified portfolio, among other things, are leading to a rapid increase in demand for lithium-ion batteries and massive investments in battery development and production [3,4]. The production of lithium-ion batteries is very time-consuming and cost-intensive and can still be considered challenging regarding energy consumption. Studies [5,6,7,8] show that especially the formation accounts for a great share of the operational cost and total energy consumption per year within battery cell production. The formation is one of the central stages in the production of lithium-ion battery cells. It involves the initial charging and discharging of the manufactured cells and influences their electrochemical performance throughout their lifetime by ensuring the formation of a protective layer that prevents cell decomposition reactions between anode and electrolyte. [9]

2. Overview of the Battery Production Processes

The materials and cell chemistry (for the anode and cathode) of a battery cell must be defined as well as the cell format. As a first step, these parameters must be determined. Product specifications have far-reaching implications, especially for battery cells for production processes. After that, the resulting technology chains can be examined in more detail. This review will focus on the prismatic cell with conventional cell chemistry and dimensions to narrow down the innovation scope (Figure 1).

The overall process of battery cell production can be divided into three stages: Electrode production, cell assembly and cell finishing (Figure 1). The individual process steps may vary depending on the cell format and the materials selected, but the basic sequence is essentially identical for all common lithium-ion batteries. Starting with electrode production, the raw materials are first processed into anode and cathode. These are then assembled into battery cells together with a separator, electrolyte and housing in cell assembly. In the last production step of cell finishing, the manufactured cells are formed and aged, followed by quality control (or characterization), which is also performed during aging. Afterwards, the battery cells are ready to be graded, packed, and shipped.

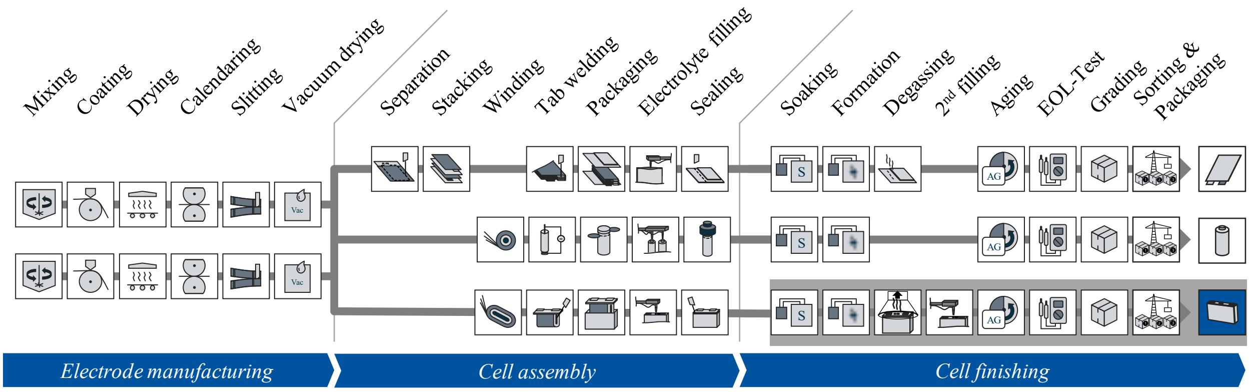


Figure 1: Overview of the process steps in the production of lithium-ion battery cells with different formats [10,11]

Figure 1 provides an overview of the battery cell production process chain. In electrode production, there are two lines of the same configuration each for anode and cathode. In cell assembly, the process steps depend on the cell format and design. The focus of this paper relates to the area of cell finishing. Due to long process times of up to 7-28 days in total, electrolyte wetting and the subsequent process steps of formation and aging in particular are major bottlenecks in battery production. The process sequence is variable and product dependent. [12,13,14]

This paper explores process innovations in cell finishing to classify different approaches and opportunities for optimization to address this bottleneck. The objective is to provide insights into how different process innovations in cell finishing will promote and shape the large-scale production of lithium-ion battery cells.

3. Process Chain in the Cell Finishing

Cell finishing is the last stage in the production of lithium-ion batteries. The battery cells are fully assembled. The cells are now electrochemically activated. Depending on the finishing protocol, the battery cells pass through the process steps and measurements in a different order. [10,11]

3.1 Soaking

During the soaking process, the cells are stored in a high-temperature environment to reduce the viscosity of their electrolyte and thereby ensure its homogeneous distribution in the cell. The required duration of the process at a given temperature is highly dependent on the size of the cell, its format, the cell chemistry, and the electrolyte-filling process [15]. It is common to consider the process as finished without validating its successful completion since the direct determination of the homogeneous electrolyte distribution requires complex measurement procedures [12,16].

Innovations

One option to indirectly determine the wetting degree of the cells is electrical internal resistance measurements [17,18]. Such measurements have the advantage of being very quick and they do not require the cells to be removed from their trays. Furthermore, no additional measuring equipment is required since both direct current (DC) and alternating current (AC) internal resistance are part of the regular quality control measurements. However, since both measurements do not take place within the soaking units, additional transport routes and logistical challenges arise. In addition, the validity of these indirect measurements is significantly lower compared to a direct analysis of the wetting degree, as several other factors influence the results. Therefore, resistance measurements are primarily advantageous if they are performed several times so that the interfering factors can be subtracted, and the actual course of the electrolyte distribution can be approximated. [19]

Evaluation

The implementation of electrical resistance measurements during the soaking process is a simple method for an indirect evaluation of the process progress. However, due to the additional transport distances and measurement procedures, it is only economical if the processing time saved exceeds the costs for additional measuring equipment or additional transport routes. Therefore, it is advantageous for large cells that would require an exceptionally long soaking time. The applicability for large-scale production with fully occupied transport systems is therefore limited. But the future potential can be significant if methods are found by which a single measurement during pre-forming is sufficient to analyze cell-specific the required soaking time. The foundation can be artificial intelligence (AI) methods or extensive knowledge about analyzed cells. In comparison, non-electrical methods for determining process progress typically require the removal of cells from their trays or time-consuming measurements. The implementation of such methods is therefore even more costly but offers a comparable acceleration potential. [17,20]

3.2 Formation

Formation represents the processes of cell finishing in which the manufactured and soaked battery cells are charged and discharged for the first time and thereby activated. However, there are several key differences in comparison to the regular charging process, which must be considered when designing a formation protocol. The primary objective of the formation is to cause the controlled development of passivating boundary layers on the surfaces of the electrodes. [12,21,22,23]

The traditional method to avoid damaging reactions within the cell during formation is to charge and discharge at low C rates between their upper and lower voltage thresholds for at least two full cycles [21,22]. However, this results in the process taking up to 48 hours. Through a detailed analysis of the reactions leading to a sufficient solid electrolyte interphase (SEI) and the deleterious effects that may occur, accelerated formation procedures can be applied.

Innovations

The easiest way to implement accelerated formation protocols is to use adjusted current and voltage thresholds. This method has the advantage that no increased requirements are imposed on the equipment. A typical way to speed up the process is to increase the current during the discharge phase [23]. This can prevent the damaging reactions at the anode that occur primarily during charging, while at the same time accelerating the process. Further acceleration can be achieved by not fully discharging the cells. This takes advantage of the fact that the functionally more important inorganic compounds in the SEI are formed primarily in the high cell voltage range [22,23].

In the so-called dual-current formation procedure, the charging power is adjusted in two stages depending on the cell voltage. As in a traditional formation procedure, the charging process starts with a low C rate in the range of 0.1 C. Once the cell voltage exceeds a predetermined value, the charging rate is increased abruptly to a value that is typically around 70 % of the C-rate capability of the cell. Thereby, there is sufficient time for the formation reactions of the organic SEI compounds to occur. Another positive effect is that the increased charge rates accelerate the formation of inorganic SEI compounds in the upper cell voltage range. However, many damaging reactions are also driven by the combination of high charge rates and high cell voltages. Therefore, a decision on the timing of the change and the increased charge rate must be balanced between the demand for acceleration and the risk of damage. [23,24,25]

It can be useful to perform part of the formation before soaking or between two soaking sub-processes. This additional formation step, which aims to set the cell voltage before the soaking, is usually called pre-charge. By charging to about 2.5 V, decomposition effects that occur after a certain time between the uncharged anode and the copper foil can be avoided. This allows the soaking process to be carried out for a longer time, which is especially important for large format cells. During the pre-formation, charging must be conducted at particularly low C rates of about 0.05 C due to the uncompleted electrolyte distribution. By increasing the targeted voltage of the pre-formation to around 3.3 V, the increased cell temperature during soaking can be utilized to initiate and accelerate initial SEI-forming reactions. After storage above 40 °C and at a cell voltage of at least 3.3 V for 24 hours, a sizable portion of the organic compounds has already formed in the SEI. Thus, the subsequent main formation can start with higher C-rates without negative influences on the cell. [23,25]

Evaluation

The main advantage of any alternative formation procedure based solely on adjusted thresholds for current and voltage is that it is quite simple to implement in any existing cell finishing line. The only condition that such methods impose on the equipment is that it must be capable of delivering the desired current. At the same time, such methods provide a time-saving potential since typically a large part of the formation time takes place in unnecessary potential ranges. Therefore, it can be concluded that these methods offer a good mix of applicability for large-scale production and acceleration potential. [22,23]

Besides simply adjusting the threshold values, several other electrical methods have the potential to accelerate the formation process. However, these often place special demands on measurement electronics and power electronics. The possibility of subsequently integrating them into an existing series production can therefore be limited. An even greater acceleration potential can be achieved by using a dual-current procedure. But the applicability of this process depends very much on the cell chemistry and requires power electronics that can provide the high currents needed during the second charging phase. [23,24,25]

A major disadvantage of pre-charging into the SEI forming potential range is that this acceleration must be substituted with an extended pre-charge phase. In addition, a high degree of wetting of the electrodes with electrolyte should already be present before the pre-charge to prevent inhomogeneous SEI formation. Therefore, the overall acceleration potential of this technology is limited, but a positive influence on cell performance can be observed while at the same time being easily applicable in large-scale production. [23,25]

3.3 Degassing

During formation, some components of the electrolyte are reduced [26,27]. The resulting gases accumulate inside the battery cell, as these are already sealed. In hardcase cells, the pressure rises due to gas buildup inside the cell. For safety and quality reasons, the gas is therefore vented from the cell in the degassing process step, which is usually integrated as a separate station in fully automatic finishing lines [28]. In prismatic cells, a port, such as a valve is provided in the housing for degassing, through which the gas can be extracted. In smaller cells, e.g. cylindrical cells, the gas remains in the cell. In case of pouch cells, the gas escapes in an extra gas pocket, which is pierced and extracted in a vacuum chamber. Then the emptied gas pocket is cut off and the cell is finally sealed on the open side. [29]

Innovations

Innovations in the context of degassing and final sealing of lithium-ion battery cells address in particular the reduction of process time and can influence the cell design. The elimination of a separate degassing process and the associated production station could be realized by extracting the produced gases while still forming. Immediately after formation, the gas is removed from the cell using internal pressure through a slight vacuum applied to ports or check valves. In addition to saving time, this would have a positive impact on the quality and performance of the battery cell, as the risk of plating is reduced. [30]

Another approach involves wetting the cathodes and anodes before assembly, forming the pre-wetted electrodes into an assembly, and then housing them. This process reduces the time required for the complete wetting of the electrodes and requires dedicated equipment. The gas produced during formation can escape directly, which eliminates the need for a degassing and capping station. [31]

Evaluation

Innovations in the field of degassing often influence both the production process chain and the cell design. The solutions presented have the potential to save time but require new plant technology. Since the handling of activated battery cells requires different safety requirements for fire protection in factories, it is easier to implement solutions that are based on established production process chains. The integration of degassing into the formation plant technology offers an approach with the potential for application in large-scale production.

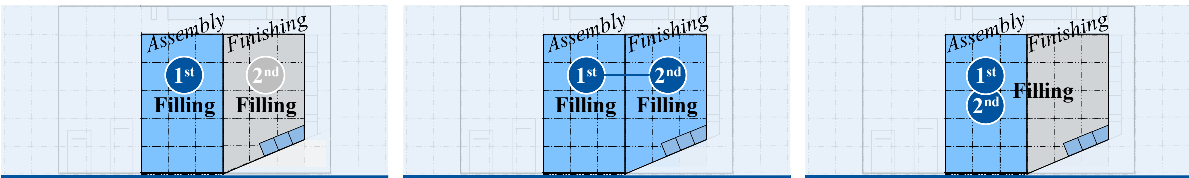
3.4 Electrolyte Filling (2nd filling)

The electrolyte filling of large prismatic battery cells is usually conducted in two steps. The so-called 1st filling, which describes the initial electrolyte filling, is an essential part of the cell assembly (Figure 1). In practice, filling systems have several dosing units. The partially assembled cells, the electrolyte solution and the inert gas are fed to the electrolyte filling unit. The electrolyte solution is dispensed into the previously evacuated cell housing via a dosing lance [32]. Complete filling of the housing and uniform wetting of the electrodes are essential for the quality and performance of the battery cell. [33]

As a rule, large prismatic battery cells are only provisionally sealed after 1st filling or temporarily closed with a stopper if a further filling step is planned. 2nd filling is necessary to compensate for the reduction of electrolytes during the formation and to refill the cell. In the battery cell's initial charging and discharging processes, a reduction of the electrolyte can be observed due to the electrochemical activation of the cell and the formation of interphase layers such as the SEI [26]. 2nd filling only affects large-format cells, since the loss fractions of the electrolyte after formation are the highest. In addition, it is also possible to add further additives to increase the lithium-ion conductivity and stabilize the SEI layer. [22,34,35]

Innovations

An open question is the technical implementation of 2nd filling. There are various concepts currently discussed in the industry, each with a different degree of innovation potential. Three noteworthy options have different advantages and disadvantages based on expert talks (Figure 2).



	Option 1	Option 2	Option 3
	2nd filling is not provided or executed	*1st filling in assembly* *2nd filling in finishing*	*1st filling in assembly* *2nd filling in assembly*
Advantages	▪ Complexity reduction for the process and logistics ▪ Only a small performance reduction depending on the cell	▪ Flexibility in cell chemistry ▪ Standard process for assembly ▪ 2nd filling can be leveraged	▪ Flexibility in cell chemistry ▪ Process sequence can be realized in a single plant technology ▪ 2nd filling can be leveraged
Disadvantages	▪ Lower innovation and flexibility level ▪ Deteriorated cell performance due to insufficient electrolyte	▪ Increased transport and logistics requirements due to temporarily sealed cells ▪ Process-related encapsulation or clean/dry room requirements are needed in the cell finishing	▪ Increased transport distances and logistics requirements due to temporarily sealed cells ▪ Influence of waiting time on unfilled cells unknown ▪ Buffer areas needed

Figure 2: Advantages and disadvantages of different options for 2nd filling

Evaluation

In option 1, 2nd filling is not intended. In general, the electrolyte losses are in the low single digits [26]. Therefore, the electrochemical cell performance is expected to deteriorate only slightly (Figure 2).

In option 2, 1st filling is performed in the cell assembly and the 2nd filling is in the cell finishing (Figure 2). The advantages of second filling can be leveraged. It should be noted that prismatic battery cells must be provisionally sealed for the transfer from the assembly to the cell finishing and the initial process steps of soaking and formation. In addition, an equipment solution for the second filling is required. This results in increased space requirements and high demands on the process environment. Therefore, process-related encapsulation by mini-environments or during degassing (via a bell system) is one solution to address the dry and clean room requirements.

Another innovative idea is to bundle the two filling processes into the cell assembly ideally on the same equipment (Figure 2). The high process environment standards in the cell assembly favor the bundling of the filling stations there. However, the battery cells must be returned from cell finishing to the cell assembly and vice versa. As a result, new logistic processes and plant interfaces must be developed and defined. The increased effort favors smaller laboratory and pilot lines.

The three options promise different advantages and disadvantages (Figure 2). Depending on the constraints and desired flexibility of the planned battery factory, all three alternatives must be carefully evaluated.

3.5 Aging, End-Of-Line Testing and Grading

After formation, degassing and a potential additional 2nd electrolyte filling, the battery cell is finalized. The cells are then stored for up to three weeks at room temperature in the cell finishing plant for quality assurance purposes. The cells are typically neither pressurized nor energized in trays. During storage, also called aging, the open circuit voltage (OCV) is measured at regular intervals to determine the self-discharge rate of the battery cell. [28]

The scope of the subsequent End-Of-Line (EOL) tests varies depending on the cell format, previous production process chain and manufacturer. The classical electrical measurements at the end of the production process chain are the self-discharge determined by the OCV measurements, alternating current internal resistance (ACIR) at a single frequency (typically 1 kHz), direct-current internal resistance (DCIR), and battery cell capacity calculated during formation [29]. For measurements that are typically not performed in one of the previous process steps, plant manufacturers implement separate EOL stations. These stations also include measurements of weight, dimensions, and visual inspection. Depending on the subsequent application, surface brushing and labelling or printing of the cells may also be integrated into this station. Based on the measured quality parameters determined in the EOL test, the battery cells are classified into different quality classes. [36,37]

Innovations

Innovations in the field of aging and EOL tests address the reduction of lead times and the significant space requirement. One innovative approach to reducing the significant footprint of aging by eliminating the need for long rest periods between OCV measurements is called potentiostatic aging. In this method, the cells do not rest currentless but are kept at a constant cell voltage by charging them with microcurrents. Evaluation of the charge thus induced over up to 24 hours allows the self-discharge behavior of the cells to be determined. Since the measurements are no longer performed only in specific intervals but are recorded continuously, the obtained information goes beyond the self-discharge. For instance, other defects, such as micro-shorts on the separator, can also be detected based on short-term peaks in the required charging rate. [38]

In addition to the potential future integration of electrical EOL tests into the formation procedure, there are many approaches for innovative measurement methods. By collecting extensive data and evaluating it during the aging process in adapted carrier concepts, a digital estimation of the cell quality can be made, and the aging time can be adjusted or shortened to meet the requirements of each cell. [29]

Regular EOL tests are insufficient to obtain detailed information about the condition within the cell. A possibility to gain additional data is electrochemical impedance spectroscopy (EIS). This technique can obtain information about diffusion mechanisms, charge transfer resistances and the boundary layers at the electrode surfaces. However, since EIS measurements can take up to 60 minutes per cell and require very precise measurement and power electronics, implementation in large-scale production would lead to immense additional costs. However, innovative approaches exist that make it possible to determine the entire frequency spectrum of an EIS measurement within a few seconds by pulse analysis, thereby drastically accelerating the process without significantly degrading the information value. [39,40,41]

Evaluation

Metrological innovations in the field of aging or EOL testing, which pursue the purpose of shortening aging, have the potential for significant cost and space savings in production operations. In principle, potentiostatic aging can be integrated, but this requires adjustments to the cell finishing plant concept. The integration of electrical EOL tests into the formation procedure as well as AI-based quality prediction can be implemented with existing equipment concepts and therefore offer feasibility in volume production. By integrating pulsed impedance measurements, the technology can be implemented in large-scale production that is usually limited to the laboratory scale.

3.6 Sorting and Packaging

The cells are sorted into several classes according to the specifications ("grades") and filled into packaging units on holding structures in an automated manner for high-volume production. For safety-critical cells, packaging in safety transport containers is typically required. These packaging units are dispensed onto a conveyor belt or a facility for temporary storage with a specified capacity. The packaging units are then placed on a pallet. The capacity of the intermediate storage facility must be matched to the production campaigns so that the transport of the batteries to the storage facility can take place in the targeted schedule. [28,42]

Innovations

The automation degree of the packaging unit is a central adjusting lever for throughput and innovation. In large-scale production with high throughputs, fully automated AGVs (Automated Guided Vehicles) and multi-axis industrial robots are used. These robotic arms allow maximum utilization of the workspace and flexibility. [43]

Additionally, the packaging must meet a variety of requirements for lithium-ion battery cells (UN certifications). In addition to ensuring the structural integrity of the cells, increased safety requirements must be considered. The fire hazard of batteries can be mitigated by the packaging. Modern packaging solutions provide improved flame retardance and arrestment, thermal management, pressure management, blast containment, and gas and smoke filtration. Furthermore, re-engineering allows for a reduction in product complexity through new material solutions while increasing the intrinsic safety of the packaging. [44, 45]

Evaluation

The degree of packaging automation is essential for large-scale production to achieve cost and time reductions. However, the leverage at the end of the process chain is limited since the process cycle times have lower reduction potential in comparison to the processes in electrode production, cell assembly or cell finishing. Furthermore, automation solutions in the packaging process are characterized by cross-industry adaptability and applicability in scaled productions. The same applies to modern packaging solutions that can be used universally in production (e.g. storage and transport) and sustainable packaging materials.

4. Results and Discussion

The innovations presented along the process chain in cell finishing were assessed regarding their potential and applicability in large-scale production. The assessment is based on insights from leading industry experts and publications in the field of cell finishing. The potential refers to the possible time and cost savings achieved with the innovations. Furthermore, the applicability of the innovations remains significant, as this determines whether the innovations can be used in large-scale production or if increased implementation effort is necessary. In addition, the scaling level of the concept must be technically achievable.

It can be stated that the process innovations in cell finishing mainly focus on the bottleneck processes with the longest cycle times and largest investment requirements. The soaking, formation, and aging can be identified as such processes. There, experience and an understanding of the electrochemical principles are crucial. New process protocols and existing equipment technology will enable time reductions and potentially reduce energy costs.

In addition, quality-enhancing measures such as 2^{nd} filling are becoming increasingly important. Here, the focus shifts depending on the objective of cell production. The innovations presented must be adapted to the logistics and environmental constraints of the factory concept and the desired flexibility of production.

It can be expected that these innovations will be associated with increased costs in the initial phase and will typically move in first where high-quality and more costly battery cells are produced. That's where the plant technology's increased costs and integration efforts are profitable at first. This also means that in large-scale production, the trade-off between low cost ($/kWh) and quality results in a much longer time horizon before new process innovations can be introduced.

5. Conclusion and Outlook

New process innovations are supporting the development of so-called Gigafactories in Europe [46]. As well as improving product quality, these technologies could reduce costs and accelerate production times significantly. At the same time, sustainability through energy savings and thus an improvement in energy consumption through process innovations and further developments in plant technology is increasingly important. Research and industry efforts make it possible to exploit this potential. Batteries with higher requirements will be the first to benefit from the upcoming innovations due to the current cost pressure in battery cell production. Trickle-down effects into more price-sensitive cell production are expected mid to long-term. These activities and developments will be complemented by research factories, which will enable European machine and plant manufacturers to bring their process innovations into series production sooner.

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References

[1] Welter, K., 2019. Die Lithium-Ionen-Batterie: Eine Erfindung voller Energie. Chemie in unserer Zeit 53 (6), 362–364.

[2] Thielmann, A., Wietschel, M., Funke, S., Grimm, A., Hettesheimer, T., Langkau, S., Loibl, A., Moll, C., Neef, C., Plötz, P., Sievers, L., Espinoza, L.T., Edler, J., 2020. Batterien für Elektroautos:. Faktencheck und Handlungsbedarf. Fraunhofer ISI, Karlsruhe.

[3] Bechberger, M., Vorholt, F., Bünting, A., Oehl-Schalla, N., Arnold-Triangeli, L., Beermann, V., Bilge, P., Giacomini, M., Marscheider, J., Neupert, S.P., Korzynietz, R., Solmaz, S., Dietrich, F., Kowal, J., Wolf, S., 2021. Sustainability of battery cell production in Europe. How sustainable are batteries and electric mobility really?. VDI/VDE Innovation + Technik GmbH, Berlin.

[4] Bibra, E.M., Connelly, E., Dhir, S., Drtil, M., Henriot, P., Hwang, I., Le Marois, J.-B., McBain, S., Paoli, L., Teter, J., 2022. Global EV Outlook 2022. Securing supplies for an electric future. International Energy Agency (IEA).

[5] Degen, F., Schütte, M., 2022. Life cycle assessment of the energy consumption and GHG emissions of state-of-the-art automotive battery cell production. Journal of Cleaner Production 330, 129798, 1-12.

[6] Liu, Y., Zhang, R., Wang, J., Wang, Y., 2021. Current and future lithium-ion battery manufacturing. iScience 24 (4), 102332, 1–17.

[7] Küpper, D., Kuhlmann, K., Wolf, S., Pieper, C., Xu, G., Ahmad, J., 2018. The Future of Battery Production for Electric Vehicles. BCG.

[8] Orangi, S., Strømman, A.H., 2022. A Techno-Economic Model for Benchmarking the Production Cost of Lithium-Ion Battery Cells. Batteries 8 (8), 83, 1–24.

[9] Tokranov, A., Kumar, R., Li, C., Minne, S., Xiao, X., Sheldon, B.W., 2016. Control and Optimization of the Electrochemical and Mechanical Properties of the Solid Electrolyte Interphase on Silicon Electrodes in Lithium Ion Batteries. Advanced Energy Materials 6 (8), 1502302, 1–12.

[10] Heimes, H.H., Kampker, A., vom Hemdt, A., Kreisköther, K.D., Michaelis, S., Rahimzei, E., 2019. Manufacturing of lithium-ion battery cell components. PEM of RWTH Aachen University and VDMA, Frankfurt am Main.

[11] Kwade, A., Haselrieder, W., Leithoff, R., Modlinger, A., Dietrich, F., Droeder, K., 2018. Current status and challenges for automotive battery production technologies. Nature Energy 3 (4), 290–300.

[12] Hagemeister, J., Stock, S., Linke, M., Fischer, M., Drees, R., Kurrat, M., Daub, R., 2022. Lean Cell Finalization in Lithium-Ion Battery Production: Determining the Required Electrolyte Wetting Degree to Begin the Formation. Energy Technology, 2200686, 1–12.

[13] Grimm, J., Köse, E., Weeber, M., Sauer, A., Birke, K.P., 2021. Energy Flexibility in Battery Cell Manufacturing. Procedia CIRP 99, 531–536.

[14] Stock, S., Ceruti, A., Günter, F.J., Reinhart, G., 2021. Introducing Inline Process and Product Analysis for the Lean Cell Finalization in Lithium-Ion Battery Production. Procedia CIRP 104, 1052–1058.

[15] Günter, F.J., Rössler, S., Schulz, M., Braunwarth, W., Gilles, R., Reinhart, G., 2020. Influence of the Cell Format on the Electrolyte Filling Process of Lithium-Ion Cells. Energy Technology 8 (2), 1801108, 1–7.

[16] Davoodabadi, A., Li, J., Zhou, H., Wood, D.L., Singler, T.J., Jin, C., 2019. Effect of calendering and temperature on electrolyte wetting in lithium-ion battery electrodes. Journal of Energy Storage 26, 101034, 1–32.

[17] Günter, F.J., Habedank, J.B., Schreiner, D., Neuwirth, T., Gilles, R., Reinhart, G., 2018. Introduction to Electrochemical Impedance Spectroscopy as a Measurement Method for the Wetting Degree of Lithium-Ion Cells. Journal of The Electrochemical Society 165 (14), A3249-A3256.

[18] Francis, C.F.J., Kyratzis, I.L., Best, A.S., 2020. Lithium-Ion Battery Separators for Ionic-Liquid Electrolytes: A Review. Advanced Materials 32 (18), 1904205, 1-22.

[19] Islam, S.M.R., Park, S.-Y., Balasingam, B., 2020. Unification of Internal Resistance Estimation Methods for Li-Ion Batteries Using Hysteresis-Free Equivalent Circuit Models. Batteries 6 (2), 32, 1–20.

[20] Schweiger, H.-G., Obeidi, O., Komesker, O., Raschke, A., Schiemann, M., Zehner, C., Gehnen, M., Keller, M., Birke, P., 2010. Comparison of several methods for determining the internal resistance of lithium ion cells. Sensors 10 (6), 5604–5625.

[21] Wood, D.L., Li, J., Daniel, C., 2015. Prospects for reducing the processing cost of lithium ion batteries. Journal of Power Sources 275, 234–242.

[22] An, S.J., Li, J., Du, Z., Daniel, C., Wood, D.L., 2017. Fast formation cycling for lithium ion batteries. Journal of Power Sources 342, 846–852.

[23] Theil, S., 2016. Elektrolytalterung in Lithium-Ionen-Batterien. Dissertation, Ulm.

[24] Chiang, P.-C.J., Wu, M.-S., Lin, J.-C., 2005. A Novel Dual-Current Formation Process for Advanced Lithium-Ion Batteries. Electrochemical and Solid-State Letters 8 (8), A423-A427.

[25] German, F., 2015. Untersuchungen zur SEI-Bildung und Optimierung der Formation an Lithium-Ionen Voll- und Halbzellen. Dissertation, Karlsruhe.

[26] An, S.J., Li, J., Daniel, C., Mohanty, D., Nagpure, S., Wood, D.L., 2016. The state of understanding of the lithium-ion-battery graphite solid electrolyte interphase (SEI) and its relationship to formation cycling. Carbon 105, 52–76.

[27] Self, J., Aiken, C.P., Petibon, R., Dahn, J.R., 2015. Survey of Gas Expansion in Li-Ion NMC Pouch Cells. Journal of The Electrochemical Society 162 (6), A796-A802.

[28] Heimes, H.H., Kampker, A., Lienemann, C., Locke, M., Offermanns, C., Michaelis, S., Rahimzei, E., 2018. Lithium-ion battery cell production process. PEM of RWTH Aachen University and VDMA, Frankfurt am Main.

[29] Michaelis, S., Rahimzei, E., Kampker, A., Heimes, H.H., Lienemann, C., Offermanns, C., Kehrer, M., Thielmann, A., Hettesheimer, T., Neef, C., Kwade, A., Haselrieder, W., Rahlfs, S., Uerlich, R., Bognar, N., 2018. Roadmap Battery Production Equipment 2030. VDMA.

[30] Hock, R.J., Franz, J., Polnick, U., Weiler, C. 2019. Verfahren zur Herstellung einer Lithium-lonen-Pouchzelle. Patent. Aktenzeichen DE: 10 2019 003 594.1. Germany.

[31] Hock, R.J., Franz, J., Polnick, U., Weiler, C. 2019. Verfahren zur Herstellung einer Lithium-lonen-Batteriezelle. Patent. Aktenzeichen DE: 10 2019 003 574.7. Germany.

[32] Röth, T., Kampker, A., Deutskens, C., Kreisköther, K., Heimes, H.H., Schittny, B., Ivanescu, S., Büning, M.K., Reinders, C., Wessel, S., Haunreiter, A., Reisgen, U., Thiele, R., Hameyer, K., Doncker, R.W. de, Sauer, U., van Hoek, H., Hübner, M., Hennen, M., Stolze, T., Vetter, A., Hagedorn, J., Müller, D., Rewitz, K., Wesseling, M., Flieger, B., 2018. Entwicklung von elektrofahrzeugspezifischen Systemen, in: Kampker, A., Vallée, D., Schnettler, A. (Eds.), Elektromobilität, 2 ed. Springer Verlag, Berlin, pp. 279–386.

[33] Kampker, A., Hohenthanner, C.-R., Deutskens, C., Heimes, H.H., Sesterheim, C., 2013. Fertigungsverfahren von Lithium-Ionen-Zellen und -Batterien, in: Korthauer, R. (Ed.), Handbuch Lithium-Ionen-Batterien, 1 ed. Springer Verlag, Berlin, pp. 237–247.

[34] Park, S., Jeong, S.Y., Lee, T.K., Park, M.W., Lim, H.Y., Sung, J., Cho, J., Kwak, S.K., Hong, S.Y., Choi, N.-S., 2021. Replacing conventional battery electrolyte additives with dioxolone derivatives for high-energy-density lithium-ion batteries. Nature communications 12 (1), 838.

[35] Kim, K., Ma, H., Park, S., Choi, N.-S., 2020. Electrolyte-Additive-Driven Interfacial Engineering for High-Capacity Electrodes in Lithium-Ion Batteries: Promise and Challenges. ACS Energy Lett. 5 (5), 1537–1553.

[36] R-Smith, N.A.-Z., Ragulskis, M., Kasper, M., Wagner, S., Pumsleitner, J., Zollo, B., Groebmeyer, A., Kienberger, F., 2021. Multiplexed 16 × 16 Li-Ion Cell Measurements Including Internal Resistance for Quality Inspection and Classification. IEEE Transactions on Instrumentation and Measurement 70, 1–9.

[37] Kampker, A. (Ed.), 2014. Elektromobilproduktion, 1, 1 ed. Springer Verlag, Berlin, Heidelberg.

[38] Zimmerman, A.H., 2004. Self-discharge losses in lithium-ion cells. IEEE Aerospace and Electronic Systems Magazine 19 (2), 19–24.

[39] Westerhoff, U., Kurbach, K., Lienesch, F., Kurrat, M., 2016. Analysis of Lithium-Ion Battery Models Based on Electrochemical Impedance Spectroscopy. Energy Technol. 4 (12), 1620–1630.

[40] Choi, W., Shin, H.-C., Kim, J.M., Choi, J.-Y., Yoon, W.-S., 2020. Modeling and Applications of Electrochemical Impedance Spectroscopy (EIS) for Lithium-ion Batteries. J. Electrochem. Sci. Technol 11 (1), 1–13.

[41] Nusev, G., Juricic, D., Gaberscek, M., Moskon, J., Boskoski, P., 2021. Fast Impedance Measurement of Li-Ion Battery Using Discrete Random Binary Excitation and Wavelet Transform. IEEE Access 9, 46152–46165.

[42] Kartini, E., Sudaryanto, S., Honggowiranto, W., Sudjatno, A., Fadjri, A., Marto, I., Rofika, R.N.S., 2019. Grading of Lithium Ion Battery Module for Public street lighting. IOP Conference Series: Materials Science and Engineering 553 (1), 012065, 1–7.

[43] Duffner, F., Kronemeyer, N., Tübke, J., Leker, J., Winter, M., Schmuch, R., 2021. Post-lithium-ion battery cell production and its compatibility with lithium-ion cell production infrastructure. Nature Energy 6 (2), 123–134.

[44] Huo, H., Xing, Y., Pecht, M., Züger, B.J., Khare, N., Vezzini, A., 2017. Safety Requirements for Transportation of Lithium Batteries. Energies 10 (6), 793.

[45] Harper, G., Sommerville, R., Kendrick, E., Driscoll, L., Slater, P., Stolkin, R., Walton, A., Christensen, P., Heidrich, O., Lambert, S., Abbott, A., Ryder, K., Gaines, L., Anderson, P., 2019. Recycling lithium-ion batteries from electric vehicles. Nature 575, 75–86.

[46] Cooke, P., 2020. Gigafactory Logistics in Space and Time: Tesla's Fourth Gigafactory and Its Rivals. Sustainability 12 (5), 2044, 1–16.

Biography

Jan Felix Plumeyer (*1997) is a research assistant at the Chair of Production Engineering of E-Mobility Components (PEM) at RWTH Aachen University. He studied mechanical engineering and business administration with a specialization in production technology and operations research & management at RWTH Aachen University.

Nils Menebröker (*1993) is a research assistant at the Fraunhofer Research Institution for Battery Cell Production FFB in Münster in the department for product and process qualification. He studied electromobility with a specialization in energy storage and infrastructure at the Technical University of Braunschweig.

Henning Clever (*1992) is a research assistant and group lead for the battery production management group at the Chair of Production Engineering of E-Mobility Components (PEM) at RWTH Aachen University. He studied mechanical engineering with a specialization in production technology at RWTH Aachen University.

Lukas Kokozinski (*1995) is a research assistant at the Fraunhofer Research Institution for Battery Cell Production FFB in Münster in the department for production technology. He studied mechanical engineering with a specialization in production technology and corporate organization at RWTH Aachen University.

Dr.-Ing. Saskia Wessel (*1990) studied and earned her doctorate in mechanical engineering at RWTH Aachen University. Since January 2020, she is the division director for "Product and Production Technology" at Fraunhofer FFB in Münster.

Dr.-Ing. Heiner Hans Heimes (*1983) studied mechanical engineering with a focus on production engineering at RWTH Aachen University. Since 2019, Dr.-Ing. Heimes has held the role of the executive engineer of the PEM facility.

Prof. Dr.-Ing. Achim Kampker (*1976) is head of the Chair of Production Engineering of E-Mobility Components (PEM) at RWTH Aachen University and Deputy Head of Fraunhofer Research Institution for Battery Cell Production (FFB).

4th Conference on Production Systems and Logistics

Operational Concepts For The Deployment Of AI-Supported Maintenance Strategies At Distribution System Operators

Kajan Kandiah[1], Lars Frehen[1], Max-Ferdinand Stroh[1], Volker Stich[1]
[1]*FIR an der RWTH Aachen, Aachen, Germany*

Abstract

Climate change is leading to massive changes, especially in the areas of energy and mobility. As a connecting element of the energy and mobility transition, electricity grids will play a key role. Bidirectional energy flows and massive fluctuation in generation and consumption patterns lead to high stresses on components and systems, especially in the distribution grid. This confronts Distribution System Operators (DSOs) with new challenges to continue to ensure security of supply in an economical and resource-efficient manner. New maintenance strategies can enable operators to address these challenges. Novel sensors and artificial intelligence enable the technical use of methods such as Predictive Maintenance to detect and predict the probability of failure of critical components based on current condition data. Whereas Predictive Maintenance is already being used in many areas of the manufacturing industry today, the procedures are still new in operating medium-voltage switchgear in the distribution grid, which are critical for ensuring the security of supply. Today's maintenance processes are not automated and are based on Preventive Maintenance strategies and differ very much from those of production environments. For example, the used IT-systems differ as well as the level of involvement of service contractors and regulative requirements and limitations. The use of Predictive Maintenance in the operation of critical infrastructures therefore places special demands on existing maintenance strategies at DSOs to economically ensure security of supply. This paper proposes an operational concept consisting of a process model, IT-system landscape, and information logistics model compatible with the current process and system architecture to deploy new maintenance strategies at DSOs.

Keywords

Predictive Maintenance; Artificial Intelligence; Distribution System Operator; Operational Concepts; Energy transition; Mobility transition

1. Introduction

The focus of the German climate and energy policy is on a massive and area-wide integration of renewable energies [1,2] as well as on the integration of charging stations for electro-mobility into the existing power grid. The resulting numerous load fluctuations [3,4], e.g., caused by decentralized solar plants, as well as the temporally and spatially concentrated energy demand caused by charging infrastructure (eMobility), lead to very large loads that can lead up to overload on electrical equipment and components, such as switchgear. Literature and the conducted interviews show that typical switchgear assets are 30 years or older [5]. This imposes an immediate threat since operators are not aware about their current operation condition. Therefore, to achieve the goals of the energy and mobility transition while maintaining the same quality of supply, on the one hand, grid operators need an improved understanding of the current status and impending failures of components but on the other hand, have to deal with increasing cost pressure while maintaining the security

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of supply. Novel sensors paired with new Artificial Intelligence (AI) approaches are now making condition-based monitoring of assets for this use case technically possible [6]. The research project AproSys, which this work is part of builds upon the work of the finished project FLEMING, which was focused on a technical solution that consisted of low-cost sensor solutions paired with a corresponding machine-learning approach to classify condition states and make prognoses about the future state of components in switchgear.

In this paper, we concise an operational concept based on the current processes and procedures at distribution system operators (DSOs) as well as necessary system landscape to implement condition monitoring and novel maintenance paradigms in organizations of DSOs. This research should answer the question: *How does a holistic operational concept have to be designed to offer Predictive Maintenance Strategies in combination with legacy systems for medium-voltage switchgear at DSOs*? Therefore, we will describe the technical foundations this research focused on and then describe the used methodology to derive the operational concept. The overall objective is to contribute to a more stable grid by reducing maintenance costs and downtimes for distribution grid operators and to instruct the implementation of such systems into an operating business environment at DSOs.

2. Technical Foundations

In this chapter, we will introduce the technical foundations on which this research is based. Hence the status quo from the perspective of DSOs and switchgear will be explained as well as the relevant maintenance strategies.

2.1 Switchgears and their typical fault patterns

The total energy grid is composed of different grid layers with different properties and functions. As part of the research for a Predictive Maintenance application, we focused on medium voltage switchgear that connects medium and low voltage grids and is maintained by DSOs. As part of the distribution grid, it fulfils essential safety functions as well as controlling functions of the grid by providing energy to the typical "last mile" between homes and substations. Switchgears play an important role in the isolation of error patterns in the grid and its components. They come in metal enclosures and can be used in different operating settings such as urban buildings or dedicated substations in rural areas. Air is the most used insulation gas inside the switchgear. The subcomponent "circuit breaker" performs the error isolation function by closing or opening the affected circuit. [6] While the circuit breaker is crucial for error management, it has the highest failure rate of all components inside a medium-voltage switchgear. [9,6–8] The circuit breaker is composed of four components: Pole, Housing, Linkage, and Drive. The most common error patterns according to IEEE guidelines are: failure in the closed position, failure to close, failure to close (Properly), failure to stay closed, failure in the open position, failure to open, failure to open properly, and failure to stay open [9,6].

2.2 Common and AI-enabled Maintenance strategies

The terminology *Maintenance* refers to a comprehensive set of technical, administrative, and management procedures carried out during an object's lifetime to keep it in working order or return it to it [10]. The most common maintenance strategies are: Preventive Maintenance, Reactive Maintenance, and Predictive Maintenance. [12,11]

Reactive maintenance describes the process of operating equipment till it fails. This approach maximizes the total operating time but can lead to severe damages through increasing defects in other equipment or long, expensive downtime. *Preventive maintenance* exploits knowledge about the typical lifetime of the equipment. With this approach, healthy equipment will be replaced or repaired periodically before defects occur. This leads to minimal unscheduled downtimes at the risk of over-maintenance parts. [6] The more sophisticated approach of *Predictive maintenance* monitors the equipment's condition through different parameters and predicts the health based on intelligent AI-enabled algorithms, like machine learning. [13,6] It then predicts possible downtimes or defects and can trigger corrective action. This can maximize the equipment's operating hours while reducing repair costs and avoiding unscheduled downtime. [6] Therefore to offer condition-based monitoring Predictive Maintenance will be the focus of this research.

3. Methodology

To solve the research hypothesis and to derive an operational concept for the application of Predictive Maintenance concepts for DSOs we gathered the status quo and identified the constraints and requirements to implement such a new system into the operational structure. To allow the interview to proceed as openly and flexibly as possible in a structured manner, the semi-structured interview approach was used to interview grid controllers and foremen of DSOs of different sizes and different grid topologies (s. Table 1). Within the framework of this method, some questions are planned in advance and consolidated in an interview guideline based on a user story framework; however, the majority of the course of the conversation is kept open. Based on the guideline, the topic and the interview direction are specifically controlled. This design creates the basis for new insights that the interviewer had not previously considered and makes it possible to gather and structure existing insights [14]. The interviewed grid operators and relevant data regarding the grid topology are described in Table 1. The choice of partners ensured that we were able to gather different insights into the needs for grid operators of different sizes. We also interviewed business departments to record the initial business process landscape. The requirements and constraints were structured into user stories and built the base on which the operational model was developed.

Table 1: Overview of the interviewed grid operators and their respective grid topology (HV – high voltage; MV – medium voltage; LV – low voltage)

Grid operator	Habitants in area	Area served [km²]	Power line length [km]	Operated grid level
1	100.000 – 999.000	100 – 499	10.000 – 20.000	HV, MV, LV
2	<100.000	<100	<10.000	MV, LV,
3	100.000 – 999.000	<100	<10.000	MV, LV
4	>1.000.000	>1.000	>20.000	HV, MV, LV
5	>1.000.000	500 – 1.000	>20.000	HV, MV, LV
6	100.000 – 999.000	100 – 499	<10.000	HV, MV, LV
7	<100.000	<100	<10.000	MV, LV,
8	100.000 – 999.999	100 – 499	<10.000	HV, MV, LV

Generally, the purpose of operational concepts is to provide an overview of the activities utilizing one or more specific systems, or a group of related systems, in the organizational operational environment from the users' and operators' perspectives [15]. Therefore, we base the modelling of the operational concept on the common *Architecture of Integrated Information Systems (ARIS) Framework* and will detail the operational concept by describing the business process model, the IT-system landscape, and an information logistic model. Originally developed for the description and modelling of computer-based information systems, the ARIS-Framework has proven itself at the business concept level, i.e., at the semantic model level with (partially) formalized description languages, in the course of business process modelling, for solving organizational process problems, and for reducing complexity in the description of operational information systems [16]. It provides a structured approach for designing and implementing information systems that align with the overall goals and objectives of the organization. Therefore the framework describes in different layers the need for an organization view, function view, data view, process view, and product view.

[17] The context of the framework and the chosen models for the result documentation is outlined in Figure 1.

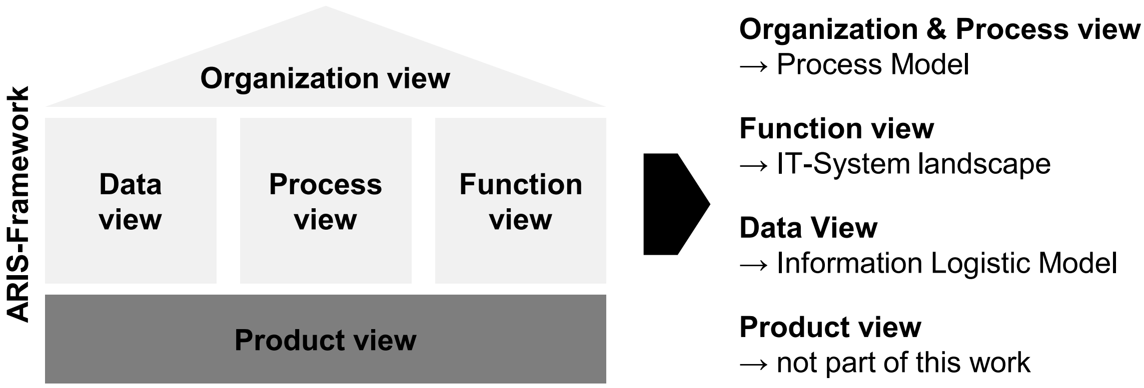

Figure 1 Context of the research methodology and models based on the ARIS-Framework based on [18]

The process and organizational view were modelled using the common *Business Process Model And Notation* in the 2nd version [19]. Furthermore, the description of the IT-system landscape describes the function view and is based on a typical UML-Class Diagram, which was abstracted for the applied use case [20]. For the data view, we model the information logistic concept using the *Information Logistics Notation (ILN)*, as illustrated by NIENKE et al. [21]. Because traditional interpretations of information logistics only model information as part of the flow of goods inside an organization [22]. We interpret information as an own logistical asset [23]. The ILN differentiates between stakeholders, database systems, and processing systems, representing objects that are characterized through an information sink on the left and an information source on the right side. Information flows are visualized through arrows between the objects. [21]

4. Operational Concept

The Operational Concept for the use of condition-monitoring based Predictive Maintenance strategies for medium-voltage switchgear is described based on the ARIS-Framework and will cover a Process Model (s. Chapter 4.1), a description of the IT-system landscape (s. Chapter 4.2) and an Information Logistics Model (s. Chapter 4.3).

4.1 Process Model

The process model for DSOs regarding Predictive Maintenance methods for switchgear equipment is visualized in Figure 4 in the Appendix of the paper. It describes the necessary actors, systems, and activities that must interact to offer Predictive Maintenance to DSOs. The model is designed to work as a business process visualization that helps employees to work with the system and as an instruction to implement it at DSOs. Therefore, it illustrates the organization and process view of the ARIS-Framework.

The relevant actors are the employees in the control centre and the installation technician. To interact in this system the process model introduces an Asset Management System (AMS), Geo-Information-System (GIS), and Machine-Learning-System (MLS). The model also interacts with external actors that are not part of the DSO's organisation and provides different services.

The process is characterized by reducing the need for additional interaction with the foreman and triggering the maintenance activities condition based on demand. The industrial technician now can check and gather the necessary parts based on the information he receives from the Predictive Maintenance report. The need to first check the premises while doing preventive maintenance to order the correct parts now becomes obsolete. Furthermore, the process describes how the workflow can be structured to skip the need to digitize a paper-based maintenance protocol. Additionally, the process illustrates the possibility to include external service providers when the necessary workforce or specific data sources are not available.

4.2 IT-System landscape

The IT-system landscape as detailed in Figure 2 illustrates the different IT-systems, databases, functions, and interfaces as well as their interaction with each other to enable a condition-based maintenance application compatible with the proposed processes at DSOs. This represents the function view of the ARIS-Framework.

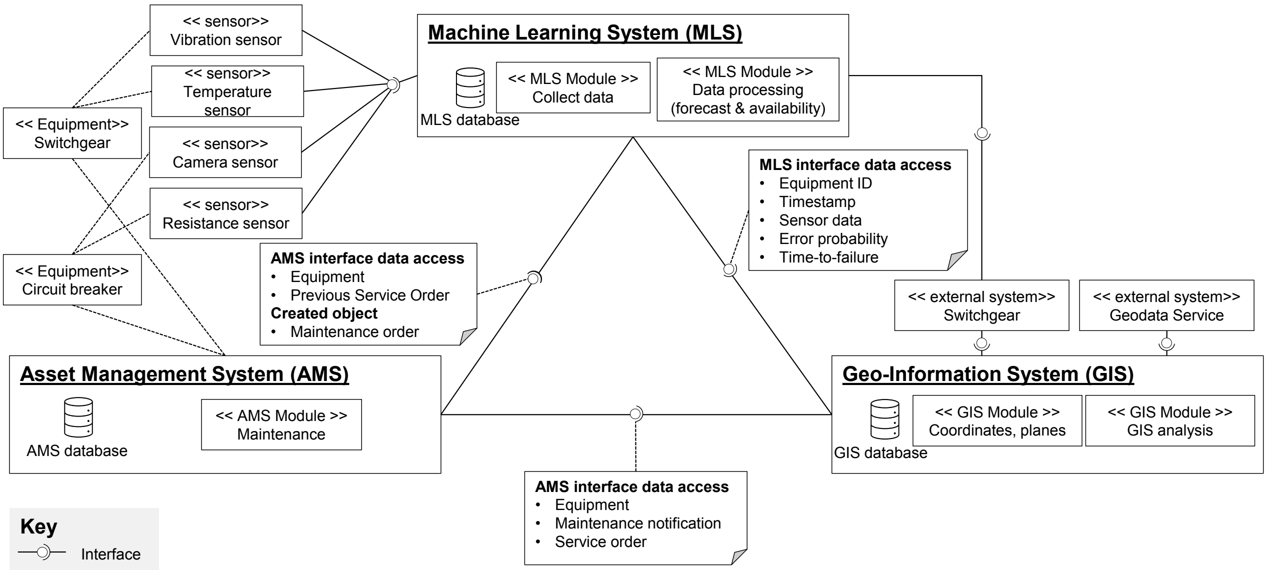

Figure 2 IT-system landscape and interfaces based on [24]

The AMS must share an interface with the MLS and contains the database that contains all the asset data regarding the circuit breaker and switchgear as well as the legacy maintenance function module which is based on a common Enterprise-Resource-Planning system architecture. Further an interface to the GIS is essential to share the notification and service orders. The MLS is the only system that is connected to the sensor hardware, which range from vibration, temperature, camera, and resistance sensors. Data will be collected in a dedicated database in the MLS, which includes the processing. To complete the architecture the MLS shares an interface with the GIS, which incorporates the necessary locations-based functions. While the AMS and GIS are mostly legacy systems that are already in use at DSOs the addition of the MLS makes the interfaces necessary to integrate it into the architecture. The proposed architecture can run on-premises or in the cloud but regulative restrictions regarding critical infrastructure must be evaluated in this case.

4.3 Information Logistic Model

The ILM in Figure 3 illustrates the information flow in the proposed system and the different information structures and dependencies and shows the data view of the ARIS-Framework. Therefore, this model shows how the connectivity in the whole application context is realized on the information layer.

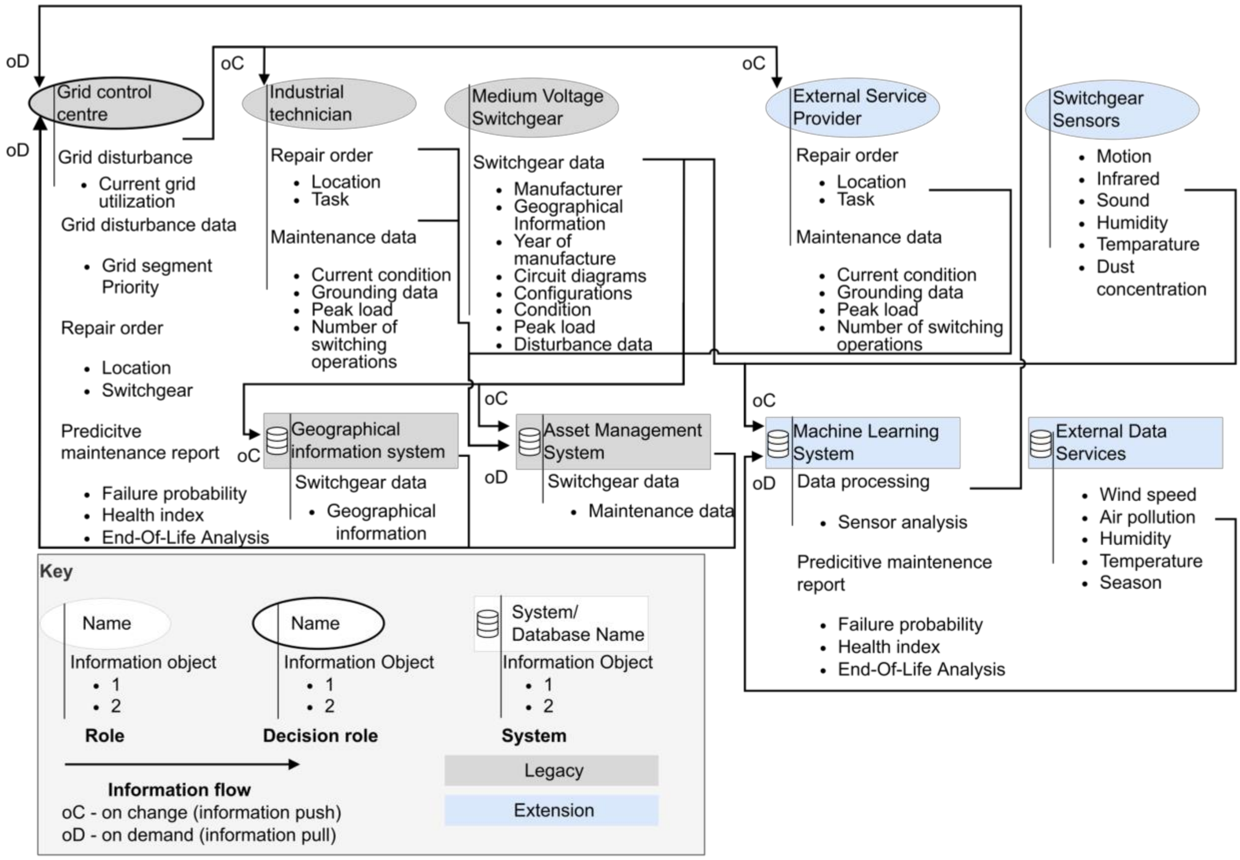

Figure 3 Information Logistics Model

As the decision role the Grid Control Centre needs to receive all information on demand. Other roles that must be considered while modelling the information logistics are the industrial technician, external service provider and the switchgear including the sensors, which push and pull information. The MLS takes a central role in pulling all information and pushing the results information to the Grid Control Centre. Overall, this model extends legacy systems at current DSOs and illustrates the extended information flow that derive from gathering, processing and evaluating data and information that come from the novel switchgear sensors and external sources.

5. Summary & Outlook

This paper presents an operational concept for the condition-based Predictive Maintenance of medium voltage switchgear specifically designed after the requirements of DSOs. It extends the current status quo of preventive maintenance strategies at DSOs and offers an operational concept for different abstraction layers in organizations. Therefore, this research gives DSOs an important indication and design guideline on how to implement AI-based maintenance strategies into their current asset management and how to structure the operations. Furthermore, this research creates further possibilities to research and create Service Systems and to lower cost for DSOs and enabling equipment resilience in the energy distribution grid. The operational concept offers further possibilities to be adapted for the use on other equipment or branches, which needs further evaluation. The implementation with the technical solution has to be evaluated as well as the practical relevance for DSOs in everyday operations.

Acknowledgments

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Appendix

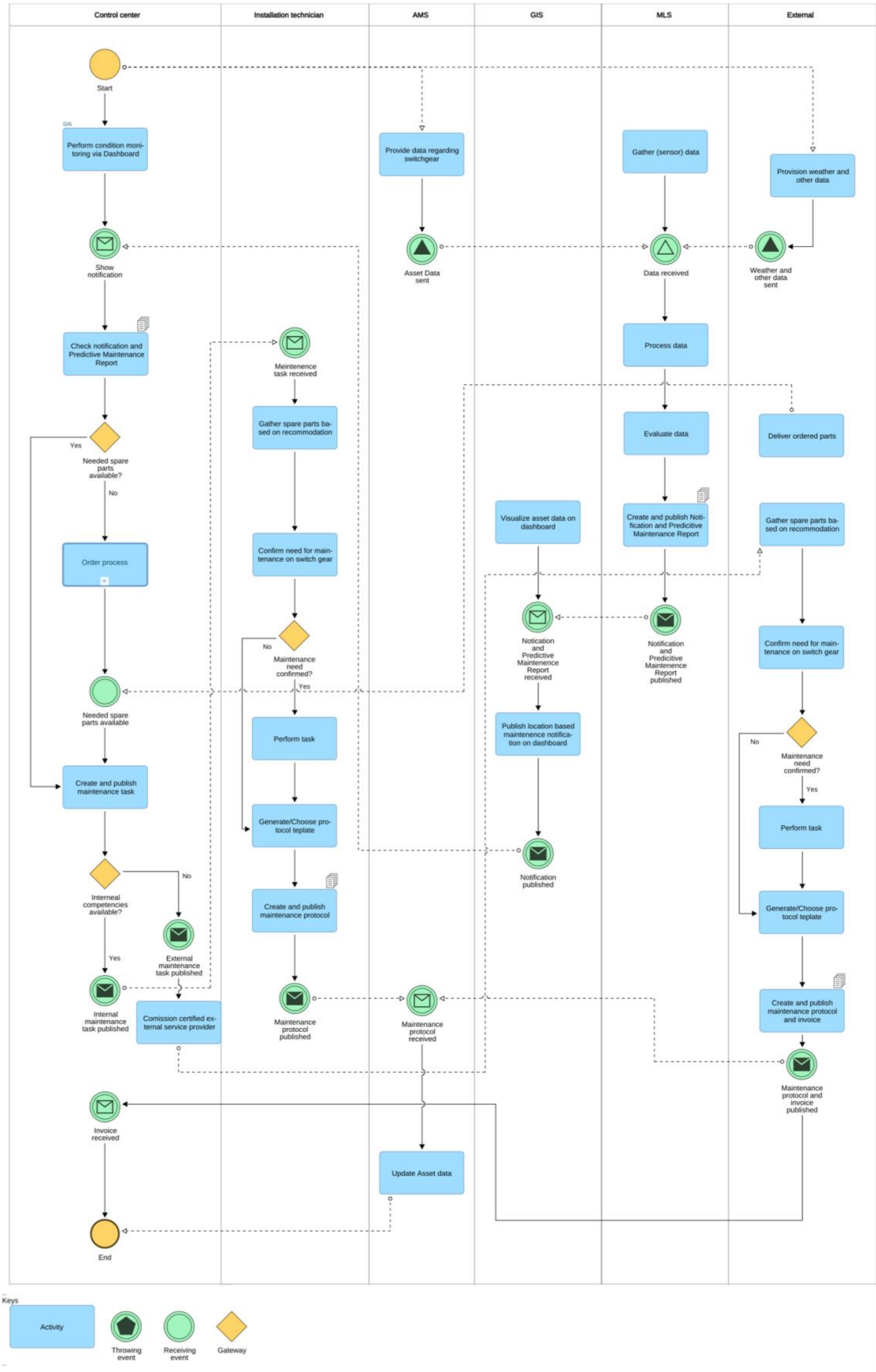

Figure 4 Overall Process Model

References

[1] Renn, O., Marshall, J.P., 2016. Coal, nuclear and renewable energy policies in Germany: From the 1950s to the "Energiewende". Energy Policy 99, 224–232.

[2] Schiffer, H.-W., 2019. Zielvorgaben und staatliche Strategien für eine nachhaltige Energieversorgung. Wirtschaftsdienst 99 (2), 141–147.

[3] Bundesnetzagentur für Elektrizität, Gas, Telekommunikation, Post und Eisenbahnen, 2019. Bericht zum Zustand und Ausbau der Verteilernetze 2018: Report, Bonn. https://www.bundesnetzagentur.de/SharedDocs/Downloads/DE/Sachgebiete/Energie/Unternehmen_Institutionen/NetzentwicklungUndSmartGrid/ZustandAusbauVerteilernetze2020.pdf?__blob=publicationFile&v=3.

[4] Goop, J., Odenberger, M., Johnsson, F., 2016. Distributed solar and wind power – Impact on distribution losses. Energy 112, 273–284.

[5] Gräf, T., 2020. Operational Aged Switchgear with the Age up to 50 Years: Investigations, Testing, Results. Considerations for Design and Operation of New Switchgear, in: Németh, B. (Ed.), Proceedings of the 21st International Symposium on High Voltage Engineering. Volume 1, 1st ed. 2020 ed. Springer, Cham.

[6] Hoffmann, M.W., Wildermuth, S., Gitzel, R., Boyaci, A., Gebhardt, J., Kaul, H., Amihai, I., Forg, B., Suriyah, M., Leibfried, T., Stich, V., Hicking, J., Bremer, M., Kaminski, L., Beverungen, D., zur Heiden, P., Tornede, T., 2020. Integration of Novel Sensors and Machine Learning for Predictive Maintenance in Medium Voltage Switchgear to Enable the Energy and Mobility Revolutions. Sensors (Basel, Switzerland) 20 (7).

[7] Zhang, X., Gockenbach, E., 2007. Component Reliability Modeling of Distribution Systems Based on the Evaluation of Failure Statistics. IEEE Trans. Dielect. Electr. Insul. 14 (5), 1183–1191.

[8] Zhang, X., Gockenbach, E., Wasserberg, V., Borsi, H., 2007. Estimation of the Lifetime of the Electrical Components in Distribution Networks. IEEE Trans. Power Delivery 22 (1), 515–522.

[9] IEEE Guide for Diagnostics and Failure Investigation of Power Circuit Breakers," in IEEE Std C37.10-1995 , 1996.

[10] European Committee for Standardization (CEN), 2001. Maintenance Terminology.

[11] Wang, K.S., 2014. Key Techniques in Intelligent Predictive Maintenance (IPdM) – A Framework of Intelligent Faults Diagnosis and Prognosis System (IFDaPS). AMR 1039, 490–505.

[12] Mobley, R.K., 2002. An introduction to predictive maintenance, 2. ed. ed. Butterworth-Heinemann, Amsterdam, 438 pp.

[13] Hastie, T., Tibshirani, R., Friedman, J., 2009. The Elements of Statistical Learning, Second Edition: Data Mining, Inference, and Prediction, 2., Ed. ed. Springer, New York, NY, XX, 744 S.

[14] Weßel, C., 2010. Semi-strukturierte Interviews im Software-Engineering: Indikationsstellung, Vorbereitung, Durchführung und Auswertung – Ein Fall-basiertes Tutorium, in: Fähnrich, K.-P., Franczyk, B. (Eds.), Informatik 2010. Service Science – Neue Perspektiven für die Informatik. Gesellschaft für Informatik e.V., Bonn, pp. 927–937.

[15] ISO/IEC/IEEE, 2018. Systems and software engineering.

[16] Software AG, 2015. ARIS-Methode: Version 9.8, Darmstadt. https://documentation.softwareag.com/aris/aris98d/ARIS-Methode.pdf. Accessed 13.01.23.

[17] Scheer, A.-W., 2002. ARIS - Vom Geschäftsprozess zum Anwendungssystem, Vierte, durchgesehene Auflage ed. Springer, Berlin, 186 pp.

[18] Tbaishat, D., 2017. Business process modelling using ARIS: process architecture. LM 38 (2/3), 88–107.

[19] Allweyer, T., 2009. BPMN 2.0 - Business Process Model and Notation: Einführung in den Standard für die Geschäftsprozessmodellierung. Books on Demand, Norderstedt, Online-Ressource.

[20] Fowler, M., 2010. UML distilled: A brief guide to the standard object modeling language, 3. ed, 16. printing ed. Addison-Wesley, Boston, Mass., 175 pp.

[21] Nienke, S., Zeller, V., Zöllner, O., Schuh, G., 2018. Introducing an Information Logistics Approach to Support the Development of Future Energy Grid Management, in: Proceedings of the 20th International Conference on Enterprise Information Systems - (Volume 2). March 21 - 24, 2018. International Conference on Enterprise Information Systems, Funchal, pp. 239–246.

[22] Immoor, K.H., 1998. Informationslogistik als Dienstleistung für vernetzte Unternehmen. Logistik im Unternehmen 12 (3), 48–50.

[23] Krcmar, H., 2015. Informationsmanagement, 6th Edition ed. Springer Gabler, Berlin, 814 pp.

[24] zur Heiden, P., Priefer, J., Beverungen, D., 2022. Smart Service für die prädiktive Instandhaltung zentraler Komponenten des Mittelspannungs-Netzes, in: Bruhn, M., Hadwich, K. (Eds.), Smart Services. Band 1: Konzepte – Methoden – Prozesse. Springer Fachmedien Wiesbaden; Imprint Springer Gabler, Wiesbaden, pp. 435–457.

Biography

Kajan Kandiah (*1994) has been working at the Institute for Industrial Management (FIR) at the RWTH Aachen University since 2020. In his current position as part of the Information Management he works in the technical group IT-complexity management. He specializes in IT-Architecture management, Smart Grid and transformation strategies.

Lars Kaminski (*1993) started working as a project manager at FIR at RWTH Aachen University in 2019. In his current position within the technical group IT complexity management, he specialized within IT architecture management and the development of transformation strategies with respect to energy management systems and information security.

Max-Ferdinand Stroh (*1991) is a researcher at FIR at RWTH Aachen University since 2017 in the department Information Management. He is head of the department Information Management. His scientific work is focused on the practical application of AI, smart products, and IT-OT-Integration.

Prof. Dr.-Ing. Volker Stich (*1954) has been head of the Institute for Industrial Management (FIR) at the RWTH Aachen University since 1997. Prof. Dr.-Ing. Volker Stich worked for 10 years for the St. Gobain-Automotive Group and lead the management of European plant logistics. In addition, he was responsible for the worldwide coordination of future vehicle development projects.

4th Conference on Production Systems and Logistics

Towards Finding Optimal Solutions For Constrained Warehouse Layouts Using Answer Set Programming

Pascal Kaiser[1], Andre Thevapalan[2], Moritz Roidl[1], Gabriele Kern-Isberner[2], Marco Wilhelm[2]

[1]*Chair of Material Handling and Warehousing, TU Dortmund University, Germany*
[2]*Chair of Logic in Computer Science – Information Engineering, TU Dortmund University, Germany*

Abstract

A minimum requirement of feasible order picking layouts is the accessibility of every storage location. Obeying only this requirement typically leads to a vast amount of different layouts that are theoretically possible. Being able to generate all of these layouts automatically opens the door for new layouts and is valuable training data for reinforcement learning, e.g., for operating strategies of automated guided vehicles. We propose an approach using answer set programming that is able to generate and select optimal order picking layouts with regards to a defined objective function for given warehouse structures in a short amount of time. This constitutes a significant step towards reliable artificial intelligence. In a first step all feasible layout solutions are generated and in a second step an objective function is applied to get an optimal layout with regards to a defined layout problem. In brownfield projects this can lead to non-traditional layouts that are manually hard to find. The implementation can be customized for different use cases in the field of order picking layout generation, while the core logic stays the same.

Keywords

warehousing; layout planning; order picking; optimization; answer set programming

1. Introduction

Warehouse layout planning is a well-studied problem with good results for predefined shapes and designs [1]. However, a completely rule-based generation without predefined shapes and designs is missing. This is considered a poorly structured decision problem [2]. Therefore, planners rely on their personal experience in designing warehouses [3]. Although there are systematic planning approaches to address this problem [2], the automation of the internal layout design problem depends on idealized conditions, e.g., rectangular space, predefined layout (multi-block, fishbone, etc.) or parallel aisles [4–6]. Each of these designs have to follow the same rules to be a feasible solution for an order picking system, e.g., every storage location has to be accessible.

For highly constrained warehouses with spatial or resource-related constraints, it is even more difficult to find viable layout options. This is the case, for example, in brownfield projects with given structural restrictions and other constraints (e.g., existing material flow restrictions). Planning such highly constrained order picking layouts can be challenging even for experts, with no good solutions being found. One reason for this may be the planners bias based on their personal experience, and new layout options may not even be considered. Formalizing this expert knowledge to be machine-readable creates new possibilities for the automated generation of layouts. When all of the rules for the layout generation are formalized, it is no longer necessary to idealize the conditions (e.g., rectangular space, predefined layout). The layouts are generated

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implicitly following the formalized knowledge. We are investigating the use of a declarative rule-based approach for the automated generation of layouts for this problem.

Answer set programming (ASP) is a declarative problem solving approach from the area of logic programming [7] which can solve highly complex combinatorial problems [8]. Such problems are modeled in form of logic programs which consist of possibly defeasible rules that lead to a conclusion when the premise of the rule applies. The defeasibility of a rule is formalized by the use of default negation which causes that the rule is usually applicable unless the default-negated part of the rule is true. Therewith, ASP can resolve conflicts which arise from competing objectives automatically which represents an added value compared to classical constraint programming. Typically, ASP programs have several feasible solutions from which the optimal solutions with regard to a certain objective function can be filtered. In [9,10] the authors showed that ASP is an appropriate method for logistical problems. Here, we formalize the constraints and the basic objectives of the warehouse layout generation task by ASP rules and optimize the area utilization in order to find suitable warehouse layouts.

The goal of this paper is to show that ASP is predestined to generate optimal order picking layouts respecting a defined objective function by reason of its declarative nature, readability, and versatility. After the formalization of the knowledge in a logic program, the implementation is capable of generating every optimal layout that satisfies all building restrictions and constraints, considering the optimization objective. Furthermore, it is possible to add and remove constraints and objectives in form of rules in a straightforward manner. Default negation allows to easily define exceptions to general rules. Together with their declarative nature, which deems the order of rules irrelevant, answer set programs are generally easily extendable. We will show that with all these key advantages, ASP constitutes an effective tool to assist the planning of layouts especially in brownfield projects. To demonstrate the benefits of ASP, we extended the solution presented in [9] in order to showcase an implementation that creates layouts for a manual order picking process based on given building restrictions and constraints abstracted from a real-world example.

The remainder of this paper is structured as follows. After presenting an introduction into answer set programming and warehouse layout generation in Section 2, Section 3 outlines the goals of this paper and provides an overview of the implementation's main functionalities. In Section 4, the developed implementation is illustrated and key components are explained. Then, the program is used to generate a possible layout for a given problem instance (building restrictions, number of racks, base position, etc.). The final section concludes the paper with a short summary and provides an outlook on future work.

2. Preliminaries

This section provides the necessary background on ASP and layout generation. Therefore, we first introduce ASP with the underlying definitions in order to illustrate on which bases the implementation in Section 4 is built. Afterwards we elaborate on the challenges of the layout generation and which indicators and goals can be pursued with different layouts.

2.1 Answer Set Programming

Answer set programming [7] constitutes a declarative programming paradigm based on logic programs which allows for a rule-based description of real-world problems. ASP features the concept of *default negation* with which it is possible to formulate default statements that hold unless an exceptional case arises. Therewith, conflicts in ASP programs can be resolved automatically. For more details, see [8,11]. Here, we consider ASP based on *normal logic programs (NLPs)*, which are sets of *rules r* of the form

$$h :- b_1, \dots, b_m, not\ b_{m+1}, \dots, not\ b_n. \quad (1)$$

where h and each b_i are atoms. An atom a is of the form $p(t_1, \dots, t_k)$ where p is a predicate of arity k, and each t_i is either a constant or a variable, like in classical first-order logic. Conventionally, variables are written in uppercase letters and constants in lowercase letters. Variable-free programs, rules, respectively atoms are called *ground*. The prefix *not* in r indicates a default-negated atom. Intuitively, the rule r states that unless any of the default-negated atoms is true, the *rule head h* follows from $b_1, \dots, b_m$. Otherwise, the rule is blocked. Rules with $n = 0$ are *facts*, in this case we omit the symbol ": -", and rules with an empty head are *constraints*. Constraints serve to filter out unwanted solutions.

The semantics of an NLP $\mathcal{P}$ is defined over *reducts* of $\mathcal{P}$ which are built w.r.t. possible solutions of $\mathcal{P}$, more formally w.r.t. *interpretations* which are sets of ground atoms. The *reduct* $\mathcal{P}^{\mathcal{I}}$ of a ground NLP $\mathcal{P}$ w.r.t. an interpretation $\mathcal{I}$ is basically $\mathcal{P}$ but from which all rules r are removed that contain a default-negated atom not b_i with $b_i \in \mathcal{I}$. Further, from all remaining rules the default-negated atoms are removed as well as they are satisfied in $\mathcal{I}$ and, hence, do not block r. An interpretation $\mathcal{I}$ now is a solution of $\mathcal{P}$, formally called answer set, if $\mathcal{I}$ satisfies every rule in $\mathcal{P}^{\mathcal{I}}$, i.e., if $\{b_1, \dots, b_m\} \subseteq \mathcal{I}$ implies $h \in \mathcal{I}$ for every rule $h :- b_1, \dots, b_m \in \mathcal{P}^{\mathcal{I}}$, and $\mathcal{I}$ is set-minimal with this property. An interpretation $\mathcal{I}$ is an answer set of a non-ground NLP $\mathcal{P}$ if $\mathcal{I}$ is an answer set of the grounding of $\mathcal{P}$ which means the ground NLP $\mathcal{P}'$ that is obtained by replacing every variable in $\mathcal{P}$ by each available constant once. While logic programs have a unique solution, NLPs with default negation may have several answer sets.

The implementation described in this paper is implemented with the ASP system *clingo*[1]. Technically, the grounding of NLPs is executed by *ASP grounders* (e.g., *gringo*) and the answer sets are computed by *ASP solvers* (e.g., *clasp*). Clingo offers several language extensions and the integration of external methods (either in the programming language *Python*[2] or *Lua*[3]) into the solving process which will be shown later.

2.2 Warehouse Layout Generation

A large extent of the warehousing costs is already determined during the design phase. This design phase is characterized by many trade-offs between conflicting objectives which means it is a highly complex task, resulting in a large number of feasible designs. The authors in [12] define the warehouse design as a structured approach to decision making at a strategic, tactical and operational level.

An integral part of the warehouse design process are decisions on the warehouse layouts. It can be distinguished between two types of layout decision problems. The first type of decision problems is the placement of various departments such as receiving, picking, storage, etc. [13]. This is usually called the facility layout problem and it results in a warehouse block layout that is often based on minimizing the handling costs. The second type of problem is called internal layout design or aisle configuration problem. It consists of placing the equipment, storage space, paths, etc. within the departments [4,14].

The warehouse layout problem is usually defined as finding an optimal or at least good layout of the storage or order picking area. In contrast to the other areas, the order picking area layout design is not represented sufficiently in the literature [1,4]. It is mainly focused on conventional layouts or adaptations of it (fishbone or flying-V layouts) which is sufficient for greenfield projects [5,15]. Therefore, a limited amount of different layouts can be found in the majority of warehouses today. Usually these warehouses use a conventional warehouse layout for the storage area and the order picking area. These traditional warehouse layouts have a rectangular shape with parallel straight aisles [16]. There are two possibilities to change the aisles, at the front and rear of the warehouse. These aisles meet the main aisles at a right angle (as shown on

[1] https://potassco.org/clingo/
[2] https://python.org/
[3] https://lua.org/

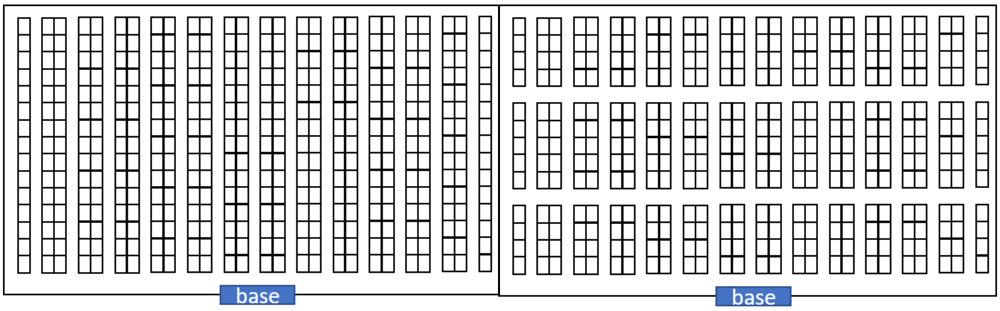

Figure 1: Order picking layouts

the left in Figure 1: Order picking layoutsFigure 1). There are some modifications of this general form that are usually created by adding one or more additional cross aisles [5]. Such layouts are then called multi-block layouts (as shown on the right in Figure 1) [17].

The optimization of layouts usually takes place regarding two objectives, capacity and performance. These two aspects are conflicting with each other, optimizing the capacity usually has negative influence on the performance and vice versa. Several objectives can be pursued within these categories, e.g., minimizing inventory, maximizing storage capacity, maximizing area or space utilization, minimizing travel distance or travel time. Ultimately all these objectives aim at reducing costs [1,18–20]. Within a greenfield project, the capacity is usually set for the warehouse and thus, the optimization aspect is performance. In contrast, in a brownfield project the total available space is set [21]. Maximizing the capacity can be an important objective. Nevertheless, the performance still has to be considered in order to reduce the operational costs. This leads to the problem of warehouse layout planners on how to define the objective function and generate warehouse layouts with given restrictions.

3. Problem Formulation

In order to assist the layout planning process, we propose a modular framework that allows planners to input project-specific key values like the size of the available warehouse, the available types of racks and their respective sizes, and the amount of racks that have to be positioned. They are also able to define more detailed, project-specific properties and constraints regarding the project, e.g., inaccessible parts of the warehouse, constraints regarding the placement of racks of specific types, or the minimum/maximum distances between elements. The implementation presented in this paper constitutes a key part of such a framework with the goal to integrate ASP into the layout planning process. An overview of the framework's workflow is depicted in **Error! Reference source not found.**. It starts with the user who can enter the aforementioned key instance values. This instance data is then added to the problem encoding which contains the general facts and conditions that hold for the typical warehouse layouts like ensuring that each rack must be accessible. The problem encoding can be adapted and extended by further project-specific rules and constraints. The ASP solver computes the answer sets of the logic program where each answer set represents a layout based on the knowledge base modeled in the logic program. Subsequently, the set of layouts can be further reduced using additional algorithms via external functions. The filtered layouts can then be rendered as 2D graphics and displayed to the user.

4. Implementation

In this section, we outline the main aspects of the implementation.

Problem Instance: In ASP, logic programs are often divided into the *problem encoding* and the *problem instance* [8]. The problem instance can be viewed as the input data for the logic program that varies from

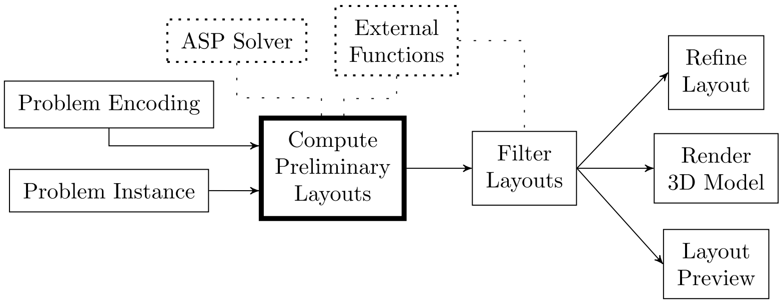

Figure 2: Framework overview

case to case. The base of our implementation is a logic program where the problem encoding contains the encoding of structural warehouse elements, the definition of general dependencies, and constraints regarding their positioning. The problem instance comprises case-based, individual specifications, e.g., details regarding the structure of the order picking area. Thus, the same problem encoding can be used for different use cases.

Let $\mathcal{P}$ be the answer set program of our implementation. The following rules r_1-r_8 constitute a part of the problem instance of $\mathcal{P}$[4].

```
r1: #const size_x = 20.
r2: #const size_y = 20.
r3: elem_quantity(1,47).
r4: elem_quantity(2,13).
r5: coords(1,1..size_x/2,1..size_y/2).
r6: coords(2,size_x/2+1..size_x,1..size_y/2).
r7: blocked(1..2,1..2).
r8: blocked(19..20,1..5).
```

The order picking area is represented by a *grid structure* comprising *x* columns and *y* rows where a *cell* stands for a specific position in the area and is denoted by its coordinates. This kind of representation allows a coarse-grained but flexible modeling of the available area. A cell is either free, blocked from the start (which is illustrated by rules r_7 and r_8), or occupied by another element, e.g., a rack. Using the representation of an order picking area as a grid offers high flexibility with respect to scalability. In rules r_1 and r_2, a language extension called *constants* is used that works analogously to constants in common programming languages, i.e., constants are globally accessible but fixed variables. With the constants `size_x` and `size_y`, the size of the area is defined. Other mandatory instance values include the amount of racks for each rack type that each layout has to contain and the area restriction regarding each type of racks, i.e., the planner is able to define that certain rack types must be positioned in specific areas of the layout. Here, r_3 and r_4 define that 47 racks of type 1 and 13 of type 2 must appear in a layout. Rule r_5 ensures that racks of type 1 are only allowed to be positioned inside the lower left quadrant of the warehouse whereas rule r_6 states that racks of type 2 must be positioned in the lower right quadrant.

In the following, we present the key parts of the problem encoding.

Defining Part: In the defining part, we provide auxiliary predicates and specify further general details regarding the order picking area and the structural elements. The following rules lay down the dimensions regarding two of the four rack types and state the possible orientations a rack can have.

```
r9: elem_type(1,"BlockStorage",1,1).
r10: elem_type(2,"ShelvedRacking",3,1).
r11: types_rack(1;2;3;4).
r12: orient(h;v).
```

Rule r_9 represents an element type named "BlockStorage" with id 1 that occupies exactly one cell. With rule r_{10} another rack type named "ShelvedRacking" is defined with id 2 and the width of three cells and depth of one cell. In rule r_{11}, the distinction between racks and other structural elements like conveyor belts or bases is stipulated by explicitly stating that element types with ids 1,2,3 and 4 are rack types. The concept of

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[4] The code snippets partially contain language extensions that go beyond the definitions stated in Section 2. For a formal explanation of such extensions, we refer the reader to [22].

rotating an element is represented by *orientation*-literals in rule r_{12}. The available orientations are *horizontal* where an element either faces the north or south side of the layout and *vertical*, where the element faces the east or west side.

Another important functionality in this encoding is the assurance that in every layout, each rack is accessible from the base, that is, there must be a path consisting of free cells from the base to each rack.

```
r13: reach(10,5,1).      r14: reach(11,5,2).
r15: reach(X,Y,TID) :- reach(X+1,Y,TID), not blocked(X,Y), coords(X,Y).
r16: elem_reach(ID,TID,h,X,Y) :- elem(ID,TID,_,h,X,Y), reach(X,Y+1,TID).
```

For this, we define the cells directly above the base as "reachable" (e.g., rules r_{13} and r_{14} for rack types 1 and 2, respectively). Using (recursive) rules like rule r_{15}, every free cell that is adjacent to a reachable cell is also flagged as reachable. In case of r_{15}, we mark all cells right of a reachable cell as reachable if they are not blocked. This rule shows how default negation can be used to define exceptions to a general rule, that is, a cell in the layout is reachable unless it is marked as blocked. By rule r_{16}, the program collects all horizontally positioned elements that have a reachable cell above. Doing this for all possible combinations of racks and neighboring cells, we can later check if all racks are indeed accessible, that is, if all racks have a reachable cell in front of them.

Generating Part: In the generating part of this program, the goal is to calculate the position of all racks that are requested via the instance data. A rack that is positioned in a layout is represented by the cells it occupies and a cell that is occupied by a rack is encoded by an `elem`-literal. The following rules r_{17}-r_{19} constitute a segment of the program's *generating part*.

```
r17: elem_core_coords(T,X,Y) : coords(T,X,Y) :- elem_quant(T,Q).
r18: 1 {elem_core(@get_rack_id(X,Y),T,O,X,Y) : orient(O)} 1
          :- elem_core_coords(T,X,Y), elem_orient(T).
r19: 1 {elem(ID,T,N,O,X,Y) : coords(T,X,Y) , not blocked(X,Y)} 1
          :- X=STX..ENX,Y=STY..ENY, elem_core(ID,T,h,STX,STY),
             elem_type(T,N,SX,SY), ENX=STX+SX-1, ENY=STY+SY-1.
```

The exact positions of a rack are gradually computed. Keep in mind that the declarative nature of ASP does not involve a specific order or preference over rules. Instead, the importance of rules can be indirectly given using certain dependencies between rules. In this case, we compute more general `elem_core_coords`-literals that encode the starting point of each rack, i.e., racks larger and taller than one cell is first represented by a single cell and expanded according to their actual size using another rule. Rule r_{17} states that for every rack type T there have to be Q `elem_core_coords`-literals in the answer set. The coordinate restrictions defined in r_5 and r_6 are used to let the racks appear in specific areas of the layout according to their type. Before the racks can be expanded, their respective orientation have to be established. In r_{18}, to each `elem_core_coords`-literal, an orientation (see r_{12}) is added, yielding fitting `elem_core`-literals. In the head of r18, the external atom `@get_rack_id(X,Y)` represents the return value of a function that is located in a connected Python script. This function uses the coordinate values X and Y to compute and return a unique id for the respective rack based on its coordinates. This does not only create explicit references to each rack, it also induces a total ordering over all racks.

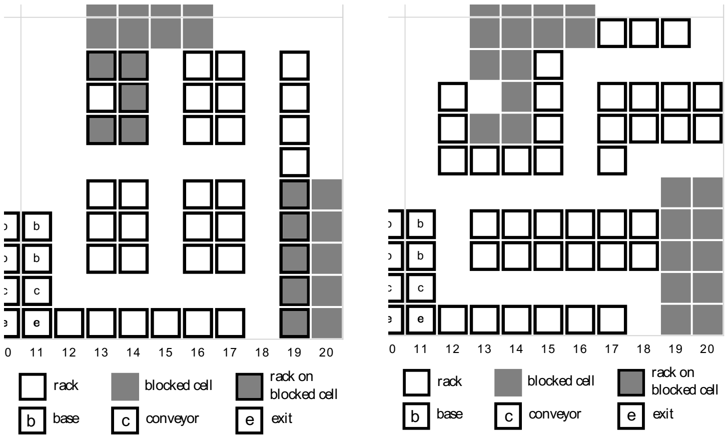

Figure 3: Effect of the default-negated literal not blocked(X,Y) in rule r_{19}: Consideration of blocked areas

For racks that are derived to be horizontal, rule r_{19} states the expansion of each `elem_core`-literal by deriving the aforementioned `elem`-literals. A literal `elem(ID,T,N,O,X,Y)` encodes a (part of a) rack named *N* of type *T* with an id ID that is occupying cell (X, Y). Since during the expansion, the value in ID is adopted from the respective `elem_core_coords`-literal, every such unique identifier in `elem(ID,T,N,O,X,Y)` refers to each part of the expanded rack in the layout. Note that *N* identifies each of these parts as belonging to rack *N*.

The default-negated body literal `not blocked(X,Y)` in rule r_{19} prevents the ASP solver from placing racks on blocked cells. The effect of this literal is that, by default, a rack can be expanded to any cell of the grid unless this cell is blocked (see Figure 3). For vertical racks, a rule analogously to r_{19} is considered in the implementation.

Testing Part: According to the generating part, the layouts contain the correct number of racks and are positioned in the respective area, but there are no restrictions defined yet to ensure that the positioning of the racks is sound (e.g., racks do not overlap with other racks and every rack is accessible). For that reason, in the *testing part* of the program, constraints are added that prevent undesirable layouts.

```
r20: :- elem(ID1,_,_,_,X,Y),elem(ID2,_,_,_,X,Y),ID1!=ID2.
r21: :- elem(_,300,_,_,X,Y),elem(_,T,_,_,X-1..X+1,Y-1..Y+1), types_rack(T).
r22: :- not elem_reach(ID,TID,O,X,Y), elem(ID,TID,_,O,X,Y).
```

As only the starting points of racks are positioned in the layout and expanded separately according to the actual respective size, the expansion can lead to the overlapping of racks. Rule r_{20} prevents such errors by stating that rack parts that share the same coordinates must not belong to different racks. Another aspect to consider are minimum distances, e.g., between racks and the base. With rule r_{21}, any layout that is solved contains a clearance of at least one cell between the base and racks of any type, where `element(_,300,_,_,X,Y)` stands for any element that belongs to the base. Rule r_{22} makes sure that every layout where a positioned rack is not accessible from the base is omitted. In this manner, further constraints can be added to satisfy further restrictions and requirements.

Optimization Criteria: As logic programs output all possible solutions that satisfy all rules, a vast amount of layouts can arise. Therefore, for all computed layouts further properties are calculated externally in order to obtain optimal layouts. From the logistical viewpoint, there are several key values that can be used to define optimal layouts. In the current implementation, we exemplify the optimization of such values by minimizing the path lengths between each pair of racks and additionally minimizing the path from each rack to the base. In both cases, we use an external Python script that computes the different minimal path lengths for each layout using existing algorithms for breadth-first search and outputs those layouts that have minimal values.

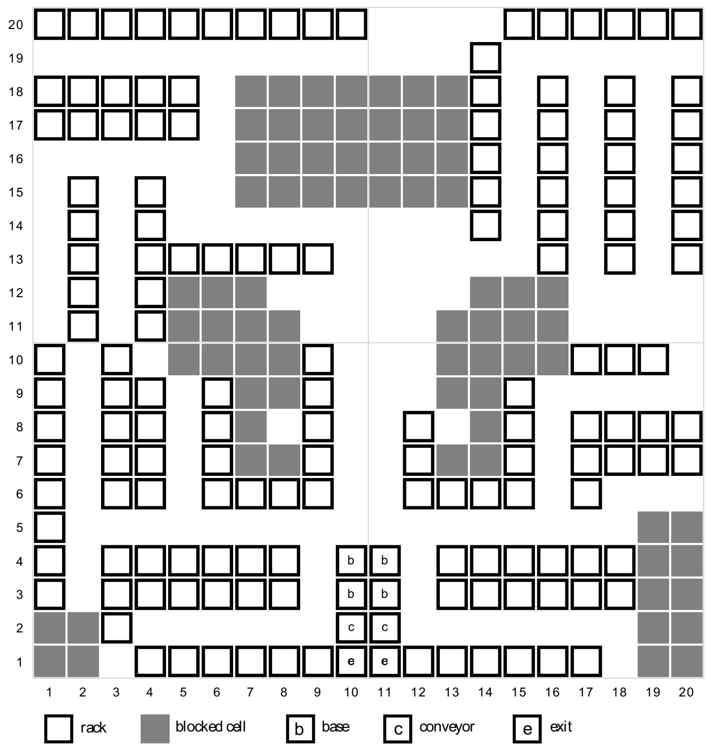

Figure 4: Example of a generated layout

5. Case Study

In order to show the capabilities of the implementation, we conduct a small case study based on a real-world example. The aim of this case study is to illustrate that it is possible to generate order picking layouts based on defined rules and show its different possibilities, e.g., positioning of different systems, constructional constraints and implementation of objective function. The goal of the use case is the positioning of different types of racks inside a predefined layout for a manual order picking system. Such different types of racks can be e.g., shelf storage or pallet racks. The basic layout is a 20 meters by 20 meters square with restricted cells. Within restricted cells, racks cannot be positioned. These cells can be e.g., walls, pillars or rooms and are colored grey in Figure 4. Further restricted cells are the basis, where every picking task starts and ends, and a corresponding conveyor belt. This information is encoded in the problem instance (Section 4).

To show that the implementation is able to handle different types of racks, the task is to position four types of racks. Since from a logistical point of view, it is not advantageous to mix different kinds of racks, for each group of racks an area where to put them is predefined. The racks to be positioned are 47 1x1-racks of size 1 meter by 1 meter, 13 1x3-racks of size 1 meter by 3 meters, seven 1x5-racks of size 1 meter by 5 meters and five 1x6-racks of size 1 meter by 6 meters. Racks are marked as black outlined rectangles. The smallest racks should be positioned in the bottom left quadrant of the layout, the next bigger kind of racks in the bottom right quadrant of the layout. The second largest racks in the top left quadrant and the largest racks in the top right quadrant. The defining part (Section 4) of the encoding specifies these different types of racks. Besides defining the different types of racks, further layout specific restrictions can be defined.

In order to generate valid layouts, basic rules of layout planning have to be obeyed. These are general rules that apply for most of the warehouses, such as two racks cannot be positioned in the same cell or that every rack needs to be accessible from one side. This is encoded in the testing part (Section 4).

With these defined input parameters, we are generating unique layout models for the racks. The layout generation results in 474 different models for the 1x1 racks, 163 different models for the 1x3-racks, 22 models for the 1x5-racks and 826 different models for the 1x6-racks. The generation of all layouts took approximately 51 seconds. In order to get an optimal solution, we are calculating the travel distance between two racks and between the racks and the base for each model. The objective is to minimize the total travel distance in the layout. For this calculation, the orientation of a rack has to be considered, i.e., a rack must face a reachable cell. In some cases, a rack can have multiple possible orientations. As in each layout a unique orientation must be specified for each rack, additional models can arise. As a consequence, regarding the 1x1-racks, 1x3-racks, 1x5-racks, and 1x6 racks, we obtain 653440, 169, 32, and 1340 different models, respectively. The current implementation allows the calculation of distances in 50-200 milliseconds per model. Here, we reach total execution times of 107263.05 seconds (1x1-racks), 36.5 seconds (1x3-racks), 8.99 seconds (1x5-racks), and 169.47 seconds (1x6-racks). Considering all requirements and the optimization directives, we get ultimately a single layout that is optimal w.r.t the total travel distance (see Figure 4). If desired, a user can always inspect the next best options to obtain a better overview of the results.

To make further improvements to the layout, a manual refinement process can follow. In this case for example, the rack in cell (3,2) creates a dead space to guarantee minimum travel distances. The dead space can be avoided by moving this rack into cell (3,1). Additionally, the rack in cell (2,11)-(2,15) could be moved to cell (1,11)-(1,15) to get a passage between the different areas. To improve the visualization of the layout for a warehouse planner, the output data of the program can be used to generate a three-dimensional layout. This layout can then be used to validate the generated layouts as showcased in [9]. After this refinement process, the new rack positions can then be entered into the program instance in order to check if all defined constraints are still obeyed. This ensures that the warehouse planner does not generate an invalid layout.

6. Conclusion and Future Work

We have shown that ASP poses a powerful tool to enhance the layout planning workflow by presenting a logic program that generates feasible layouts where structural elements are positioned in a highly-constrained warehouse meeting predefined optimization directives. As a solver for ASP computes all possible answer sets that satisfy the program, all computed layouts meet the requirements and conditions defined in the program's rules. To yield the most preferred layouts, specifications can be refined further, e.g., by adapting and adding suitable constraints and optimizations statements. The declarative nature of ASP innately implies a high degree of modularity (e.g., the generated solutions are independent of the actual order of the rules in a program) which allows for a continuous improvement of the program and therefore the layout generation process. This simplifies the process of adding or changing constraints in a logic program. Thus, using ASP allows a step by step approach of implementing the constraints and focusing on rather difficult problems at the beginning.

The presented solution is able to generate restricted warehouse layouts within a short amount of time. In future work, we want to optimize the calculation of the travel distances to reduce the total computation time even further. For this, we will explore ways to decrease the number of models without sacrificing the expressiveness of the encoding and further algorithms to measure the distances.

The generated layouts (including those computed without any optimization directives) can be utilized to create additional input data to train operating strategies of *automated guided vehicles* (*AGVs*). As the solver computes every possible layout w.r.t. the program's rules, the AGVs are able to train on potential edge cases, i.e., layouts that in manual layout planning perhaps would not have been taken into consideration. This kind of reinforcement learning constitutes a significant step towards reliable artificial intelligence.

The proposed framework aims at supporting a layout planner in the decision-making process rather than replacing them. One aspect that reflects the need for the planner is highlighted in the case study where even in technically optimal layouts further refinements might be necessary. The possibility to manually refine generated layouts is also crucial and the implementation of a refinement step is part of our future work.

References

[1] Dukic, G., and Opetuk, T., 2012, “Warehouse Layouts,” Warehousing in the Global Supply Chain.

[2] Schmidt, M., 2018, Distribution Center Design Process: Ein Systemtechnikorientiertes Vorgehensmodell Zur Konzeptplanung von Logistikzentren.

[3] Wunderle, A., and Sommer, T., 2014, “Erfahrung Und Augenmaß Zählen,” Hebezeuge Fördermittel.

[4] de Koster, R., Le-Duc, T., and Roodbergen, K. J., 2007, “Design and Control of Warehouse Order Picking: A Literature Review,” European Journal of Operational Research.

[5] Roodbergen, K. J., and Vis, I. F. A., 2006, “A Model for Warehouse Layout,” IIE Transactions.

[6] Cardona, L. F., Soto, D. F., Rivera, L., and Martinez, H. J., 2015, “Detailed Design of Fishbone Warehouse Layouts with Vertical Travel,” International Journal of Production Economics.

[7] Gelfond, M., and Lifschitz, V., 1991, “Classical Negation in Logic Programs and Disjunctive Databases,” New Gener. Comput.

[8] Gebser, M., Kaminski, R., Kaufmann, B., and Schaub, T., 2012, Answer Set Solving in Practice.

[9] Kaiser, P., Thevapalan, A., Reining, C., Kern-Isberner, G., and ten Hompel, M., 2021, “Generating Highly Constrained Warehouse Layouts Using Answer Set Programming,” Logistics Journal : Proceedings.

[10] Kaiser, P., Thevapalan, A., Reining, C., Roidl, M., Kern-Isberner, G., and ten Hompel, M., 2022, “Hybrid Production: Enabled By Controlling The Output Sequence Of A Matrix Production Using Answer Set Programming,” Procedia CIRP.

[11] Brewka, G., Eiter, T., and Truszczynski, M., 2011, “Answer Set Programming at a Glance,” Commun. ACM, 54(12), pp. 92–103.

[12] Rouwenhorst, B., Reuter, B., Stockrahm, V., van Houtum, G. J., Mantel, R. J., and Zijm, W. H. M., 2000, “Warehouse Design and Control: Framework and Literature Review,” European Journal of Operational Research.

[13] Mohsen, 2002, “A Framework for the Design of Warehouse Layout,” Facilities.

[14] Grosse, E. H., Glock, C. H., and Neumann, W. P., 2015, “Human Factors in Order Picking System Design: A Content Analysis.”

[15] Öztürkoğlu, Ö., Gue, K. R., and Meller, R. D., 2012, “Optimal Unit-Load Warehouse Designs for Single-Command Operations,” IIE Transactions.

[16] Zhang, Z. Y., Liang, Y., Hou, Y. P., and Wang, Q., 2021, “Designing a Warehouse Internal Layout Using a Parabolic Aisles Based Method,” Advances in Production Engineering & Management.

[17] Sancakli, E., Dumlupinar, I., Akcin, A. O., Cinar, E., Geylani, I., and Düzgit, Z., 2022, “Design of a Routing Algorithm for Efficient Order Picking in a Non-Traditional Rectangular Warehouse Layout,” Digitizing Production Systems.

[18] Arnold, D., and Furmans, K., 2007, Materialfluss in Logistiksystemen: Mit 19 Tabellen, Springer.

[19] Köbler, J., Schöning, U., and Torán, J., 1993, “Decision Problems, Search Problems, and Counting Problems,” The Graph Isomorphism Problem: Its Structural Complexity.

[20] Noortwyck, R., Müller, T., Wehking, K.-H., and Weyrich, M., 2018, “Dezentrale Assistierte Planung: Integrierte Layout- Und Systemplanung von Intralogistiksystemen Auf Grundlage Einer Agentenbasierten Software,” Logistics Journal : Proceedings.

[21] Accorsi, R., Baruffaldi, G., and Manzini, R., 2017, “Design and Manage Deep Lane Storage System Layout. An Iterative Decision-Support Model,” The International Journal of Advanced Manufacturing Technology.

[22] Gebser, M., Kaminski, R., Kaufmann, B., Lindauer, M., Ostrowski, M., Romero, J., Schaub, T., Thiele, S., and Wanko, P., “Potassco Guide Version 2.2.0 (2019).”

Biography

Pascal Kaiser is a research assistant at the Chair of Material Handling and Warehousing, TU Dortmund University.

Andre Thevapalan is a research assistant in the working group Information Engineering at the Chair of Logic in Computer Science at the Department of Computer Science, TU Dortmund University.

Moritz Roidl is the chief engineer at the Chair of Material Handling and Warehousing, TU Dortmund University.

Prof. Dr. Gabriele Kern-Isberner is the head of the working group Information Engineering at the Chair of Logic in Computer Science at the Department of Computer Science, TU Dortmund University

Marco Wilhelm is a research assistant in the working group Information Engineering at the Chair of Logic in Computer Science at the Department of Computer Science, TU Dortmund University.

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Opportunities And Challenges Of The Asset Administration Shell For Holistic Traceability In Supply Chain Management

Nils Kuenster[1], Fabian Dietrich[1,2], Daniel Palm[1,3]

[1]ESB Business School, Reutlingen University, Alteburgstr. 150, 72762 Reutlingen, Germany

[2]Department of Industrial Engineering, Stellenbosch University, 145 Banghoek Rd., 7600, Stellenbosch, South Africa

[3]Fraunhofer Institute for Manufacturing Engineering and Automation, Alteburgstr. 150, 72762 Reutlingen, Germany

Abstract

Due to changing regulatory environments, evolving sustainability requirements, and the need to perform effective supply chain risk management, traceability systems have become an increasingly important aspect of supply chain management. However, globalized, interconnected supply chains require a dynamic mapping of direct and indirect relationships between companies and assets, driving traceability systems' complexity. Here, the standardization of data formats provides an essential aspect to facilitate asset-related information sharing across companies. In this regard, the Asset Administration Shell is available as a holistic standardized digital representation of an asset. The representation of an asset via an Administration Shell includes data ensuring a clear identification of the Administration Shell and its assets as well as data describing aspects of the asset's technical functionality in so-called submodels. Based on current literature and available prototypical concepts, this paper identifies the opportunities and challenges of the Asset Administration Shell when aiming to map interconnected multi-tier supply chains holistically and contextualizes their role in achieving holistic supply chain traceability.

Keywords

Supply Chain Management; Interconnected Supply Chains; Asset Administration Shell; Traceability; Industry 4.0

1. Introduction

The importance of traceability for contemporary supply chains increases to address the growing demands from customers, supply chain partners, and regulatory bodies [1]. Emerging regulations aim to assign companies responsibility for compliance with social and environmental standards along their entire supply chain. This includes national regulations, such as the German 'Act on Corporate Due Diligence Obligations for the Prevention of Human Rights Violations in Supply Chains' [1], as well as international initiatives, such as the "EU rules on due diligence in supply chains" [2]. Here, traceability is a vital instrument for monitoring the compliance of supply chain partners along the entire value chain. Furthermore, traceability improves a company's ability to deal with supply chain disruptions by enabling more effective decision-making [3]. Olsen and Borit define traceability as "the ability to access any or all information relating to that which is under consideration, throughout its entire life cycle by means of recorded identifications"[4]. In contrast to the term visibility, which is sometimes used in a similar context, traceability focuses on an object to be traced and not on information on a supply chain level [5]. In a supply chain, the object to be traced is a product or service. For a given object, traceability systems capture the origin, processing history, and

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location through supply chains [6]. Traceability focuses on the idea of product provenance [3,5]. To ensure a record of provenance, a traceability system must provide end-to-end traceability on an object or asset level [6]. Corresponding traceability systems require the capability to capture and store information for every relevant object-related supply chain event along the supply chain [6]. At the same time, supply chains have evolved into interconnected supply networks and display dynamic changes regarding the relationships and roles of the involved actors [7], driving the complexity of traceability systems. Standards can address the high complexity of traceability systems [6].

Standardized data formats and interfaces are also required in Industry 4.0 to advance interoperability as an aim of Industry 4.0 [8,9]. Therefore, the 'Initiative Industry 4.0' promotes the adoption of the Asset Administration Shell (AAS) [10], which provides a "standardized digital representation of an asset" [11]. The reference architecture model for industry 4.0 (RAMI 4.0) models the basic components of Industry 4.0 [12]. The RAMI 4.0 introduces the term Industry 4.0 component to consolidate the architecture requirements for a single subsystem [13]. Therefore, an Industry 4.0 component links an AAS and the corresponding asset, combining the physical and digital worlds [8,12]. The AAS uses several core concepts to create interoperable digital representations. The first concept describes distinct aspects of the asset in sematic submodels. Different submodels can relate to different stages of the lifecycle of an asset [11]. Submodels can be standardized and become templates to be shared in repositories. Another essential concept is identification. The AAS assigns unique identifiers to AASs, assets, instances, and templates of submodels and property definitions [10,11]. Figure 1 illustrates the fundamental structure of an AAS representing an assembly consisting of several components.

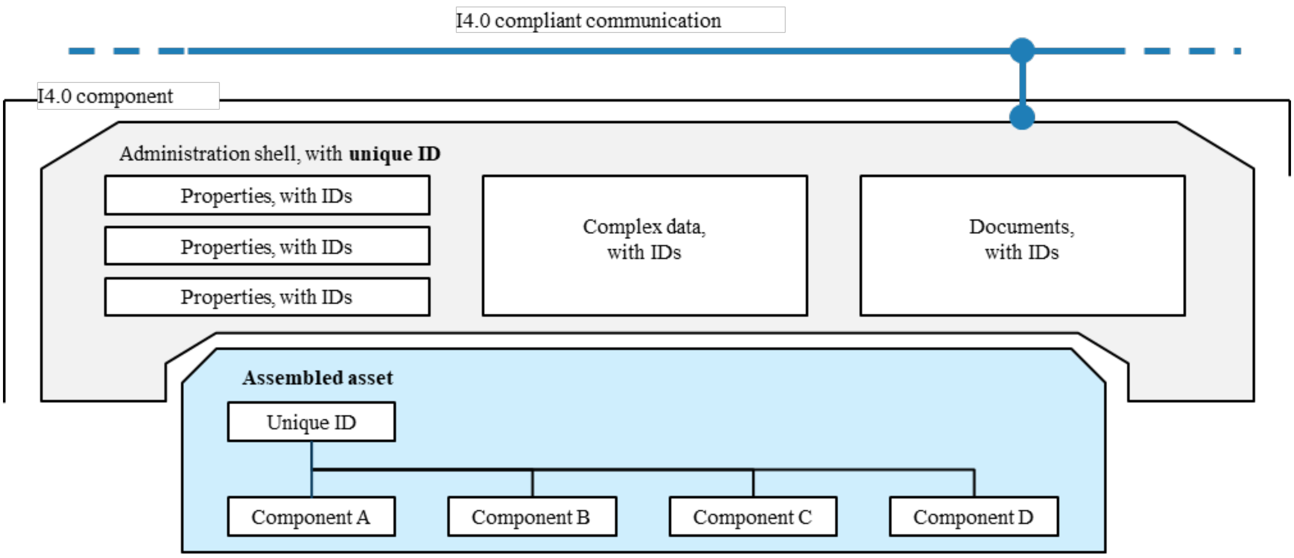

Figure 1: Asset Administration Shell (adjusted from [11])

Consequently, the AAS holds a pivotal role in achieving interoperability between objects and applications in smart factories and value chains to realize the goals of Industry 4.0 [11,14].

2. Rational and methodology of the paper

End-to-end traceability includes the ability to query data from upstream and downstream supply chains, which requires extensive sharing of relevant data between partners across a supply chain [6]. With the complexity and dynamic nature of connections in supply networks [7], organizing this data exchange without compromising the quality of traceability information becomes a complex task. Standardization in identification, sharing, and capturing traceability enables the efficient use of traceability systems [6]. Since the AAS represents the asset in a standardized digital way [11], AAS shows promising capabilities when applied in traceability systems. Some research addresses important aspects of AAS for traceability systems. Deuter and Imort investigate the use of AAS through several lifecycle phases of a product [15]. They, however, do not address the exchange of the product and the corresponding AAS between different organizations. Hang et al. describe the channeling of AAS between organizations for a production scenario [16] without addressing traceability specifically. Al Assadi et al. show the potential of AAS to serve as a basis for environmental impact analysis [17]. Their implementation was limited to one inter-organizational process and therefore did not consider traceability requirements. Adisorn et al. recognize the potential of the AAS for sharing product data over the whole product lifecycle and through the whole supply chain by suggesting it as a means of implementing digital product passports [18]. Plociennik et al. expand this idea and the AAS to implement a digital product passport for e-waste sorting [19]. Although AAS shows conceptual promise and is used in neighboring contexts, there are no papers addressing the concept of supply chain traceability. Therefore, this paper investigates the use of AAS in traceability systems. Initially, this paper infers requirements for storing and sharing traceability data from technical standards for traceability systems and applications scenarios for supply chain traceability and maps them to the features of the AAS. Furthermore, the paper investigates specific opportunities for AAS in supply chain traceability and analyzes the challenges that AAS faces in this application scenario.

3. The AAS in supply chain traceability

This section explores the use of AAS in supply chain traceability, starting with the requirements for sharing traceability data. Based on these requirements, this section analyzes the opportunities and challenges of AAS in a supply chain traceability context.

3.1 Requirements

Traceability in supply chains can serve different purposes. There is initial evidence that high levels of supply chain traceability positively affect an organization's environmental and cost performance [23]. Furthermore, traceability can help combat counterfeiting and other illegal activities, reducing companies' reputational risks and facilitating supply chain cooperation [20]. However, while traceability systems collect and store relevant information regarding the traced object, this may not be sufficient to achieve the business objectives. Consequently, gaining useful insights from traceability data can require further analysis and the application of methods such as artificial intelligence [21].

Traceability systems require the mapping of the supply chain in an information system. In complex supply chains, this constitutes a difficult task and requires suitable models [22]. Recording object-related supply chain events throughout objects' lifecycles is an important part of this mapping [6]. Derived from the specifications of the Event Product Code Information Services (EPCIS) standard, the following generic object-related supply chain events emerge [23]:

- *Object events*. An event describing something that happens to one or more objects (e.g., the creation of an object).
- *Aggregation events*. An event where two or more objects aggregate into a new object. The traceability data of the aggregated object contains the information on the objects used for aggregation.
- *Transformation events*. An event where an object is fully or partially consumed and one or more other objects are created as output of the event.
- *Transaction events*. An event where an object is involved in a business transaction (e.g., the transfer of ownership)

Traceability data refers to the data used to describe the individual event [6]. This data should include key data elements (KDE) identifying the traced object(what?), the parties involved (who?), the location of the event (where?), the time of the event happening (when?), and the business transaction the event relates to (why?). Depending on the traceability systems' purpose, traceability data requirements can increase. For example, when aiming to manage sustainability within the traceability system, specific information such as CO^2 or water consumption of material and processes must be available [24,25].

To attain end-to-end traceability object related traceability data must be exchanged between supply chain partners. GS1 defines the modes of organizing the exchange of traceability data in supply chains [6]:

- *One step up- one step down*. The 'one step up- one step down' model [6] refers to the exchange of traceability data only with immediate supply chain partners. While it is still common practice to use this model, it provides limited visibility and eventually leads to overall limited knowledge of supply chains [26].
- *Centralized*. In a centralized approach, all traceability data is collected and managed in a central repository [6]. The repository requires a central trusted authority to provide infrastructure and enforce standards for the supply chain [25]. In a complex and dynamic supply chain agreeing on a central authority can be challenging to achieve [10]
- *Networked*. In networked approaches, participants store their own data and enable all participants to query traceability data [6]. This model requires control mechanisms to manage the permissions of data access. In addition, effective querying requires standards regarding the available data [23].
- *Cumulative*. In cumulative traceability systems, participants cumulate data at every step of the supply chain to achieve a complete mapping of the downstream supply chain [6]. This model creates an asymmetry between the participants. Downstream participants receive more data to increase their visibility. Simultaneously those companies must store and process greater amounts of data [6].
- *Decentralized*. Combining mechanisms from the cumulative and networked model, the decentralized model replicates end-to-end traceability data and stores it distributed with all participants using, for example, blockchain technology [6]. While this model can create a distributed storage of traceability data, the processing and storage capability in this model is limited [27].

End-to-end traceability cannot be ensured by using the "one-up one-down" model, and the centralized model has limited viability in complex supply chains. Therefore, those models will not be considered when inferring requirements of AAS for supply chain traceability. The efficient use of networked and cumulative traceability systems requires the standardization of traceability data. Decentralized traceability systems are limited in their storage and processing performance. Adopting this model may necessitate separate storage and processing capabilities. Thus, organizing traceability systems with some degree of decentralization requires standardized data formats. In addition, the possible business applications of traceability systems cause more complex data about the traced objects and the supply chain events to be stored and communicated. Therefore, traceability systems require a standardized data interface capable of mapping complex attributes and functionalities.

The AAS addresses those requirements. As a standardized digital representation of an object, the AAS meets the standardization requirement [10]. The AAS allows flexible and holistic mapping of assets, with Wagner et al. expecting a convergence of the terms AAS and digital twin [28]. Therefore, the AAS meets the requirements of digitally mapping complex attributes and functionalities.

3.2 Opportunities

Opportunities of the AAS in supply chain traceability mean potential improvements in the traceability system, which can be achieved using AAS to share traceability data. Table 1 summarizes the identified opportunities.

Table 1: Opportunities of the AAS

Opportunity	Explanation	Source
Decentralized networks	Traceability systems can avoid the potential disadvantages of centralized networks while maintaining data quality.	[16],[29]
Standardized data interfaces	Standardized data interfaces simplify participation in traceability systems.	[30]
Machine-readable data	Structure and semantic modeling of the data allows automated analysis of the data.	[31]

Decentralized networks. Traceability systems require a high degree of quality of their traceability data [6]. Coordinating the exchange and maintaining the data quality can be a central authority's task. Yui names three disadvantages of centralized traceability systems [32]:

- *Single-point of failure.* Central authorities in traceability act as a single point of failure. A full or partial breakdown in a central system can endanger the integrity of the whole traceability record.
- *Processing capability.* A central authority in traceability systems must assume the costs of providing the necessary processing power and maintaining the infrastructure, as dealing with the data created by many objects in complex supply chains requires a lot of processing power.
- *Storage.* Similar to the processing capability, central authorities must provide sizeable amounts of storage space to store the traceability data of every object in the system.

Companies tend to dislike centralized data-sharing models because they fear losing control over sensitive data [33]. Especially in dynamic supply chains without dominant focal companies, a commitment of all participants to one central authority is unlikely [26]. As centralized traceability systems carry these disadvantages, decentralized solutions can be advantageous. AAS allows a standardized peer-to-peer sharing of object-related data [16,29] traceability system circumventing the need for a central coordinator while maintaining high data quality.

Standardized data interfaces. AASs' core concept is improving interoperability between components [14]. The structure of the AAS achieves this by standardizing the representation of the asset data [30]. Standardized data interfaces allow end-to-end traceability in supply chains [6,34,23]. Integrating every new supply chain partner into the traceability system without agreeing upon standards is complex and requires effort. In addition, as emerging supply networks display dynamic changes in the composition and interactions of participants [7], the challenge of coordinating data exchange becomes more complex. Implementing standardized data interfaces allows companies to participate in traceability systems for supply chains they are only temporally a part of without requiring implementation efforts.

Machine-readable data. Besides enabling data exchange between different actors in value chains, interoperability extends to the communication between machines [30]. The semantic modeling of the information contained in the AAS connects the data with a self-description [31]. Thus creating smart interfaces between machines, allowing not only the exchange of data but also conveying information about the meaning of the data [35]. This property can facilitate the integration of external data sources, such as machinery, into the traceability system. Furthermore, it can enhance the data contained in the AAS to analyze the traceability systems' business purpose.

3.3 Challenges

Challenges of the AAS in supply chain traceability refer to potential implementation barriers for AAS in traceability systems. Table 2 summarizes the identified challenges.

Table 2: Challenges of AAS in supply chain traceability

Challenges	Explanation	Source
Data sovereignty	Participants require control over the access and usage of their traceability data to avoid misuse of sensitive data.	[11],[29],[36],[37],[38]
Data inconsistencies	Traceability data requires end-to-end consistency. Different formats and interfaces can cause inconsistencies when exchanging AAS	[14],[15],[36],[16],[39],[40]
Consistent IDs	AAS requires globally unique identifiers.	[10],[11]
Data granularity	The granularity of the data models used in the traceability systems is undetermined.	[14],[13]
Available models	Submodels mapping relevant aspects of the object are required to be available.	[14]

Data sovereignty. Data sovereignty describes "meaningful control, ownership, and other claims to data or data infrastructures" [41]. Ensuring data sovereignty requires procedural or administrative measures as well as technical considerations [42]. Industrial actors in supply chains risk giving up much of their specific deep knowledge when participating in data exchange ecosystems that do not ensure their data sovereignty [43]. Both primary data and metadata have to be part of data sovereignty considerations [42]. Traceability systems require sharing data with known or unknown actors in supply networks. Without data sovereign exchange mechanisms, companies face the risk of competitors benefitting from their sensitive data. Reservations concerning the appropriate use of their data can inhibit companies from sharing data [33]. Regarding the AAS, data sovereignty is often discussed in terms of access management [29,36]. Several papers propose approaches for ensuring that every participant can only access the data it is authorized to by using connectors [29,38], encryption [36], or network access [37]. Usage control extends the idea of access control by enabling the data owner to influence its use after sharing the data [44]. Usage control could be achieved by sharing AAS through International Data Spaces networks [38].

Data inconsistencies. Meaningful end-to-end traceability is achieved by combining traceability data from different participants. During this process, the consistency of traceability must be ensured. Inconsistent data can lead to faulty provenance records and difficulties in gaining traceability insights. Since the submodel concept of the AAS allows flexible creation, there is a risk of high numbers of submodels and emerging ontologies [14]. When multiple participants model traceability data using different ontologies the overall record looses consistency Traceability systems might include IoT systems automatically capturing traceability data [6] or integrating data from other systems such as ERP or CAD. There is a challenge integrating these external data sources in the AAS [15,39,40] and, therefore, in the traceability systems. Furthermore, objects in supply chains can change their object-related data when experiencing certain supply chain events. Therefore, a traceability system with shared data requires a version control mechanism that works across different supply chain partners [39].

Consistent IDs. A key aspect of the AAS is the identification of ASs, assets, and submodels [10,11]. To ensure interoperability, the AAS requires globally unique identifiers. Inconsistent identification causes problems within the logistical processes as well as services in the product lifecycle [10]. As the AAS does not require a central authority to manage the identifiers, their global uniqueness is challenging to achieve [10]. Logistical objects might be identified in several contexts (e.g., part numbers, order numbers). There is a risk of mixing different identification schemes and violating the identification's consistency [12].

Data granularity. The AAS tries to model an object comprehensively and allows for nested models. However, in the application, the issue of model granularity arises [13,14]. Communicating and storing overly granular and, therefore, big data models in traceability systems is costly in terms of infrastructure. Furthermore, the effort of modeling highly granular models might deter actors from participating in traceability systems.

Available models. Wei et al. explain that the current AAS applications focus on the smart manufacturing domain [14]. Therefore, submodels describing aspects of the object relating to supply chain management or logistics might be missing. A traceability system could, however, require these models to provide traceability data for application scenarios.

4. Results and conclusion

The challenges identified in the analysis show that the AAS by itself is not sufficient to holistically map supply chains for traceability but instead should be integrated into a traceability system. We propose a high-level framework exemplifying the possible role of AAS in a traceability system ordered in a physical layer, a product data layer, and an event layer in Figure 2. End-to-end traceability starts with the creation of the product on the physical layer. Simultaneously, on the product data layer, an AAS as the digital representation of the product is created. Here, the product is assigned a unique identifier, and its properties are described in submodels. An object event described by the five KDE of the EPICS standard is recorded on the event layer. Unique identification of the physical product is a central concept of the AAS as well as a KDE of the EPICS standard connecting the product data layer and the event layer.

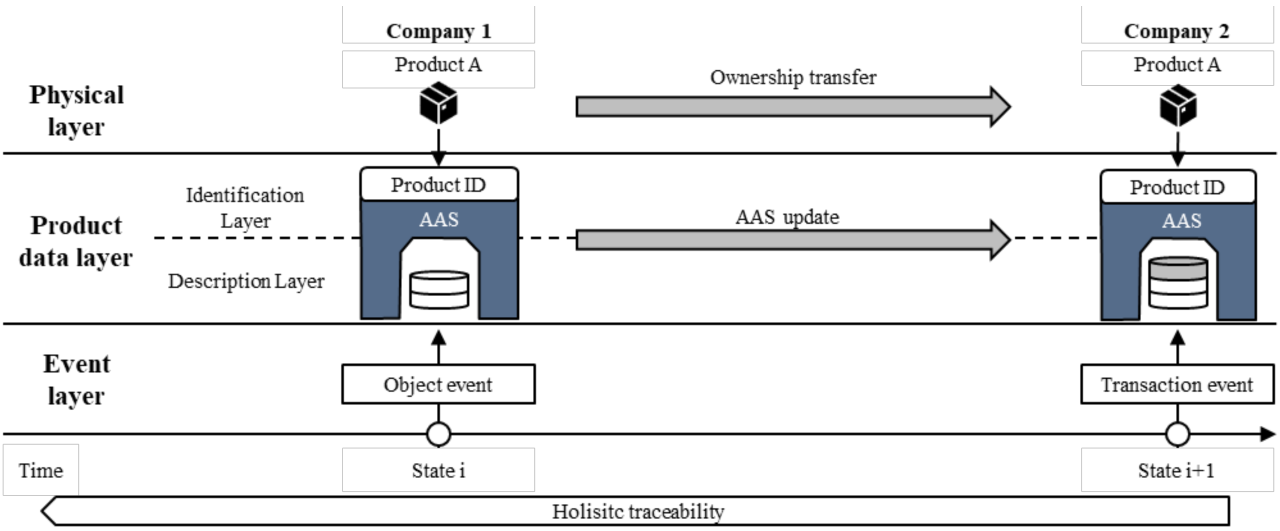

Figure 2: Framework for holistic supply chain traceability considering AAS

After the creation event, the product will experience other supply chain events along its value chain. Figure 2 exemplifies a subsequent event, namely the transfer of product A from company 1 to company 2 on the physical layer. On the event layer, this is represented by a transaction event that records the connected KDE. Any supply chain event causes an AAS update on the product data layer. In traceability systems, the AAS update process requires three elements depending on the specific event.

Identification. Each product receives a unique identification included in the AAS. In case of a product transfer, the ownership of the AAS changes; however, the AAS maintains its unique identification.

Data access. In case of a transaction event, the new owner needs the ability to access the data inside the submodels of the AAS.

Product data update. Every event needs to be recorded in the AAS and consequently causes a change in at least one submodel of the AAS.

Efficiently organizing these AAS updates relates to several challenges and is yet to be solved. Maintaining consistency of the identification and the data inside the submodels of an AAS across the entire supply chain presents a challenge that requires further research into methods and best practices. Emerging technologies, such as the blockchain, show the potential to ensure global uniqueness of identification. However, further research needs to explore a possible combination of such approaches. As AAS can include sensitive business information, organizations require meaningful control over the data they share in AAS. Initiatives such as International Data Spaces or Gaia-X [45] address the need for sovereign data exchange between organizations. Initial research into the combination of AAS with International Data Spaces is already being conducted [46] and should continue to support the emergence of holistic supply chain traceability.

Traceability in supply chains bears potential both in terms of improving the performance of supply chains and meeting the expectations of external stakeholders and regulators. Existing solutions, however, reach limitations when trying to establish end-to-end traceability in dynamic supply chains. This paper highlights the potential of AAS to improve traceability systems by providing standardized data formats for the exchange of traceability data capable of handling complex data structures. This leads to a more decentralized exchange of traceability data, reducing the complexity for participants in traceability networks. Based on the identified opportunities of AAS in supply chain traceability and considering the challenges elaborated in the analysis, this paper proposes a high-level framework outlining the role of AAS in a supply chain traceability system. The framework underlines the process of updating and sharing AAS at traceability events as a central challenge indicating the need for further research into this process.

References

[1] Bundestag, 2021. Act on Corporate Due Diligence Obligations in Supply Chains Germany, 23 pp.

[2] European Union, 2020. Towards a mandatory EU system of due diligence for supply chains. https://www.europarl.europa.eu/thinktank/en/document/EPRS_BRI(2020)659299.

[3] Razak, G.M., Hendry, L.C., Stevenson, M., 2021. Supply chain traceability: a review of the benefits and its relationship with supply chain resilience. Production Planning & Control, 1–21.

[4] Olsen, P., Borit, M., 2013. How to define traceability. Trends in Food Science & Technology 29 (2), 142–150.

[5] Roy, V., 2021. Contrasting supply chain traceability and supply chain visibility: are they interchangeable? The International Journal of Logistics Management 32 (3), 942–972.

[6] GS1, 2017. GS1 Global Traceability Standard: GS1's framework for the design of interoperable traceability systems for supply chains.

[7] Ivanov, D., Dolgui, A., 2020. Viability of intertwined supply networks: extending the supply chain resilience angles towards survivability. A position paper motivated by COVID-19 outbreak. International Journal of Production Research 58 (10), 2904–2915.

[8] Lu, Y., 2017. Industry 4.0: A survey on technologies, applications and open research issues. Journal of Industrial Information Integration 6, 1–10.

[9] Lelli, F., 2019. Interoperability of the Time of Industry 4.0 and the Internet of Things. Future Internet 11 (2).

[10] Adolphs, P., Auer, S., Bedenbender, H., Billmann,, M., Hankel, M., Heidel, R., Hoffmeister, M., Haimo, H., Jochem, M., Kiele-Dunsche, M., Koschnick, G., Koziolek, H., Linke, L., Pichler, R., Schewe, F., Schneider, K., Waser, B., 2016. Structure of the Administration Shell: Continuation of the Development of the Reference Model for the Industrie 4.0 Component. http://sf-eu.net/wp-content/uploads/2016/08/bmwi-2016-plattform-industrie-4.0-structure-of-the-administration-shell-en.pdf.

[11] Bader, S., Barnstedt, E., Bedenbender, H., Billmann, M., Boss, B., Braunmandl, A., Clauer, E., Deppe, T., Diedrich, C., Flubacher, B., Fritsche, W., Garrels, K., Graf Gatterburg, A., Hankel, M., Hillermeier, O., Michael, H., Jochem, M., Kogan, Y., Koziolek, H., Legat, C., Lüder, A., Mendes, M., Neidig, J., Orzelski, A., Pethig, F., Sauer, M., Schier, M., Schleipen, M., Schmitt, M., Schröder, T., Uhl, A., Stojanovic, L., Usländer, T., Walloschke, T., Waser, B., Wende, J., Wiegand, M., Constantin, Z., 2019. Details of the Asset Administration Shell: Part 1 -

The exchange of information between partners in the value chain of Industrie 4.0 (Version 2.0). https://www.zvei.org/fileadmin/user_upload/Presse_und_Medien/Publikationen/2020/Januar/Details_of_the_Asset_Administration_Shell_Version_2-0/Details_of-the_Asset_Administration_Shell_Version_2.PDF.

[12] Hankel, M., 2015. The Reference Architectural Model Industrie 4.0 (RAMI 4.0). ZVEI - Zentralverband Elektrotechnikund Elektronikindustrie e.V, Frankfurt am Main. https://www.zvei.org/fileadmin/user_upload/Themen/Industrie_4.0/Das_Referenzarchitekturmodell_RAMI_4.0_und_die_Industrie_4.0-Komponente/pdf/ZVEI-Industrie-40-RAMI-40-English.pdf.

[13] Ye, X., Hong, S.H., 2019. Toward Industry 4.0 Components: Insights Into and Implementation of Asset Administration Shells. IEEE Industrial Electronics Magazine 13 (1), 13–25.

[14] K. Wei, J. Z. Sun, R. J. Liu, 2019. A Review of Asset Administration Shell, in: 2019 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), pp. 1460–1465.

[15] Deuter, A., Imort, S., 2021. Product Lifecycle Management with the Asset Administration Shell.

[16] Hang, J.H., Lee, W.P., Lim, Y.M., 2021. Towards Mass Individualized Production: RAMI 4.0 Asset Data Channelling for Manufacturing Value Chain Connectivity, in: 2021 3rd International Conference on Computer Communication and the Internet (ICCCI), pp. 225–231.

[17] Al Assadi, A., Waltersmann, L., Miehe, R., Fechter, M., Sauer, A., 2021. Automated Environmental Impact Assessment (EIA) via Asset Administration Shell, in: Advances in Automotive Production Technology – Theory and Application, Berlin, Heidelberg. 2021. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 45–52.

[18] Adisorn, T., Tholen, L., Götz, T., 2021. Towards a Digital Product Passport Fit for Contributing to a Circular Economy. Energies 14 (8).

[19] Plociennik, C., Pourjafarian, M., Nazeri, A., Windholz, W., Knetsch, S., Rickert, J., Ciroth, A., Precci Lopes, Alice do Carmo, Hagedorn, T., Vogelgesang, M., Benner, W., Gassmann, A., Bergweiler, S., Ruskowski, M., Schebek, L., Weidenkaff, A., 2022. Towards a Digital Lifecycle Passport for the Circular Economy. Procedia CIRP 105, 122–127.

[20] Hastig, G.M., Sodhi, M.S., 2020. Blockchain for Supply Chain Traceability: Business Requirements and Critical Success Factors. Prod Oper Manag 29 (4), 935–954.

[21] Zhou, W., Piramuthu, S., 2015. IoT and Supply Chain Traceability, in: Future Network Systems and Security, Cham. 2015. Springer International Publishing, Cham, pp. 156–165.

[22] Dietrich, F., Hoffmann, M., Mediavilla, M.A., Louw, L., Palm, D., 2022. Towards a model for holistic mapping of supply chains by means of tracking and tracing technologies. Procedia CIRP 107, 53–58.

[23] Kennedy, A., Morgan, G., Southall, M., Traub, K., 2016. EPC Information Services (EPCIS): Standard event data, both within and across enterprises enables disparate applications to create and share visibility. https://www.nweurope.eu/media/14881/epcis-standard-12-r-2016-09-29.pdf.

[24] Germani, M., Mandolini, M., Marconi, M., Marilungo, E., Papetti, A., 2015. A System to Increase the Sustainability and Traceability of Supply Chains. Procedia CIRP 29, 227–232.

[25] Abeyratne, S.A., Monfared, R.P., 2016. Blockchain ready manufacturing supply chain using distributed ledger. International Journal of Research in Engineering and Technology 05, 1–10.

[26] Gross, T., MacCarthy, B.L., Wildgoose, N., 2018. Introduction to dynamics of manufacturing supply networks. Chaos: An Interdisciplinary Journal of Nonlinear Science 28 (9), 93111.

[27] Dietrich, F., Mehmedovic, E., Turgut, A., Louw, L., Palm, D., 2021. Classification Model Of Supply Chain Events Regarding Their Transferability To Blockchain Technology.

[28] Wagner, C., Grothoff, J., Epple, U., Drath, R., Malakuti, S., Grüner, S., Hoffmeister, M., Zimermann, P., 2017. The role of the Industry 4.0 asset administration shell and the digital twin during the life cycle of a plant, in: 2017 22nd IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), pp. 1–8.

[29] Jacoby, M., Volz, F., Weißenbacher, C., Stojanovic, L., Usländer, T., 2021. An approach for Industrie 4.0-compliant and data-sovereign Digital Twins. at - Automatisierungstechnik 69 (12), 1051–1061.

[30] Fuchs, J., Schmidt, J., Franke, J., Rehman, K., Sauer, M., Karnouskos, S., 2019. I4.0-compliant integration of assets utilizing the Asset Administration Shell, in: 2019 24th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), pp. 1243–1247.

[31] Grangel-González, I., Halilaj, L., Coskun, G., Auer, S., Collarana, D., Hoffmeister, M., 2016. Towards a Semantic Administrative Shell for Industry 4.0 Components, in: 2016 IEEE Tenth International Conference on Semantic Computing (ICSC), pp. 230–237.

[32] Yiu, N.C.K., 2021. Toward Blockchain-Enabled Supply Chain Anti-Counterfeiting and Traceability. Future Internet 13 (4).

[33] Pauer, A., Nagel, L., Fedkenhauser, T., Fritzsche-Sterr, Y., Resetko, A., 2018. Data exchange as a first step towards data economy. PricewaterhouseCoopers GmbH Wirtschaftsprüfungsgesellschaft, Düsseldorf. https://internationaldataspaces.org/wp-content/uploads/Data-exchange-PWC-study.pdf.

[34] Jæger, B., Mishra, A., 2020. IoT Platform for Seafood Farmers and Consumers. Sensors 20 (15).

[35] Müller, A., Grangel-González, I., Lange, C., 2020. An Ontological View of the RAMI4.0 Asset Administration Shell, in: Proceedings of the 12th International Joint Conference on Knowledge Discovery, Knowledge Engineering and Knowledge Management, Budapest, Hungary. 02.11.2020 - 04.11.2020. SCITEPRESS - Science and Technology Publications, pp. 165–172.

[36] Redeker, M., Volgmann, S., Pethig, F., Kalhoff, J., 2020. Towards Data Sovereignty of Asset Administration Shells across Value Added Chains, in: 2020 25th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), pp. 1151–1154.

[37] Schmitt, J., Gamer, T., Platenius-Mohr, M., Malakuti, S., Finster, S., 2019. Authorization in asset administration shells using OPC UA 67 (5), 429–442.

[38] Stojanovic, L., Usländer, T., Volz, F., Weißenbacher, C., Müller, J., Jacoby, M., Bischoff, T., 2021. Methodology and Tools for Digital Twin Management—The FA3ST Approach. IoT 2 (4), 717–740.

[39] Ye, X., Song, W.S., Seung, H.H., Kim, Y.C., Hong, S.H., 2022. Toward Data Interoperability of Enterprise and Control Applications via the Industry 4.0 Asset Administration Shell. IEEE Access 10, 35795–35803.

[40] Drath, R., Rentschler, M., Hoffmeister, M., 2019. The AutomationML Component Description in the context of the Asset Administration Shell, in: 2019 24th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), pp. 1278–1281.

[41] Hummel, P., Braun, M., Tretter, M., Dabrock, P., 2021. Data sovereignty: A review. Big Data & Society 8 (1), 2053951720982012.

[42] Dalmolen, S., Bastiaansen, H., Somers, E., Djafari, S., Kollenstart, M., Punter, M., 2019. Maintaining control over sensitive data in the Physical Internet: Towards an open, service oriented, network-model for infrastructural data sovereignty.

[43] Jarke, M., Otto, B., Ram, S., 2019. Data Sovereignty and Data Space Ecosystems. Business & Information Systems Engineering 61 (5), 549–550.

[44] Jung, C., Dörr, J., 2022. Data Usage Control, in: Otto, B., Hompel, M. ten, Wrobel, S. (Eds.), Designing Data Spaces : The Ecosystem Approach to Competitive Advantage. Springer International Publishing, Cham, pp. 129–146.

[45] Otto, B., Rubina, A., Eitel, A., Teuscher, A., Schleimer, A.M., Lange, C., Sting, D., Loukipoudis, E., Brost, G., Böge, G., Pettenpohl, H., Langkau, J., Gelhaar, J., Mitani, K., Hupperz, M., Huber, M., Jahnke, N., Brandstädter, R., Wessel, S., Bader, S., 2021. GAIA-X and IDS. Position Paper | Version 1.0, Dortmund. https://internationaldataspaces.org//wp-content/uploads/dlm_uploads/IDSA-Position-Paper-GAIA-X-and-IDS.pdf.

[46] Haße, H., van der Valk, H., Weißenberg, N., Otto, B., 2020. Shared Digital Twins : data sovereignty in logistics networks.

Biography

Nils Künster (*1995) is a Research Associate at the ESB Business School. He studied Operations Management and holds an M.Sc. from the ESB Business School of Reutlingen University. His research interest includes artificial intelligence, supply chain traceability, and circular economy.

Fabian Dietrich (*1993) has a Ph.D. in Industrial Engineering from Stellenbosch University and works as Research Project Coordinator at the ESB Business School. His research focuses on blockchain technology, supply chain management, and wireless communication technologies.

Daniel Palm (*1967) is a Professor of Supply Chain Management at the ESB Business School. Univ.Lektor Prof. Dr.techn. Dipl.-Ing. Daniel Palm is head of the teaching and research center for ValueAdded and Logistics Systems at Reutlingen University and the Reutlingen Center Industry 4.0, RZI 4.0 - a cooperation of the Fraunhofer Institutes IPA and IAO as well as Reutlingen University.

4th Conference on Production Systems and Logistics

Requirements For An IoT-Lock Enabling Asynchronous Physical Handovers Of Semi-Trailers In Road Freight Relay-Transport

Janis Simons[1], John von Stamm[1], Lisa Weichsel[2], Tobias Schröer[1], Maik Schürmeyer[3]

[1]*FIR, Institute for Indusrtial Management at RWTH Aachen University, Aachen, Germany*

[2]*Production Engineering of E-Mobility Components (PEM), RWTH Aachen University, Aachen, Germany*

[3]*Mansio GmbH, Aachen, Germany*

Abstract

In long-distance road freight transport, capacity utilization of semi-trailers is less than 30 % due to mandatory steering and rest periods. Truck parking spaces are overcrowded while resulting parking search traffic leads to additional emissions. At the same time, the acute driver shortage and customers' expectations of ever faster functioning supply chains force the highest efficiency in transport means and personnel. Multi-carrier relay-transport represents an approach to solving these problems and exploiting untapped efficiency potentials: Via a digital platform, long distances are intelligently divided into short route sections which are distributed among different carriers. At predefined switching points, the asynchronous handover of semi-trailers to rested drivers takes place. To enable a secure cross-company physical handover, IoT-locking mechanisms play a crucial role. This paper details the asynchronous handover process and introduces the technical design of an IoT-lock which provides effective theft protection while the trailer is parked and reliably connects tractor and semi-trailer during transport. Based on an analysis of stakeholder requirements, software functionalities and mechanical properties of the IoT-lock are derived, which ensure effective theft protection as well as real-time data transmission for relay transports. These form the basis for digital handover protocols that record the condition of the freight and trailer during the handover process.

Keywords:

Road Freight Transport; Relay-Transport; IoT-Lock; Asynchronous Handover; Semi-Trailer

1. Introduction, problem statement and solution

The road freight transport in Europe is facing a variety of challenges. In Germany alone, it is assumed that a lack of approximately 60.000 to 80.000 truck drivers exists [1]. In addition, transports are interrupted to comply with driving and rest periods. Truck parking spaces are occupied in the process, whereby Germany lacks 23.000 parking spaces for tractors/semi-trailers [2]. This phenomenon is accompanied by the fact that a parking lot expansion is progressing very slowly and at high costs – costs for comparatively small parking lots have risen significantly to about 80.000 EUR per space with a construction time of several years due to dramatic shortages for suitable land. [3] Road freight relay transport seems a feasible approach to address the described challenges. However, it must be considered that most of the German shipping companies (73 percent) have less than 100 employees (11 on average) [4]; therefore, internal relay-transport cannot be integrated cost-efficiently. Additionally, stolen trailers and lost freight due to theft and robbery translate into potentially high costs as well as contractual penalties for delivery delays, repairs, and lost sales as a result of production downtime.

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The interruption of transports can be avoided by securing trailers with an IoT lock at the end of the driving time and then handing them over to rested drivers. The research project 'STAFFEL' investigates a safe, cross-carrier relay-transport: on an internet platform, long distances are to be broken down into partial routes with the help of CI algorithms, which are then mediated between carriers and freight forwarders via a driving time marketplace on the basis of real-time data (e.g. traffic, infrastructure, IoT, telematics). The asynchronous handover of semi-trailers takes place at predefined switching points

Based on internal calculations comparing the driving time of a single truck running in conventional traffic (9 h/day) to a truck running in relay traffic (theoretically up to 24 h/day as only the tractor is parked due to mandatory resting hours for the drivers)., this approach can reduce the transportation time by up to 62 percent while increasing truck utilization rate by up to 163 percent. Waste of driving time, empty runs and parking search traffic are reduced. The need for truck parking spaces is reduced by up to 65% if the semitrailers are handed over and only the tractor units have to park. At the same time, attractive, self-determined work models are created for truck drivers, who can drive more regional legs and be at home more often. It quickly becomes clear that relay-transport holds a multitude of potential advantages for the transport of goods by road. However, it also becomes clear that only an asynchronous transfer protected and supported by an appropriately designed IoT-lock makes this process possible in the first place. Such a lock will be derived in this paper with regard to the system architecture.

2. Theoretical background: Fundamentals of relay-transport and IoT-applications

2.1 Road freight Relay-transport

Multi-carrier relay-transport describes the intelligent division of long transport distances into short route sections which are distributed among different carriers. The distance of the newly calculated route sections is congruent with the time that truck drivers are allowed to drive without exceeding their driving times [5]. At predefined switching points, the asynchronous handover of semi-trailers to rested drivers takes place. This approach can massively reduce the transportation time, because it eliminates the need for overnight stays by the carrier, hence resulting in lower costs. The asynchronous handover supported by an IoT lock minimises the risk of otherwise lengthy wating times caused by traffic jams or other complications which only occur on one side of the interaction. The planning process of the relay transport will be executed by an algorithm, which intelligently subdivides transportation routes of long distances into shorter sections. A distribution among different carriers and the asynchronous physical handover of semi-trailers requires a platform to orchestrate the process digitally.

2.2 IoT-applications and IoT-locks

The IoT-technology describes physical devices (e.g. locks or sensors) which can be accessed and uniquely identified through a network and can also be represented in a virtual depiction. The device can be controlled and tracked in real time. It is critical that the devices can share information via the network with other connected devices to guarantee an intelligent and well-functioning process [6]. The number of IoT devices is rising and might triple from 9.7 billion in 2020 to mora than 29 billion IoT devices in 2030 [7].

The IoT-lock within the relay transport is the central enabling technology for this approach. It provides theft protection, accessibility for authorized users and allows traceability of the trailers through real-time data transmission [7]. Improved data transmission enables effective communication and connectivity between the various parties in the supply chain, which is pivotal for relay transportation planning. Besides that, it also allows a digitalization of processes such as the typically paper-based handover protocols [8].

With regard to the state of the art in intelligent securing technologies in road freight transport, it should be noted that very few IoT securing mechanisms are currently in use. So-called "smart locks" exist without reference to road haulage, among others e.g., for securing house doors. In the field of securing semitrailers, conventional kingpin locks with keys are offered. [9] There are currently no cyber-physical security systems on the market. Either related solutions are "purely digital" and passively record the position of the trailer or they are purely physical (including a king pin lock). An exception is the trailer immobilizer, which is not a lock in the traditional sense, however, but controls the air brakes. An exception to this is the trailer immobilizer. Hence it secures the trailer by controlling the air brakes it cannot be seen as conventional lock. This system is therefore easier to manipulate than a heavy-duty lock.

3. Research Approach

This paper's scope is the definition of product features of an IoT-lock which enables the implementation of the above-described relay-transport through a digitally supported physical handover of semi-trailers. In order to achieve that, a methodical process has been chosen to ensure a complete description of the needed functionalities of the product. Figure 1 shows the steps that have been applied. After this a list of product requirements can be formulated, which are based on the identified process and the access authorizations of the users. Additionally, a derivation of technological product properties can be made to ensure that the previously identified functionalities can be fulfilled. In a last step a system architecture can be set up.

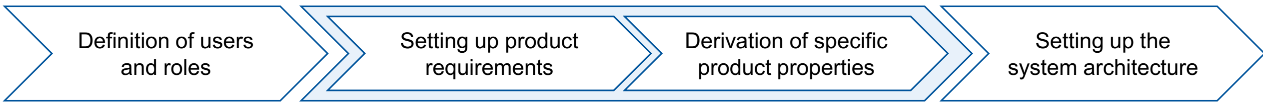

Figure 1: Methodological approach

The identification and characterization of the roles denotes the first step of the procedure in the chosen methodological approach and is based on internal discussions with the project team. In particular, the roles that are directly or indirectly involved in the use of the lock were described. A further distinction was made between authorized and unauthorized users. Consequently, four user groups could be differentiated, which are described in more detail below.

First, those users who carry out the intended physical handover of a semitrailer can be identified. The truck drivers are either those who park a semi-trailer at a predefined location or who couple the trailer. Both roles are so called authorized users, but due to the deviating processes in the two operations, it is necessary that these two roles are differentiated from each other. A third role can be described as a higher level or superior participant. This user-group is the administrative layer which organises and orchestrates the transportation processes. In particular, this group relies on planning routes, transmitting appropriate destination data, and receiving data on the location of the tractor-trailer. In this user category you could find a fourth logistics party (4PL) or other forms of service providers. A fourth group of users is the unauthorized person. Within the context of thievery, a lock must be designed to ensure an adequate theft-protection.

4. Results

4.1 Requirements and product properties

In the following a set of requirements based on the predefined roles will be presented. The basis for using a lock is the locking system itself. The driver locks the mechanism after uncoupling the semi-trailer. The system must be able to recognize and display the current status of the device (locked or unlocked), a visual display is particularly necessary. Technological components for this can be an LED, a reed contact and the corresponding coupling to the motor position of the lock-mechanism. In addition, a corresponding display in the app is necessary.

In a lot of situations, a basic network connection is existing and needed. The driver and the administrative users must have the option of accessing the lock remotely. Possible component functionalities for this are

LTE (GSM as fallback), Sigfox, LoRa or NB-IoT/ LTE-M [10]. Furthermore, it must be possible to run updates of the system. This is ensured with the help of Over The Air Updates (OTA). Since the driver parks the semi-trailer at various locations and a risk of an insufficient or lacking internet connection is given, the lock must be opened offline and independently of the internet connection. Discussions within a project workshop showed that this could be realized by an RFID chip, Bluetooth LE or a Bluetooth Beacon. In principle, it must be possible to carry out updates to the system. This is ensured by means of over-the-air updates (OTA).

Another requirement is that the system must be able to determine the exact location of the semi-trailer so that this position data can be made available to the administrator. Here, a solution using LTE or GNSS is also suitable. In terms of distinguishing between authorized and unauthorized users, the system must be capable of recognizing the authorized driver. RFID, Bluetooth LE or an app control in combination with a Bluetooth Beacon can be used for this purpose. A corresponding alarm or theft protection can be ensured by integrating a buzzer that emits an acoustic signal. Also, to be derived in this context is the requirement that a corresponding event can be forwarded on the system side and sent to the user (e.g. push notification). With regard to anti-theft protection, a corresponding system-side detection of the transaction is also relevant. Requirements can be derived that the system must be capable of detecting unauthorized access to a trailer and identifying tampering with the kingpin lock (e.g., mechanical action). These requirements can be ensured using sensors, including accelerometers, distance sensors, or a thermal sensor.

With respect to unauthorized access, in addition to mechanical security, care must be taken to prevent unauthorized access to the IT system and to ensure adequate data security protection. Cybersecurity can be implemented with appropriate end-to-end encryption and secure protocols. However, further system-side development of these components is not included in this paper.

When the driver of a tractor performs the coupling of a semi-trailer, it is important that an incorrect opening of the locking system is detected. Consequently, the system must be capable of providing feedback (e.g., alarm) if the lock does not retract during coupling to prevent damage to the trailer and tractor. This can be visual feedback (e.g., via LED) or an acoustic signal (buzzer). The corresponding feedback of an error code as well as the display of a warning message in the app communication should be ensured.

Another requirement is that malfunctions are prevented while the vehicle is in motion. This can be ensured via magnetic bolts, an advanceable automatic latch, and appropriate dimensioning of the motor. Additionally, the lock should be designed in such a way that no removable components (e.g., keys) must be dismantled. The driver should not have to take any other components into the cab for reasons of convenience and quick coupling and uncoupling of the semi-trailer. In addition to the above-mentioned design conditions the asynchronous transfer of a semi-trailer can lead to longer idle times. In this case, the power supply must be ensured for the entire period so that the driver receiving the trailer can carry out the coupling process. For this purpose, a battery pack must be provided which has a connection to the semitrailer power supply. The charging process can then take place when the semitrailer is reconnected to the tractor unit.

The above-mentioned requirements can be distinguished into four categories; theft protection/ cyber security, data transmission/ tracking, operability and authorization and other functions (see figure 2).

Theft protection/ cyber security	Data transmission/ Tracking	Operability & Authorization	Other functions
▪ Unauthorized access is detected ▪ Authorized driver is detected ▪ Tampering with kingpin lock is detected ▪ Adequate protection against unauthorized access to IT system ▪ Adequate overall data security ▪ Access history is logged ▪ Triggering of emergency alarm ▪ Theft protection against conventional tools	▪ Determination of the exact location ▪ Software updates via radio interface (over-the-air update)	▪ Access without active internet connection ▪ Remote access possible (hotline) ▪ Temporary disconnection without loss of access authorization ▪ Emergency access for emergency services ▪ Access authorization for up to two trailers (one driver per trailer) ▪ Unlocking without detachable components	▪ Playback of an acoustic signal ▪ Feedback in case of incorrect coupling ▪ Visual feedback on the status of the lock (open/closed) ▪ Prevention of malfunctions while driving ▪ Charging via external power supply possible

Figure 2: Results of the requirements analysis

4.2 System architecture

The system architecture describes the basic structure of the IoT lock by showing the system components and their interdependencies in aggregated form. A distinction is made here between input and output and the processing layer. Figure 3 shows the below described architecture.

Opening and closing the lock is described as an input and is accomplished with the help of the smartphone. The user interacts with the user interface of the app (UI/ UX) and initiates the desired process. Bluetooth is used as the technology for data transmission in order to ensure a robust process without the need of an active internet connection. Due to the need for further modification of the trailer, RFID technology is not used here. The process of opening or closing is also forwarded to the back end of the system in the processing layer.

After the process has been triggered with the help of the smartphone app, the backend initiates the process using a gateway and LTE transmission technology and the signal is forwarded to the interlock or reed switch and the lock is opened or closed. If LTE communication fails due to a missing internet connection, it communicates with the Bluetooth receiver of the lock to open or close it. The sensor communication or the network setup takes place here via LTE-M and NB-IoT with an option for GSM as a fallback. This enables low-power communication and easy integration of new sensors into the network. GSM is used as a fallback when communicating with the backend. If the process was completed with the opening or closing of the lock, a corresponding signal is returned and the LED lights up. The state of the lock is transmitted to the backend.

As LTE communication is used within the architecture of the lock, LTE is preferred for localization of the trailer. Nevertheless, GNSS (Global Navigation Satellite System) is used to support the system whereby feedback on the trailer location is sent back to the backend, thus enabling continuous tracking of the lock.

If the lock is tampered with, if an error occurs during coupling or if the trailer is accessed, these events are registered with the help of an accelerometer and other sensors. It should be noted here that sensor technology is already present on the trailer. It still needs to be examined to what extent these can be integrated into an anti-theft system. Depending on the sensor feedback, a visual and acoustic signal is triggered (LED, buzzer) and the corresponding process is reported back to the back end.

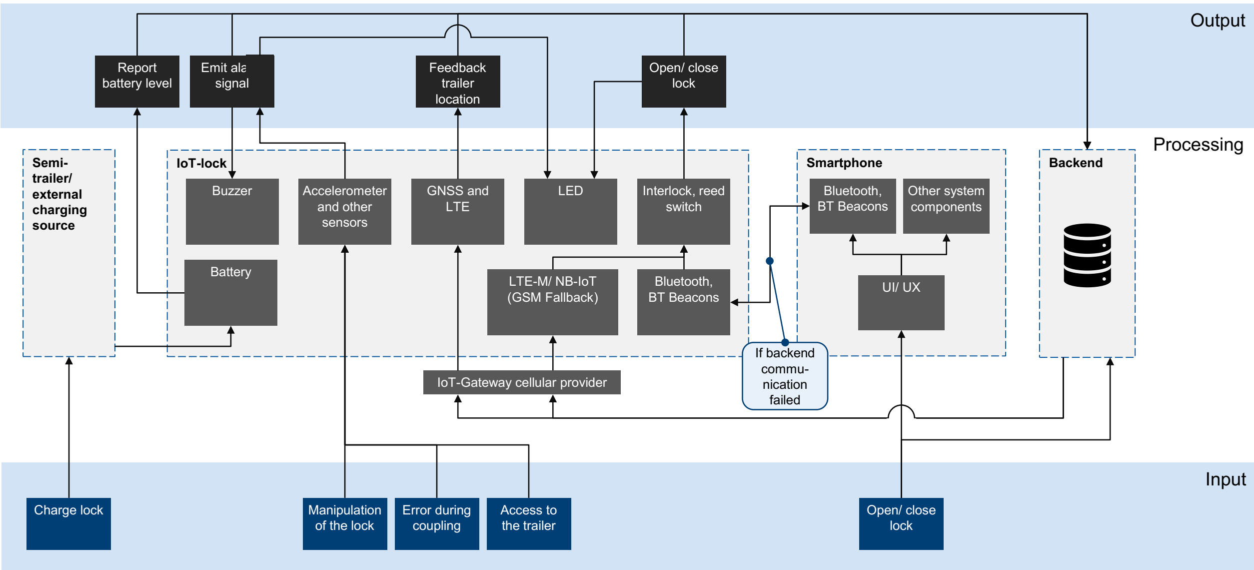

Figure 3: System architecture of the IoT-lock

The charging of the IoT lock is ensured with the help of the power supply from the semi-trailer or its external charging source. A corresponding report on the battery level is transmitted to the back end. When selecting the battery, it is to be ensured that a minimum runtime without external charging source of seven to 14 days can be achieved.

No cyber security considerations have yet been taken into account in the system architecture. In this area, too, it must still be clarified whether sensitive data is exchanged and to what extent it must be protected. Further research effort is necessary.

5. Summary and outlook

Within this paper and based on a definition of roles and users within a relay-transportation, a list of requirements for an IoT-lock has been conducted, which can be used for an asynchronous physical handover of semi-trailers. Based on those requirements, it was possible to derive necessary technological components that ensure functional fulfilment. These components and the corresponding relationships between them were also described. As a result, it was possible to draw up a system architecture that represents the functionalities of the IoT lock. Based on input factors the processing layer shows interdependencies and signal operations of the components and presents the outputs.

Further research is particularly needed in the development of the system architecture and the prototypical testing and validation phase. Since the system architecture is to be understood as a guideline for developement, possible barriers in the practical implementation of the concept must be identified. The IoT lock should serve for a safe and smooth transition of the trailer from one driver to another driver. The data exchanged in this process must be complete and meet the requirements in every situation. In addition, the extent to which sensitive data must be protected under data law and how this is ensured by the corresponding system architecture should be examined in more detail.

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References

[1] Verkehrsausschuss, Deutscher Bundestag, 2022. Gemeinsame Stellungnahme des Bundesverbandes Deutscher Omnibusunternehmen (bdo) e. V. und des Bundesverbandes Güterkraftverkehr Logistik und Entsorgung (BGL) e. V. https://www.bundestag.de/resource/blob/911288/6d79e1ce0be1bc517c93bdd2a5f4bd35/Stellungnahme-BGL-und-bdo-data.pdf Accessed 2 November 2022.

[2] Irzik, M., 2018. Lkw-Parksituation im Umfeld der BAB, Schätzung der Nachfrage 2030. Bundesanstalt für Straßenwesen, Bergisch Gladbach.

[4] Deutscher Speditions- und Logistikverband e.V. (DSLV), 2015. Zahlen, Daten, Fakten aus Spedition und Logistik 2015, p. 22.

[5] Amtsblatt der Europäischen Union. Reihe C & L (früher: Amtsblatt der Europäischen Gemeinschaften ; früher: Amtsblatt der Europäischen Gemeinschaft für Kohle und Stahl). o. J. EurLex. http://eur-lex.europa.eu/JOIndex.do?ihmlang=de.

[6] Gokhale, P., Bhat, O., & Bhat, S., 2018. Introduction to IOT. International Advanced Research Journal in Science, Engineering and Technology, 5(1), pp. 41–44.

[7] Statista, 2022. Number of Internet of Things (IoT) connected devices worldwide from 2019 to 2021, with forecasts from 2022 to 2030 | Statista. https://www.statista.com/statistics/1183457/iot-connected-devices-worldwide/ Accessed 25 October 2022.

[8] Anandhi, S., Anitha, R. & Sureshkumar, V., 2019. IoT Enabled RFID Authentication and Secure Object Tracking System for Smart Logistics. Wireless Pers Commun 104, pp. 543–560.

[8] European Commission, Directorate-General for Mobility and Transport, Piers, R., Giannelos, I., Swart, L., et al., State of play and barriers to the use of electronic transport documents for freight transport : options for EU level

policy interventions : final report, Publications Office, 2018, https://data.europa.eu/doi/10.2832/39079 , S. 7. Accessed 2 November 2022.

[9] M. Shanthini, G. Vidya, R. Arun, "IoT Enhanced Smart Door Locking System," 2020 Third International Conference on Smart Systems and Inventive Technology (ICSSIT), 2020, pp. 92–96.

[10] Linnemann, M., Sommer, A., Leufkes, R., 2019. LPWAN-Netze. In: Einsatzpotentiale von LoRaWAN in der Energiewirtschaft. Springer Vieweg, Wiesbaden.

Biography

Janis Simons, M.Sc. (*1994) is an industrial engineer and has been a project manager and doctoral candidate at the Institute for Industrial Management (FIR) at RWTH Aachen University since 2022. In his current position in the department of Production Management he supports companies in various industries in the fields of selection and implementation of IT systems. He also participates in different research projects.

John von Stamm, M.Sc. (*1992) is an industrial engineer and has been a project manager and doctoral candidate at the Institute for Industrial Management (FIR) at RWTH Aachen University since 2021. As member of the Business Transformation Department, he leads research and consulting projects focusing on digital business models, corporate sustainability, and organizational resilience

Lisa Weichsel, **M.Sc.** (*1992) is project engineer at the Chair of "Production Engineering of E-Mobility Components" (PEM) an der RWTH Aachen since 2019. She is active in the field of functional safety and has dealt with the topic in detail as part of her master's thesis and accompanied development.

Tobias Schröer M.Sc. (*1991) studied Business and Engineering at the TU Clausthal. Since 2016, he has been working as a research assistant at the Institute for Industrial Management (FIR) at RWTH Aachen and is head of the Production Management department since 2020.

Prof. Dr.-Ing. Maik Schürmeyer (*1985) graduated in 2010 as Dipl.-Ing. Mechanical Engineering at RWTH Aachen and M.Sc. Management Science Tsinghua University Beijing. From 2010 to 2014 he did his doctorate at FIR e.V. at RWTH Aachen University in the field of logistics management. Then he took over the division performance internal logistics and SCM at Zentis. Since 2017, he has been a professor of food logistics at Niederrhein University of Applied Sciences and has been the founder and managing director of MANSIO GmbH since 2020.

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Beyond Pareto Analysis: A Decision Support Model for the Prioritization of Deviations with Natural Language Processing

Yuxi Wang[1], Lukas Longard[1], Christian Hertle[2], Joachim Metternich[1]

[1]*Institute of Production Management, Technology and Machine Tools, Darmstadt, Germany*
[2]*SFM Systems GmbH, Darmstadt, Germany*

Abstract

In the manufacturing domain, the systematic problem-solving (SPS) process is essential to eliminate the root causes of deviations from expected performance. The major goal of SPS is to prevent the recurrence of known deviations. However, due to time and resource limitations, the deviations that occur on the shop floor should be prioritized before applying SPS. Therefore, a method to support the decision-making process for prioritization of deviations is required. Traditional methods, such as the Pareto analysis, are widely accepted and applied for easy use. But their performance is no more sufficient for the production environment with large fluctuations nowadays. Therefore, this paper proposes a decision support model – the error score – to prioritize deviations on the shop floor. The error score is calculated based on the process data as well as textual data found in the deviation documentation. As the quality of textual data in the deviation documentation has great effects on the performance of the model, Natural Language Processing (NLP) methods are developed to pre-process the unstructured text. To validate the model, it is applied to a real-world use case in the automotive industry to demonstrate and evaluate the performance. The study shows that the proposed model can effectively support the decision-making process on the shop floor and is superior to traditional methods.

Keywords

Systematic problem-solving (SPS); Deviation management; Natural language processing (NLP); Shop floor management; Production and manufacturing

1. Introduction

In the manufacturing domain, the systematic problem-solving (SPS) process is an essential process to ensure the stability of production. The goal of SPS is to find the root causes of occurring problems and to develop solutions as well as new standards to prevent recurrences. However, due to time and resource limitations, the deviations that occur on the shop floor should be prioritized before applying SPS [1]. In some cases, shop floor managers decide on priorities based on their personal experience. Moreover, it is possible to support the decision-making process based on historical data by means of data analysis [2]. For example, Pareto analysis has been widely accepted and applied in production. However, their performance is no longer adequate for today's highly volatile production environment, since they can only consider one aspect (e.g. number of occurrences) at a time [3].

The development of digitalization provides the possibility to get access to more information from the production process and related activities [4]. More process- and problem-related data is documented through terminals on the shop floor, such as the digital shop floor management (dSFM) system, which enable the use of data analytics and machine learning algorithms to automatically analyze the data in real-time [5].

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However, in practical applications, there is often unstructured data, such as textual data, which can cause difficulties in the automatic analysis process. To overcome this issue, the methods of natural language processing (NLP) can be utilized in data pre-processing to remove the ambiguities present in the unstructured text [6]. Based on this, the major research contributions of this work can be summarized as follows:

- A decision support model to prioritize deviations on the shop floor is developed
- NLP is used in the preprocessing steps of the model to raise the data quality of the textual data
- An application of the model on a real-world use case in the automotive industry where the proposed solution is demonstrated and evaluated.

The remainder of this paper is structured as follows. Section 2 introduces the background and related work of this study. Section 3 establishes the decision support model aiming at prioritizing the deviations for the SPS on the shop floor. Section 4 conducts a case study on an automotive company using data from the rework process. The results are listed and discussed in Section 5. Finally, Section 6 concludes this study and suggests several directions for future research.

2. Background and related work

2.1 Shop floor management

The methods of shop floor management (SFM) are widely used in industry to control and improve production processes on a daily basis [7]. The shop floor control loop is based on identifying deviations through performance indicators (KPIs), discussion about the deviations in the regular shop floor meeting, initiating SPS and the stabilization as well as standardization of the processes [8]. With the increasing popularity of digitalization, the use of dSFM systems is now gradually increasing in production companies [9]. During the use of the dSFM system, data about deviations and problems is collected and stored in the system. This data includes both structured and unstructured data. The structured data includes information like the time of the deviation as well as the product number, while the unstructured data is mainly textual and includes for example, the description of the deviation, defined measures.

When deviations occur, there are usually two ways to counteract: On the one hand, if the cause is known, quick measures should be taken. On the other hand, if the cause is unknown, a SPS should be triggered [10]. Besides, quick measures have to be taken to prevent the problem from escaping to the customer. Compared to SPS, taking quick measures skips a thorough analysis of the deviation and can quickly restore production from the deviated state back to standard. However, in order to prevent recurrences of the issue, a SPS must be applied to analyze and solve the root cause of the problem [11]. Considering the time and labor costs, it is necessary to prioritize the deviations before applying SPS. There are not many existing methods in the literature that specifically mention how to prioritize deviations; the existing methods mainly include empirical-based and data analysis-based approaches. Shop floor managers determine the prioritization by referring to their own experience and anticipating the likely outcome of the problem. The severity of the problem can also be evaluated by analyzing the historical data of its occurrence. As a commonly used method for decision support processes, Pareto analysis is widely used on the shop floor, which can helps managers to identify top errors with Pareto chart [12]. Advanced statistical tools are also being applied to assist in the decision-making process, such as presenting important problems as graphs by means of text clustering [13].

2.2 Natural language processing

NLP is an interdisciplinary research area that combines computational linguistics, computational science, cognitive science and artificial intelligence to inquire how computers process human language to perform useful tasks [14]. Textual data is an important form of human language in the production, most of which are unstructured or semi-structured. Because few restrictions can be applied to those data, the likelihood of errors and inconsistencies is higher than in structured data [15]. Figure 1 shows typical data errors and inconsistencies in textual data on the shop floor. These errors can be separated into orthography and the content. Misspellings and synonyms are the significant properties that affect the quality of textual data [16]. As an essential part of NLP, the preprocessing step of textual data normalizes the unistructural data into a computer readable form. It consists of three steps: tokenization, normalization and vectorization [17]. In a recent study, Mueller et al. have identified best practices for the handling of shop floor textual data [6].

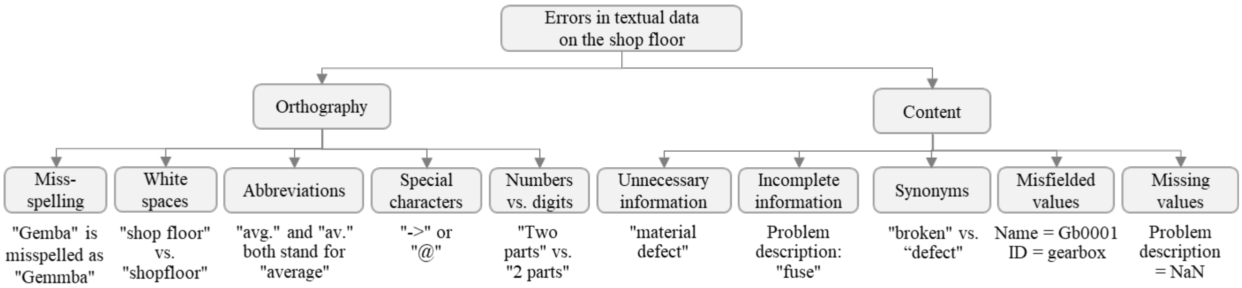

Figure 1: Typical errors in textual data on the shop floor

3. Structure of the decision support model

To improve resource allocation in form of SPS capacity on production deviations, this paper introduces a new approach to support deviation prioritization. The model in this study primarily consists of three parts: the data preprocessing with NLP, the calculation of the error score and the weight optimization. The data preprocessing analyses the deviation descriptions and utilizes NLP to raise the textual data quality. The calculation of the error score delivers the deviation ranking list based on the preprocessed textual data and the certain weights. The weight optimization adjusts the weights in a certain rhythm to enable a specific fit to the company's production environment in order to provide a better decision-making support.

For the sake of clarity, Figure 2 depicts the structure of the proposed decision support model.

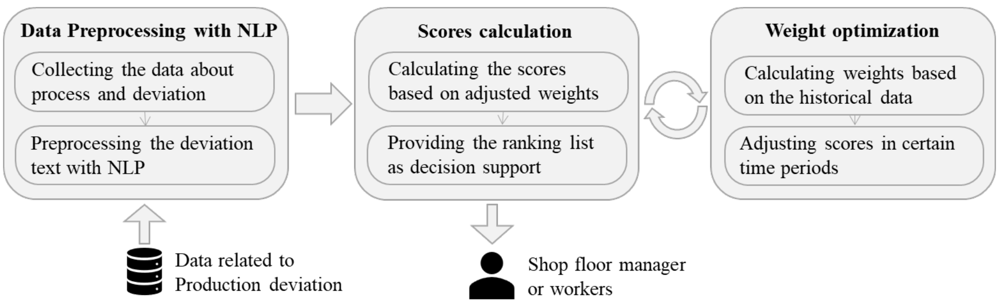

Figure 2: Structure of the decision support model

3.1 Data preprocessing with NLP

The calculation of the error score is based on the type of deviations. This process is highly related to the quality of the textual from the workers. If the quality is not sufficient, e.g., containing semantic similar description or spelling errors, this will affect the result of the designed decision-support system. Based on the analysis in Section 2.2, misspellings and abbreviations are selected to be addressed through NLP.

3.1.1 Preprocessing of misspellings

The open-source python module "Pyspellchecker" provides a function to correct misspelling. It lists a set of candidates for the input word by identifying whether the input word is included in the word frequency list, and gives the best correction for the input word [18]. However, this word frequency list is trained from existing corpus, which do not contain the words related to activities on the shop floor, and therefore cannot be directly applied to handle typos in textual data. Some adjustments are required. As shown in Figure 3, there are two operations in the preparation phase, i.e., enriching the existing dictionary and preprocessing the input textual data. At first, the shop floor-specific words including standardized abbreviations should be embedded into the word frequency list. The list employed to enrich the existing dictionary must be without spelling errors. After identifying the typos in the preprocessed data, the words that are not in the enriched dictionary are returned. Depending on the volume of the textual data, two different approaches can be used to correct the typos. If the volume is manageable, the system can list the candidates for each detected typo to be corrected manually. For large volumes, the system can automatically suggest the best correction for each identified typing error, inducing the risk of false corrections.

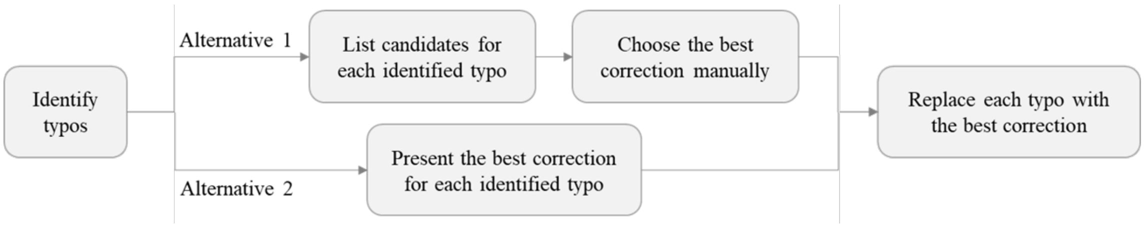

Figure 3: Pre-processing of misspellings

3.1.2 Preprocessing of abbreviations

The purpose of dealing with abbreviations is to normalize the abbreviations and thus reduce ambiguity. Based on the analysis of possible patterns in abbreviations, a rule-based algorithm is proposed. As shown in Figure 4, there are mainly three steps to check whether a token is an abbreviation. The process starts with the tokenization and filter of words. Only the abnormal words, which have potential to be abbreviations, are contained in this process to be checked. The check of regular form contains the following conditions:

- The token contains at least one and less than three letter
- The token only contains digits and letter belonging to the language in which the text is written
- The token does not begin with digits

If a token satisfies all these three conditions, it can then be saved to the list of candidates of abbreviations. If not, it is possible that the token contains special characters that affects the first check. The special characters refer to all characters, excluding digits, letters, and dots. Therefore, the special character should be transformed into a whitespace character. Those transformed spaces that locate at the beginning and the end of the original token shall be then removed. Subsequently, the process returns to the first step again. If no more special characters can be found in the token, the third step is to be performed. In the check of special form of abbreviation, the following conditions should be fulfilled:

- A special pattern can be observed in the token, which is: a letter is followed directly by a dot
- This pattern appears at least once but less than four times in the token

If a token satisfies all these three conditions, it can then be saved to the list of candidates of abbreviations. After the three steps, a list with abbreviations is generated. With the help of expert knowledge, the meaning of the abbreviations is explained and stored to normalize the abbreviation in the whole dataset.

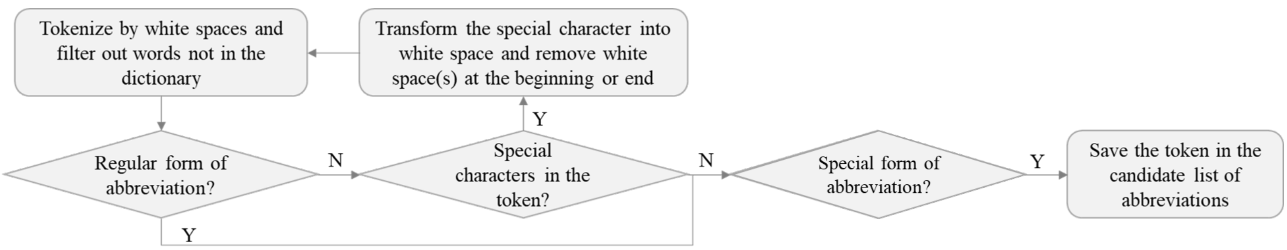

Figure 4: Pre-processing of abbreviations

3.2 Calculation of error score

A previous study by Longard et al. has shown the effectiveness of error scores in the field of rework processes in production [19]. To extend this model to more fields related to problem-solving, this work applies several adjustments to the original model, which are explained in the remainder of this section.

3.2.1 Error Score

Data analytics is applied to calculate an error score based on documented errors from the past. The following parameters are included: the total cost for the deviation and the trend of the occurrence. The goal is to faster identify errors and to prioritize which errors to focus on [20]. The error score is defined as

$$S_i^{error} = \frac{S_i^{uptrend} \cdot w_{trend} + S_i^{cost} \cdot w_{\text{cost}}}{w_{\text{trend}} + w_{\text{cost}}} \quad (3.1)$$

, where S_i^{error} is the error score for deviation i, S_i^{trend} and S_i^{cost} are the scores of the trend of occurrence and the cost of deviation. w_{trend} and w_{cost} are the weights for sub scores, with the constraint

$$w_{\text{trend}} + w_{\text{cost}} = 1 \quad (3.2).$$

This constraint is set to ensure that the optimal solution is always found during the optimization process and that the two weights do not move in the same direction at the same time. The calculation of the S_{trend} and S_{cost} should consider both process data and deviation documentation in the historical data. The formular is

$$S_i^{trend'} = \begin{cases} \frac{\sum_{d=0}^{m} C_i^{x-d}}{\sum_{d=0}^{n} C_i^{x-d}}, if \sum_{d=0}^{m} C_i^{x-d} > \sum_{d=0}^{n} C_i^{x-d} \ and \ \sum_{d=0}^{n} C_i^{x-d} \neq 0 \\ 0, otherwise \end{cases} \quad (3.3)$$

, where $S_i^{trend'}$ is the score of time tendency without standardization. C_i^{x-d} is the cost of deviation i on day $x - d$. $\sum_{d=0}^{m} C_i^{x-d}$ is the sum of the cost for the deviation i in the last m days, and $\sum_{d=0}^{n} C_i^{x-d}$is the sum of the cost for the deviation in the last n days. With this function, the score considers whether the deviation cost in the recent m days is greater than the period of n days (considering $n > m$). If $S_i^{trend'}$ is zero, which means the error shows no trend in the recent. This way, the deviations with a rising frequency of occurrence are identified. After the normalization, the score of time tendency is defined as

$$S_i^{trend} = \frac{S_i^{trend'} - \min_{1 \le i \le N} S_i^{trend'}}{\max_{1 \le i \le N} S_i^{trend'} - \min_{1 \le i \le N} S_i^{trend'}} \quad (3.4)$$

, where N is the total number of deviations. And

$$S_i^{cost'} = \sum_{d=0}^{s} C_i^{x-d} \quad (3.5)$$

, where $\sum_{d=0}^{s} C_i^{x-d}$ means the sum of the cost in the last s days. s is determined empirically, and usually in reality, when a deviation arises, the longer it causes to the production line, the larger the value of s. This gives a more complete image of the impact of the error. After the normalization, the score of cost is

$$S_i^{cost} = \frac{S_i^{cost'} - \min_{1 \le i \le N} S_i^{cost'}}{\max_{1 \le i \le N} S_i^{cost'} - \min_{1 \le i \le N} S_i^{cost'}} \quad (3.6)$$

, where N is the total number of deviations. After the calculation of S_i^{trend} and S_i^{cost}, the error score can be calculated with the pre-defined weights.

3.3 Automatic weight determination and optimization

Since the severity of a deviation is affected by trends and costs differently at different times, the two weights controlling trends and costs, w_{trend} and w_{cost}, need to be updated at intervals so that the algorithm is adapted to the current state of production in each period. This is done by a novel optimization algorithm. The basic concept of the algorithm is described in Figure 5.

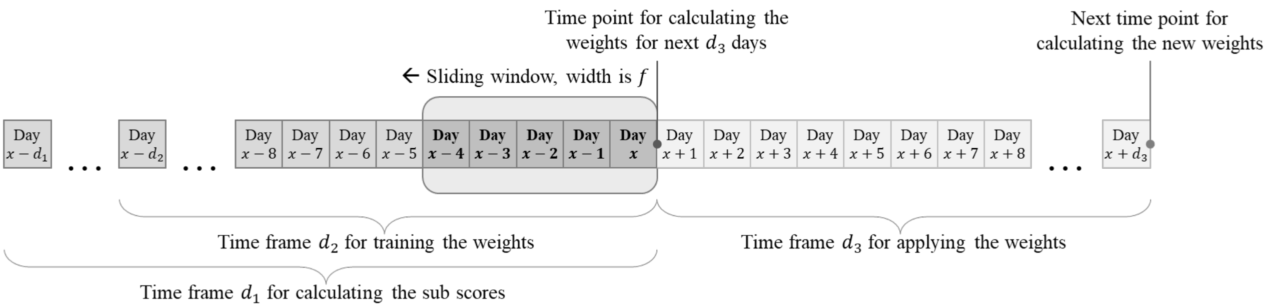

Figure 5: Weight optimization

The weight optimization process runs as follows:

- The weights w_{trend} and w_{cost} are updated in every d_3 days. The default length of d_3 is one month.
- On the day of weight optimization, the time frame for calculating the sub scores is d_1, which means $s = d_1$ and $m, n < d_1$. The default length of d_1 is three months.
- The weight optimization process considers the performance of error score in the past period, the length of this time frame is d_2. This is to make sure that the weight is not only adjusted to one day but a whole period. The default length of d_2 is one month.
- The performance of the error score is how well the error score can predict the top errors in the next f days. Therefore, the evaluation is always based on f days. This is considered as one sliding window. The default length of f is five days.
- In each siding window, one shop floor meeting is simulated, error scores are calculated, and the top deviations are ranked. With the deviation cost of the next f days, the performance of the error score is also evaluated. The performance of each sliding window is marked as P_j. In the time frame d_2, the sliding window moves to the left and simulates all the shop floor meetings in the period as shown in Figure 6. The total number of sliding windows is $d_2 - f + 2$.

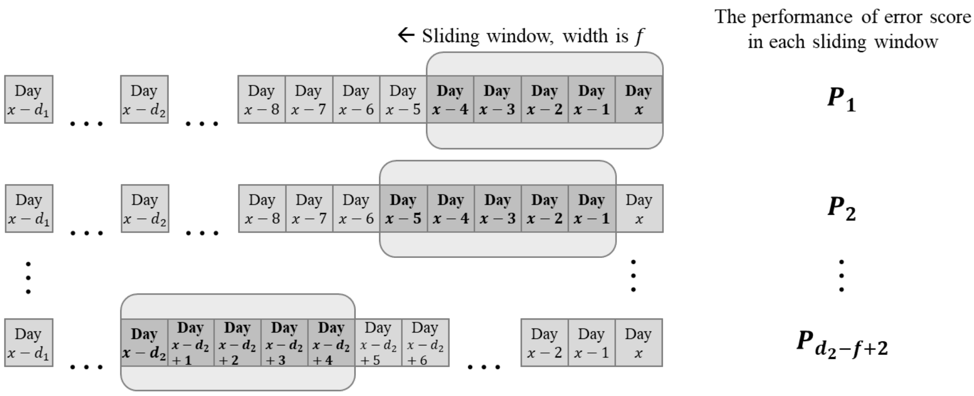

Figure 6 Weight optimization with sliding window

- The average performance P is then calculated based on the performance of all sliding windows. And the target of the algorithm is to obtain the right weights by iteration, which can achieve a better overall performance.

The average performance P is the optimization target of the algorithm. In order to achieve a higher P, the algorithm uses the method of gradient descent to find out the best weights with historical data. And the best weights are used for the calculation of error score in the next period of d_3 days.

4. Case study

In the automotive production, an effective problem-solving process is essential, as the right and immediate recognition of the deviation can prevent the severe deviation that may cause the huge consequence in the future [19]. In this work, the proposed algorithm is tested with the data from a production line of an automotive company. At the end of the production line, the workers check the quality of the products with both test equipment and eye check. The deviations are recorded in the dSFM system through the terminals at the quality gate. Products that don't fit the defined requirements are sent to the rework station. After finishing the rework, the workers record the measurements and time needed in the system. In the every-day shop floor meeting, the managers go through the rework records and identify the most serious deviations that may occur in the next days, so that the measurements can be taken as soon as possible, and the personnel plan can also be adjusted.

4.1 Dataset

The dataset contains three different sub datasets, namely a process dataset, a quality check dataset and the rework dataset. The process dataset is collected from the manufacturing execution system and contains the basic information about the product and the production process. The quality check dataset is collected from the terminal of the SFM system at the quality gate at the end of the production line, contains the results of the quality check. The rework dataset is collected from the terminals at the rework station. As shown in the section 3.1, the datasets are merged according to the product number. The failure description is in natural language. With the methods described in section 3.2, the abbreviations and misspellings are corrected and standardized, so that every failure type is identical and can be further used in the error score calculation. An excerpt of the final data, used for the error score calculation, is shown in the following table.

Table 1: Excerpt of final data for error score calculation

Product No.	Deviation Description	Rework Duration	Rework Time	Production Time
1000001	Steckplatz Drehmoment n.i.O.	60.0	09.06.2021 18:54	09.06.2021 10:12
1000003	Fehlendes Getriebe	60.0	09.06.2021 18:54	09.06.2021 13:31
1200057	DGM Einstellung	90.0	09.06.2021 18:54	09.06.2021 10:16
2257009	Beschädigte Schrauben	30.0	09.06.2021 18:54	09.06.2021 08:07

4.2 Methodology

To verify the model, the proposed method is compared with the Pareto analysis, which is often used in the production line to identify and prioritize the most serious deviations. The goal of both error score and the Pareto analysis is to generate a list of deviations, displaying them from highest to lowest severity. Therefore, the evaluation is done by comparing the overlap between the deviations recommended by the list and the deviations that occurred. For the five largest deviations that occur, if the percentage of costs resulting from deviations predicted by the error score is greater than the results of the pareto analysis, then the performance of error score is superior. Based on this understanding, the metrics are defined to evaluate the performance of the decision support system. They can be defined as follows:

$$PE(cost) = \sum_{i=1}^{5} r_i * C_i \tag{4.1}$$

$$PE(percentage) = \frac{\sum_{i=1}^{5} r_i * C_i}{\sum_{i=1}^{5} C_i} \tag{4.2}$$

$$C_i = \sum_{d=0}^{4} C_i^{x+d} \tag{4.3}$$

, where C_i^{x+d} is the cost of the deviation i on day $x + d$, $C_1, \dots, C_5$ is the cost of the top deviations. r_i means whether the deviation is suggested by the decision support system.

As the test of the algorithm lasts for a period, which means that there are more shop floor meetings and decision-making processes involved. Therefore, to get the performance of the algorithm in a period, the average performance of the algorithm is calculated as follows:

$$PE_{AVG} = \frac{\sum_{j=1}^{M} PE_j}{M} \tag{4.4}$$

, where PE_j is the performance in one day, s is the number of days in the period when the same weight is used. The larger the PE_{AVG}, the better the performance of the decision support system over the period.

To better observe the changes in the rework process after the error score is applied, the Cox-Stuart test [21] is used to assess whether there is a downward trend in rework duration.

5. Results and discussion

The proposed method is tested with the data from 06.2020 to 08.2021. After merging the process data, deviation data and the rework documentation, this results in a total of 7771 records. In the data preprocessing process, all the text related to deviation are analyzed with the algorithms to correct the misspellings and abbreviations. The 62 abbreviations automatically found by the algorithm. With the help of the expert knowledge from the shop floor, the abbreviations are replaced in the data. A new dictionary with 49 new words is trained and imported to the system, so that the algorithm for misspelling can also recognize and correct the specific words in the rework documentation. After the preprocessing with NLP, the original 1316 failure categories are lowered to 1063. Through this process, 19.33% of the original records were fused with records that had the same meaning, enhancing the accuracy of the data.

For the evaluation of the error score, the shop floor meetings from January to July are simulated. As comparison, the performance of the Pareto analysis is also calculated. As shown in Table 2, the performance of error score is overall better than the Pareto analysis.

Table 2: Results of the evaluation

Simulated Date	Performance of error score		Performance of Pareto analysis	
	$PE(cost)_{AVG}$	$PE(percentage)_{AVG}$	$PE(cost)_{AVG}$	$PE(percentage)_{AVG}$
01.2021	893, 34 min	31.84%	830.75 min	29.28%
02.2021	1215.75 min	58.27%	950.75 min	45.52%
03.2021	1007.5 min	52.56%	651.0 min	34.17%
04.2021	942.0 min	47.71%	819.0 min	40.44%
05.2021	957.75 min	47.25%	826.75 min	41.47%
06.2021	643.25 min	28.44%	522.75 min	25.25%
07.2021	678.75 min	38.33%	117.5 min	9.60%
average	**905.48 min**	**43.49%**	**647.07 min**	**32.17%**

Besides the results of simulation, the rework duration after applying the error score is also observed. Figure 6 shows the rework duration since the official Go-Live in September 2021 to September 2022. The Cox-Stuart test identifies a significant downward trend with $p - valure = 0.0063$ (see Figure 7).

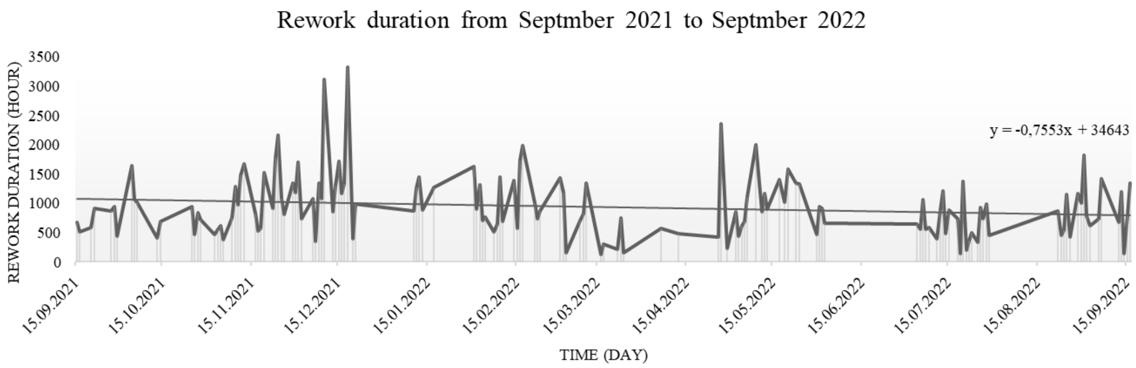

Figure 7: Rework duration from September 2021 to September 2022

This case study reveals that the proposed decision support model can be effectively and practically applied for the prioritization of the deviation in the problem-solving process. A comparative analysis with the pareto method also shows that the proposed method has a good predictive performance for the problems that may arise in the future. In addition, a trend of gradual reduction in the cost of rework time caused by errors in practice was also observed during the year when the method was applied to the actual production process. This also reflects the effectiveness of the method in practice.

6. Conclusion and future work

This paper establishes a comprehensive decision support model that utilizes process and deviation information to assist the deviation prioritization for the SPS on the shop floor. The proposed method is able to achieve better performance than the traditional Pareto analysis. It is also demonstrated by deploying the method in a real production environment. The results show that the deviation prioritization process can be improved to a certain degree with the help of this decision support system. This paper makes some attempts in dealing with heterogeneous data in production, combining structured and unstructured data for analysis. In the future, there are many more directions for the analysis of heterogeneous data, such as the graph databases that can be used to model the data involved in SFM, which can better provide the data basis for other decision support systems. In the direction of NLP, there is also a need to further analyze and study the textual data in SFM, so that more information for problem solving can be extracted.

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References

[1] Künzel, H. (Ed.), 2016. Erfolgsfaktor Lean Management 2.0: Wettbewerbsfähige Verschlankung auf nachhaltige und kundenorientierte Weise. Springer Gabler, Berlin, Heidelberg, 447 pp.

[2] Xu, Z., Dang, Y., Munro, P., 2018. Knowledge-driven intelligent quality problem-solving system in the automotive industry. Advanced Engineering Informatics 38 (2–3), 441–457.

[3] Zaidat, A., Boucher, X., Vincent, L., 2005. A framework for organization network engineering and integration. Robotics and Computer-Integrated Manufacturing 21 (3), 259–271.

[4] Khan, M., Wu, X., Xu, X., Dou, W., 2017. Big data challenges and opportunities in the hype of Industry 4.0. 2017 IEEE International Conference on Communications (ICC), 1–6.

[5] Longard, L., Meißner, A., Müller, M., Metternich, J., 2020. Digitales Shopfloor Management – Wohin geht die Reise? Zeitschrift für Wirtschaftlichen Fabrikbetrieb: ZWF 115 (9), 645–649.

[6] Müller, M., Longard, L., Metternich, J., 2022. Comparison of preprocessing approaches for text data in digital shop floor management systems. Procedia CIRP 107 (7-8), 179–184.

[7] Pötters, P., Schindler, P., Leyendecker, B., 2018. Status quo Shopfloor Management. Zeitschrift für wirtschaftlichen Fabrikbetrieb 113 (7-8), 522–525.

[8] Hertle, C., Tisch, M., Metternich, J., Abele, E., 2017. Das Darmstädter Shopfloor Management-Modell. Zeitschrift für Wirtschaftlichen Fabrikbetrieb: ZWF, Carl Hanser Verlag 112 (3), 118–120.

[9] Meißner, A., Hertle, C., Metternich, J., 2018. Digitales Shopfloor Management – Ihr Weg zur vernetzten Fabrik. Zeitschrift für Wirtschaftlichen Fabrikbetrieb : ZWF, Carl Hanser Verlag 113, 281–284.

[10] Furlan, A., Galeazzo, A., Paggiaro, A., 2019. Organizational and Perceived Learning in the Workplace: A Multilevel Perspective on Employees' Problem Solving. Organization Science 30 (2), 280–297.

[11] Choo, A.S., Nag, R., Xia, Y., 2015. The role of executive problem solving in knowledge accumulation and manufacturing improvements. Journal of Operations Management 36 (1), 63–74.

[12] Kumar, S., Sosnoski, M., 2009. Using DMAIC Six Sigma to systematically improve shopfloor production quality and costs. International Journal of Productivity and Performance Management 58 (3), 254–273.

[13] Müller, M., Alexandi, E., Metternich, J., 2021. Digital Shop Floor Management Enhanced by Natural Language Processing. Procedia CIRP 96, 21–26.

[14] Hapke, H., Howard, C., Lane, H., 2019. Natural Language Processing in Action: Understanding, analyzing, and generating text with Python MEAP V10 - Chapter 1, 40 pp.

[15] Rahm, E., Hong, H.D., 2000. Data cleaning: Problems and current approaches. IEEE Data Eng. Bull. (23), 3–13.

[16] Müller, M., Metternich, J., 2021. Production Specific Language Characteristics to Improve NLP Applications on the Shop Floor. Procedia CIRP 104, 1890–1895.

[17] Jurafsky, D., Martin, J.H. Speech and Language Processing: An Introduction to Natural Language Processing, Computational Linguistics, and Speech Recognition 2020.

[18] Bird, S., Klein, E., Loper, E., 2009. Natural language processing with Python: analyzing text with the natural language toolkit, 504 pp.

[19] Longard, L., Brungs, F., Hertle, C., Roeth, J., Metternich, J., 2021. Reduced Rework Through Data Analytics and Machine Learning – A Three Level Development Approach. SSRN Journal.

[20] Longard, L., Bardy, S., Metternich, J., 2022. Towards a Data-driven Performance Management in Digital Shop Floor Management. Hannover: publish-Ing, 11 pp.

[21] Cox, D.R., Stuart, A., 1955. Some Quick Sign Tests for Trend in Location and Dispersion. Biometrika (42(1/2)), 80–95.

Biography

Yuxi Wang, M. Sc. (*1995) is research associate and PhD student at the Institute of Production Management, Technology and Machine Tools (PTW) at the Technical University of Darmstadt since 2021. Her research interests include the further development and introduction of natural language processing to digital shop floor management and problem-solving systems.

Lukas Longard, M. Sc. (*1992) is chief engineer and PhD student at the Institute of Production Management, Technology and Machine Tools (PTW) at the Technical University of Darmstadt since 2019. His research interests include the further development and introduction of machine learning to digital shop floor management and performance management systems.

Dr.-Ing. Christian Hertle (*1987) is CEO Business Development of SFM Systems, a software provider for digital shop floor management software. He did his PhD at Technical University Darmstadt on the topic of shop floor management and how it can be used for continuous competency development in manufacturing.

Prof. Dr.-Ing. Joachim Metternich (*1968) is head of the Production Management division at the Institute of Production Management, Technology and Machine Tools (PTW) at the Technical University of Darmstadt. He is the spokesman of the medium-sized businesses digital competence center Darmstadt; he has been president of the International Association of Learning Factories (IALF) from 2015 to 2021 and he is scientific partner of the Conference on Production Systems and Logistics (CPSL).

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Cyber-Physical-Systems for Fluid Manufacturing Systems

Ali Bozkurt[1], Christian Fries[2,3], Timur Tasci[4], Urs Leberle[5], Daniel Kessler[6], Markus Joos[7], Manuel Hagg[1], Bernd Neuschwander[8], Moritz Hinderer[5]

[1]Institute of Mechanical Handling and Logistics, University of Stuttgart, Stuttgart, Germany
[2]Institute of Industrial Manufacturing and Management, University of Stuttgart, Stuttgart, Germany
[3]Fraunhofer-Institute for Manufacturing Engineering and Automation, Stuttgart, Germany
[4]Institute for Control Engineering of Machine Tools and Manufacturing Units, University of Stuttgart, Stuttgart, Germany
[5]Robert Bosch GmbH, Stuttgart, Germany
[6]Balluff GmbH, Neuhausen auf den Fildern, Germany
[7]Bär Automation GmbH, Gemmingen, Germany
[8]Pilz GmbH & Co. KG, Ostfildern, Germany

Abstract

Increased volatility continues to challenge the automotive manufacturer's production performance. More than a century after the start of mass production, changeable production systems that allow the flexibility for the economic mass production of customized products have arisen. Limitations on established production systems are driving the development of changeable production systems like the Fluid Manufacturing System (FLMS). In an FLMS, the individual production modules are mobile and consist of Cyber-Physical Systems (CPS) which can be combined ad-hoc to adapt to changing requirements. By connecting different CPS – e.g., Autonomous Mobile Robots (AMR) or smart load carriers – adaptable and flexible production will be achieved. This paper presents the first real-world initiation of an FLMS with the design and development of CPS and digital twins for production and logistics at the ARENA2036 research campus.

Keywords

cyber-physical-systems; digital twin; material flow control; human-centric production, automotive

1. Introduction

Driven by growing competition, companies need to increasingly focus on customer requirements in order to remain competitive in the long term. Exclusive differentiation based on product price and quality is no longer sufficient. On the other hand, high delivery reliability and short delivery times have become a well-recognized competitive factor. Due to their technical limitations, a traditional production system, such as the **Dedicated Manufacturing Lines** (DML), cannot achieve the required changeability to achieve these requirements especially in high mix low volume production environments. Therefore, new, changeable production systems have been developed over time. As early as in the 1990s, the term "changeability" was used to describe the ability to adapt quickly to changing influences. Since then, the term has been one of the key success factors for manufacturing companies and various systems have been developed. The **Flexible Manufacturing Systems** (FMS) enables the adjustment of production capacity and functionality within a fixed flexibility corridor (e.g., a family of parts). This requires the use of predefined functionalities, which leads to additional costs and higher complexity. The retooling of an FMS beyond the flexibility corridor takes several weeks or months [1–7]. FMSs are thus configurable within a corridor, but not reconfigurable

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beyond it. The **Reconfigurable Manufacturing Systems** (RMS) can resolve this limitation. In contrast to FMS, an RMS allows the adaptation of the production system across fixed flexibility boundaries. Koren refers to this as customer-specific flexibility. RMS thus combines the advantages of DML and FMS [8,9]. According to Koren, the productivity of an RMS is higher than that of a line, for example in large complex systems [10]. However, efficient algorithms are necessary for the real-time control of an RMS. These are also correspondingly complex [11,12]. **The Matrix Manufacturing Systems** (MMS) consists of flexibly-linked, usually dedicated process modules. Each process module provides predefined sets of technological functionalities necessary for production. An MMS enables new production control functions, as each product can determine an individual production path by selecting its process modules, depending on the available process module functionalities, the assembly precedence graph, and the current state of production resources. The cycle times of the process modules are no longer uniform [13,14]. **The Fluid Manufacturing System** (FLMS) is based on the principle of ad-hoc resource allocation and reconfiguration to individual process modules for optimal manufacturing performance [15] and develops the MMS concept further. Comprehensively using the benefits of cyber-physical systems [16,17] and their capability to self-integrate and self-parametrize, process modules can be easily aggregated from single resources to advanced manufacturing systems [18]. To fully leverage the potential of FLMS, all process modules must be modular and mobile. The requirements for mobility and modularity are on-demand adjustments of capabilities and functionalities as well as adaptable production layouts. Thus, the manufacturing system is capable of being iteratively reconfigured in variable steps to the currently required product configuration. This reconfigurability requires complex production planning and control logic, considering previously unknown degrees of freedom in production system design. New degrees of freedom are the: Operation Sequence (specifies the sequence of work operations), Work Distribution (assigns the process modules to the production order), Work Content (defines the competencies of a specific process module) and Layout Position (defines the position of production equipment on the shop floor). These freedoms affect both the planning and control complexity of the order management. Order management thus defines the new understanding of production planning and control (PPC) in which the fulfilment of customer orders is the central goal [19]. Order management covers the planning, control and monitoring of all activities (including orders, resources, ...) along the value chain from customer inquiry to shipment [20,21]. The remainder of this paper is organized as follows: Section 2 provides an overview of the state of the art, Section 3 presents various developed CPS for FLMS, Section 4 presents the initiation of the FLMS. Section 5 concludes the key points of this paper and provides an outlook.

2. Designing and Development of Cyber-physical Systems

CPS connect the physical world with the virtual world by allowing mutual control and information exchange via the internet, also known as the Industrial Internet of Things (IIoT) [22,23]. They are commonly used in engineering, manufacturing and logistics. Moreover, CPS are providing benefits for manufacturers by utilizing sensor generated data [24]. However, the boundary conditions and the new levels of freedom in an FLMS have resulted in new requirements for future CPS. These requirements affect several production assets, e.g., AMRs, machines and sensors. Some of these requirements are related to the design and others to software [18]. In the next step, each requirement for CPS in an FLMS will be described in detail.

Reconfigurability is the ability to change and evolve rapidly in order to adjust productivity, capacity and functionality [10]. Therefore, CPS have the task of enabling these requirements. For example, by adapting to different products and parts with a wide range of measures, different weight sizes, etc.

Modularity is the integrating element directed at highly customizable manufacturing engineering structures [25]. In an FLMS, all units, including CPS, are modular and can be combined ad-hoc to new resources.

Asset Administration Shells (AAS) are necessary for communication amongst the individual I4.0-components. This is embodied in the approach of this paper through the concept of submodels which broadly

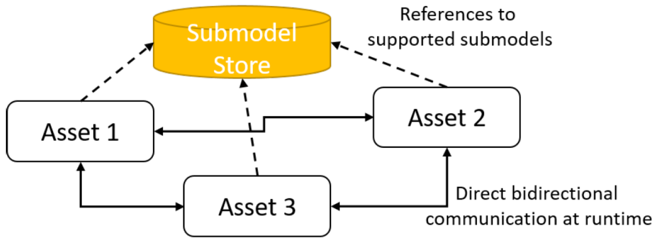

Figure 1: Communication between assets based on known submodels

describe features and capabilities. One submodel precisely explains one technical feature. Submodels are published in a central location that is accessible to each partner in order to ensure that this shared understanding is as clear as possible and is used by as many I4.0-components as possible [26]. An I4.0-component must introduce itself and specify one or more supported submodels in order to make its attributes and capabilities known to others (see Figure 1). An I4.0-component consists of the following objects:

- Submodels: An I4.0-component's technical details are specified by one submodel only. In order to achieve this, the submodel explains the traits, occasions, and actions connected to this feature.
- Properties: A submodel can specify any number of properties. A property describes a static or variable property, e.g., a position, color or serial number. If an I4.0 component communicates a property, the specification is assumed to be valid until the component sends an update.
- Events: Unlike properties, events have a unique time reference. The event contains a timestamp. Examples for events are the arrival of an AMR at the destination or the completion of an assembly process. Events also have a unique name and can communicate with other data fields. Each data field is specified in the same way as a property.
- Operations: While properties and events describe outgoing communication, operations specify services that can be called upon by other components. For example, a manufacturing process can be triggered. Operations are identified by their unique name within the submodel. Optionally, parameters can be specified. Unlike events, a return value can also be specified, e.g., to report a successful operation.

Creation of a digital twin: Representing a CPS with an AAS raises the possibility of representing any asset from the real world as a copy in the digital world. Visualization, simulation, etc. are just some examples of what can be done by utilizing the given data from an asset.

The orchestration of CPS in an FLMS is realized by Node-RED. Node-RED is a browser-based, graphical, open-source programming environment. Processes can be modeled in the form of so-called "flows" and are then processed in a server-side engine. A node is a data processing step. It is always triggered when new data is present at the input. Node-RED is designed to be supplemented with its own node types to fulfill application-specific tasks. A service ensures that, for each submodel that is currently in use, a node type is automatically created for its properties, operations and events. In this way, processes can be modeled in Node-RED that can access all the elements of the management shells and thus all assets.

Service-oriented architecture (SOA) allows IT system services to be structured and used more efficiently. At the same time, business processes can be mapped more flexibly, which reduces maintenance efforts and costs. The basis for this is the decomposition of complex business processes into their individual steps. SOA is not only comprised of components required to interact with an AVG or AMR, which can be represented as an AAS, but value-added services can also be set in this format. Utilizing this approach has an impact on the development of different services.

3. Cyber-physical Systems for FLMS

According to the requirements in the following chapter, different prototypes of CPS for FLMS and a concept for human-centric production have been developed. In the following sections, the implementation process and the concept are described in detail.

3.1 Human-centric production

In human-centric production, the user interfaces allow the easy operation and commissioning of the CPS. In addition, collaborative assistance systems enable the worker to perform simple maintenance tasks without prior training. Human-robot collaboration also makes it possible to parallelize the processes in the process modules and thus reduce cycle times [18]. In the context of the ARENA2036, a shared safety concept for human-machine collaboration in an FLMS has been developed. Taking machine safety into account, a sensible approach for automated guided vehicles (AGVs) to drop-off or pick-up locations, which are protected with safety devices, can only be realized if those devices are switched off. This entails potential hazards for workers in the working space. However, since this must be excluded by the machinery directive, additional hardware in the form of separating safety devices or additional sensors are necessary. If an AGV approaches the storage location and a Safety and Control Unit (SRU) with the safety devices switched off, there may also be a blind spot (Figure 2) behind the AGV that the laser scanners miss. A person could be behind the AGV and enter the danger zone of the SRU. This must be absolutely excluded. The designed concept provides four steps to counter the problem described. In the first step, the second asset, the SRU, controls the AGV. In order to transfer the control of the AGV to the SRU, it is necessary to clearly identify the two assets, as there may be several assets of the same design in a real environment. Initially, the transfer takes place manually. Therefore, the AGV takes a picture of the asset and sends it to a worker for confirmation, who then releases it on his smart device. In addition, approaches for the automatic handover are examined in more detail. To enable the transfer of the control functionality from the AGV to the SRU, a safe switchover is required, which is carried out via a safe operating mode selector switch. This puts the AGV into manual mode and provides the laser scanner data of the AGV via AAS (Figure 2).

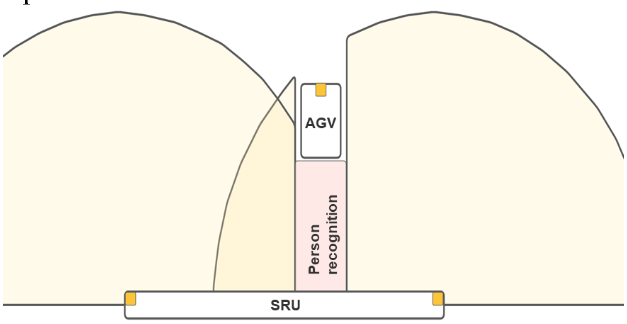

Figure 2: Person recognition in front of the AGV

In order to adjust the safety devices, it is necessary to open a corridor in front of the AGV in the area of the laser scanner of the SRU. In this way, the entry of the AGV does not trigger a system stop of the SRU. At the same time, the data of the laser scanner of the AGV, which is turned away from the SRU, must also be evaluated via AAS. Thereby, a person can be prevented from entering the safety area of the system. In addition, person detection is performed in front of the AGV in order to additionally secure the muted area. The last step of the concept is undocking and restoring the original state. Therefore, the AGV must be navigated out of the danger zone and then, as soon as the AGV is in the warning zone of the SRU, the muted zone must be reactivated before finally switching to autonomous operation again. In general, the concept was designed generically in order to combine a wide variety of assets and their safety devices. A first prototypical implementation has already taken place.

3.2 Fluid Production Logistics

In order to use the full potential of an FLMS, adaptable and flexible logistics systems are needed. Therefore, a smart load carrier and an AMR have been developed. Furthermore, different approaches for a decentralized material flow control system have been designed.

The aim of the development of **AMR** was to enable the transformation of an Autonomous Guided Vehicle from its task-based applications to an autonomous, smart and safe mobile robot platform. The AMR is an autonomous logistics unit, which is responsible for pick-up and transportation tasks as an essential part of FLMS. Depending on the size and the task, the AMR is able to transport different sizes of load carriers and car bodies. This enables more flexibility and further benefits in the logistics and production process, e.g., modularity and reconfigurability. The mobile robot system consists of two drive-rotation-axis units, which enables the AMR area-moving kinematics. Compared to differential kinematics, it is possible for the AMR to drive in the Y-direction as well as to change orientation during the drive. In addition, the AMR has two safety laser scanners, which can be used for the safety field and navigation. In order to transform the AMR into a CPS, the following key issues are considered for this purpose, which will be illustrated in the following sections: communication interface to Industry 4.0, higher-level control and target-oriented navigation. For a unified semantic description, the interfaces of the AMR are realized via an AAS. Figure 3 shows the first Version of the AAS of the AMR with its submodules, which was later expanded with further Submodules for the order management to realize the use cases in section 4.2 and 4.3.

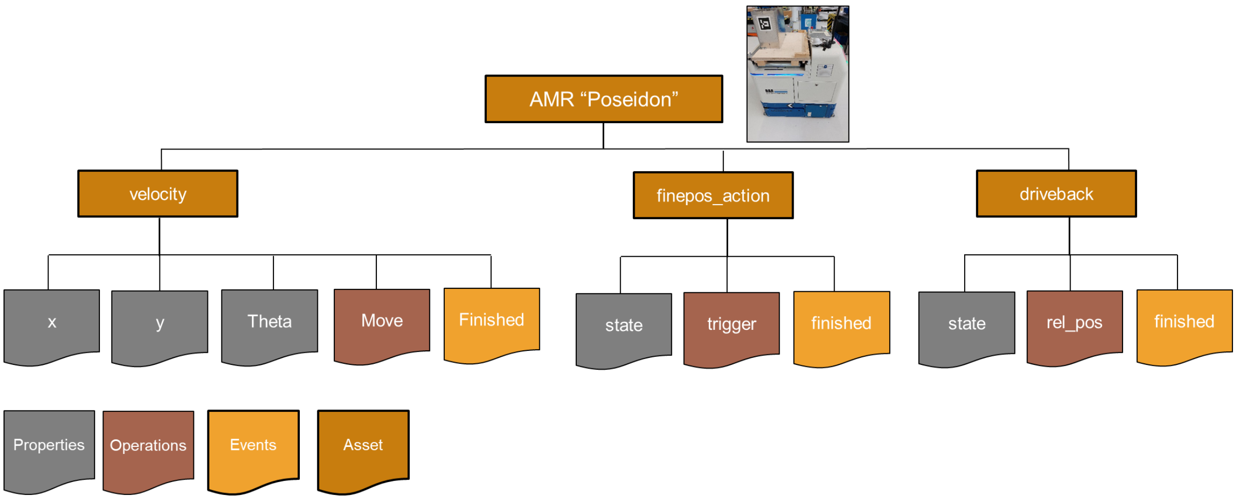

Figure 3: First Version of the AAS for the AMR “Poseidon”

An advantage of the AAS is that any size of data can be implemented in the description. Thus, the interface can be severely limited or allow full access at all levels of the control hierarchy down to the sensor level. Likewise, it offers the possibility to the other participants in the network to receive information on the components as well as to send control commands like, for example, different movements or the fine positioning of the AMR. The higher-level control system has the task of planning and coordinating AMRs within a production area. In general, it is a master control or fleet management which is used with the help of the VDA 5050 recommendation for AMRs/AGVs [27]. With this standard, it is possible to coordinate several AMR among the others, independently of the manufacturers. Navigation is an important part of the AMR, which can be described as one of the main features for the transformation into a CPS. Localization and route planning go hand in hand. The aim is to determine the current starting position in relation to the specified target position autonomously and without collision. The Robot Operating System (ROS) offers a wide range of packages so the navigation of the AMR can be safely achieved. It offers the navigation stack via a navigation algorithm by using different information such as laser scanners. The move_base requires a map of the environment which is recorded using the laser scanners and the wheel odometry of the AMR. For localization, the ROS offers different software packages. In this case, the mobile robot system uses the slam_toolbox, which has the modes "mapping" and "localization". With this combination of localization and navigation, the AMR can approach its respective workstation in the FLMS.

Smart Load Carriers are load carriers which are equipped with different sensors and computing devices to provide smart services, e.g., tracking & tracing or condition monitoring In order to fulfill an adaptable and flexible logistics system in an FLMS, the following requirements for a smart load carrier have been defined: (1) Reconfiguration for different load carrier sizes and materials, (2) Storage and visualization of condition monitoring data, (3) Decentralized control of the material flow, (4) Localization for a location-flexible material supply and (5) Provision of master data, e.g., bill of material, CAD model. Based on the requirements, several physical and virtual Smart Logistics Modules have been developed. This includes modules for Condition Monitoring, Container Management, Localization, Power Management and the Master Data via an AAS, as shown in Figure 4 [24].

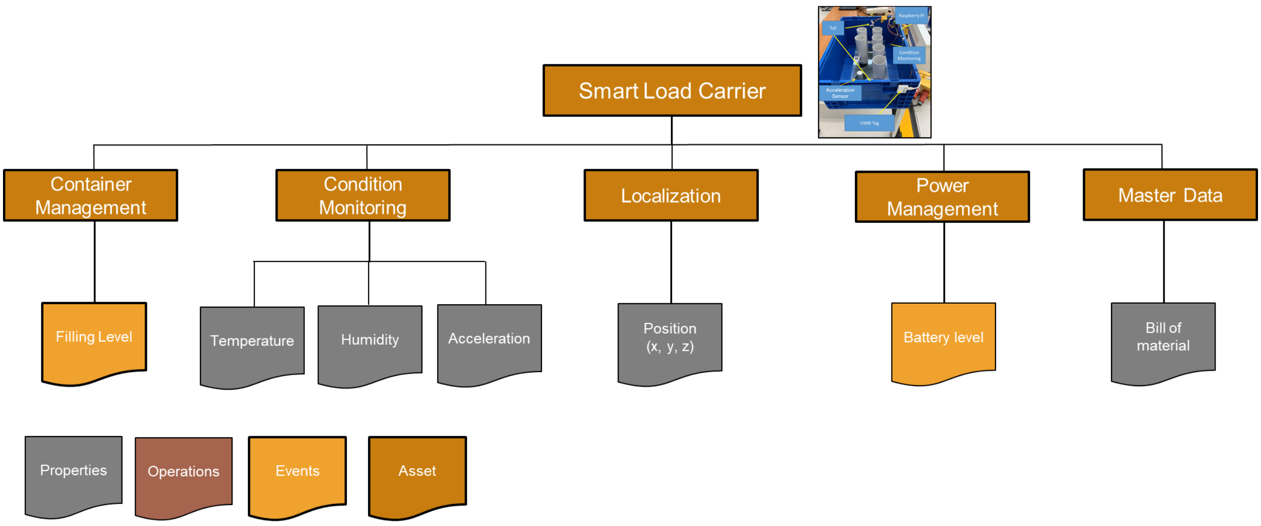

Figure 4: Modelling example for the AAS of the Smart load carrier

The smart load carrier is reconfigurable to different sizes of load carriers and parts. Moreover, it contains different interfaces for the connection and interaction with other CPSs, e.g., AMRs and Smart Products.

3.3 Assembly Process

Smart Sensors are an important part of meeting requirements for reconfigurability, fast ramp-up and flexibility in an FLMS. For this purpose, the existing sensor technology needs to become significantly more flexible and integrated more strongly into the overall system. For example, by expanding the interfaces, communication can take place across devices and systems. Thus, a fast reconfiguration to a new use case can take place within a minimal time. The Balluff Smart Camera BVS002F is used as a CPS. It is characterized by a CMOS chip of the size 1/1.8" and the recording of the image using the global shutter method. This enables better image capture with moving objects. The camera captures color images with a resolution of 1280 x 1024 pixels. The control and readout of the images is realized via Gigabit LAN. For the application positioning tasks (see Chapter 4.1), the largest possible angle of view is required in the close-up range. Therefore, a lens with an 8mm focal length for wide-angle images is used especially for the close-up range. This enables a large depth of field, so the entire working area is always sharp and refocusing the lens is not necessary. The images and results from the camera are sent to the Raspberry via an FTP interface for further evaluation and processing. The Raspberry Pi can extract the information and make it available to the other CPS components. The camera can also be reconfigured by calling various operations. Hence, it is possible to switch between different inspection programs and configurations. This allows, for example, adaptation to environmental conditions in strong or weak light conditions or switching between different use cases. The Smart Camera can perform the following operations directly on the camera: (1) Object inspection, (2) Color analysis, (3) Measurement within the image, (4) Object recognition and (5) Barcode, 2D, OCR identification, QR code. The asset administration shell of the camera provides the two properties X-position and Y-position of an object in meters (see Figure 5).

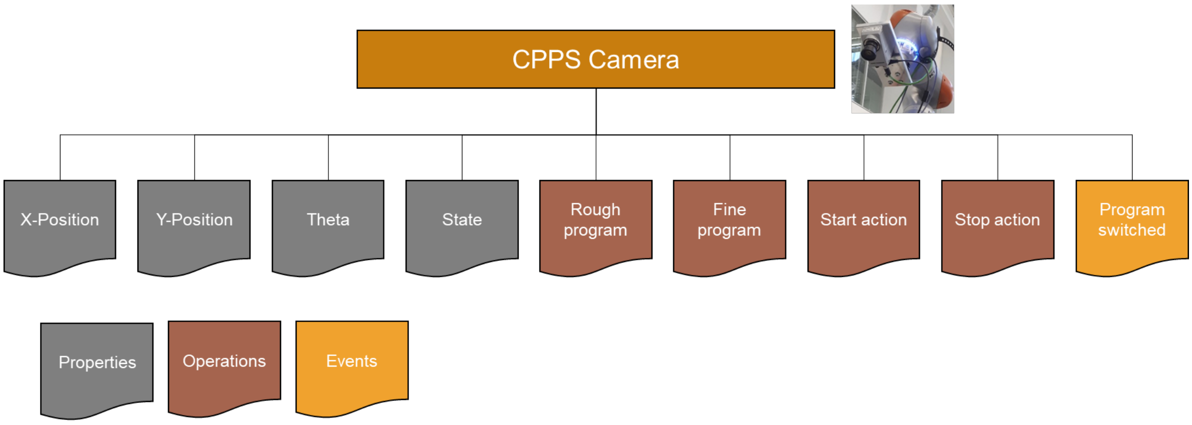

Figure 5: Modelling example for the AAS of the smart camera

In addition, the theta angle, i.e., the displacement of the object towards the camera, is output. The operation used here is the switch between the two programs Fine and Coarse Positioning on the camera. These programs can each be controlled by means of the two start and stop operations. As soon as a program change has been carried out successfully, an event is sent with a message about the change.

Smart Assembly Modules: An important aspect in the realization of FLMS is the modularization of the assembly processes involved. In classical manufacturing systems, the assembly processes and components involved are usually permanently integrated and difficult to adapt. The initial investment cost as well as the cost of changes are usually very high. An FMLS can profit from the usage of versatile and reconfigurable manufacturing concepts, in which the individual processes or components can be changed in a rapid and efficient manner. The usage of smart assembly modules (also called Mechatronic Objects (MO)) presented in this section precisely enables this modularization. The modularization considers aspects such as electrical engineering, mechanics, process technology and IT and captures them systematically at the component-level of the MO. With this modularization, an MO is standalone, possesses its own control and can be easily integrated into a higher-level manufacturing system as a part of the overall process orchestration. The overall system, in which the MOs are an integral part, is called CESA^{3}R. In the context of the project, CESA^{3}R stands for Concept for Engineering free, Scalable, Advanced Automated Assembly system for Rapid ramp up. An MO can be described and set up in a process-specific manner (see Figure 6) and usually consists of two important parts: (1) a standardized process carrier, and (2) a Process Unit that can be especially designed and constructed according to the process demands.

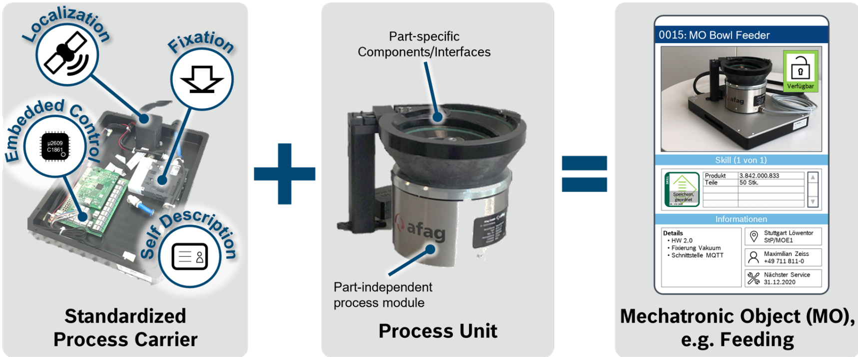

Figure 6: Structure of a Process Module

For instance, Figure 6 shows an example of a vibratory bowl feeder designed for the feeding process. The feeder is divided into a part-independent process module and a part-specific component, which can be adapted to suit different parts.

The standardized part of the MO serves as a functional sample for all MOs. This standardized process carrier is comprised of a fixation system to fix the MO during operation and a localization system to determine the position of the MO in the working area. In addition, the MO is equipped with an embedded Control which handles the inputs and outputs (IO) as well as the external communication. Finally, the MO comprises data about itself in a self-description file. The self-description integrated in each MO can provide different static and dynamic data that are useful for the overall process orchestration as an important feature of a cyber-physical system. For example, some fundamental static information, such as the identification (ID) of the MO, the available work positions and the geometry data are made available. Other dynamic data that are updated consistently during operation include, e.g., the real-time coordinates and the current operational state of the MO. For an effective standardization of the self-description, standardized data modelling for the MO is required. The data modelling used for the MO is based on the concept of the AAS. In relation to the AAS, an MO may also be described as an asset. The AAS is based on so-called submodels, which provide a standardized description of the technical aspects of an asset. A submodel can be structured into properties, events and operations.

- **Properties** describe the static and dynamic characteristics of an MO (asset). Those cover, among other information, the above-mentioned ID of an MO or the dynamically measured position of the MO origin.
- **Events** are used to communicate changes in the state of the MO to other assets. This may include the completion of a specific assembly task or a notification that an operation call has been received.
- **Operations** offer predefined functionalities for the respective MO, which can be triggered by external modules. Those operations may be used e.g. to request information or to execute a motion command.

To enhance the reusability, a single submodel should only cover a single functionality, e.g., the position data. Thus, the submodel can be used for different assembly modules and a single MO can integrate many submodels handling a variety of functionalities. Figure 7 introduces the concept of an MO using the example of a bowl feeder

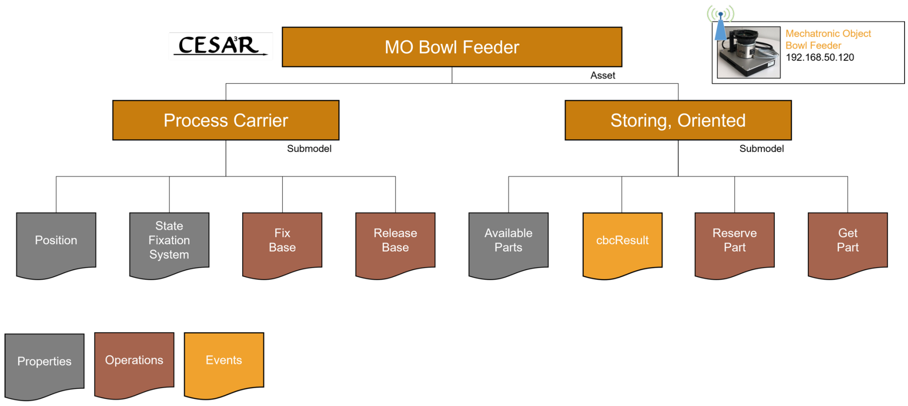

Figure 7: Modeling example for the AAS of a mechatronic object for the storage or provision of parts with the two submodels "Process Carrier" and "Storing, Oriented."

The submodel diagram shown in Figure 7 visualizes the corresponding submodels. Each MO has a submodel for the Process Carrier and one or more additional submodels, depending on the necessary skills of the equipped process unit. The introduced bowl feeder MO therefore contributes a Storing, Oriented submodel. Each submodel provides MOs defining properties such as the current position, events such as Basis Command (CBC) Result and finally operations which allow other modules and assets to reserve a part or fix the base. The reservation of a respective part guarantees that it is only used once in the process. The fix base operation allows an MO to be fixed on its current position and disable any further adjustment of its position. The MO can also be enhanced or extended with other submodules, if any functionalities should be added.

4. Instantiation of the FLMS

In the context of the project, different use cases were developed and tested. The aim through the composition of the individual use cases was the instantiation of an FLMS.

4.1 Use case – Assembly System (CESA^{3}R)

In order to verify the concepts and modules introduced with the CESA^{3}R system, a demonstration product was defined. The Battery Management System (BMS) is an easy to assemble product that provides a great use case to prove the functionality of the CESA^{3}R system. Figure 8 gives an overview of the MOs and assets involved in the assembly task.

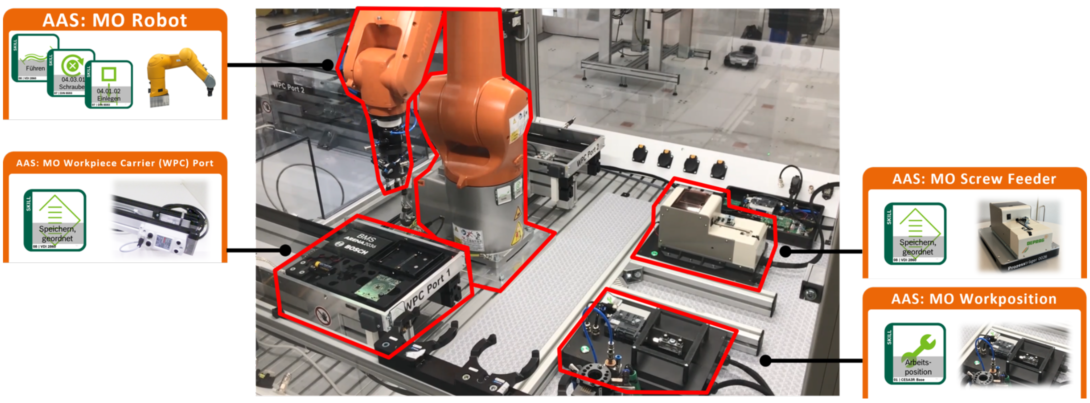

Figure 8: FluPro demonstrator and mechatronic objects (MO) for assembling the printed circuit board of the Battery Management System (BMS) demo product.

The assembly of the BMS requires a great variety of skills from robotic guidance to screwing and dispensing. For this assembly demonstration, the assembly of the printed circuit board (PCB) was chosen. Therefore, four MOs have been developed which provide the required skills:

- MO Robot for Pick&Place tasks
- MO Workpiece Carrier (WPC) Port for suppling the necessary workpieces
- MO Screw Feeder for suppling the screws used for fixing the PCB
- MO Workposition for providing a work position during the assembly procedure

The assembly starts by collecting the BMS case from the WPC Port and fixing it on an MO with the corresponding workposition skill. The PCB is attached to the BMS case using four screws. The screws are provided by the corresponding MO. The assembled case is then placed back on the workpiece carrier which is automatically moved out of the robot cell for further assembly tasks.

4.2 Use Case – Robot-based Assembly

For a fluid manufacturing process, it is important to communicate with different assets to get more flexibility. Therefore, the following use case was defined to test a precise positioning process for a robot assembly station using the AMR. For most transport processes, the accuracy of the AMR is sufficient for positioning. In order to achieve higher accuracy, an additional sensor is needed. Therefore, a flexible camera on a robot is used. Figure 9 provides an overview of all the assets involved in the positioning task.

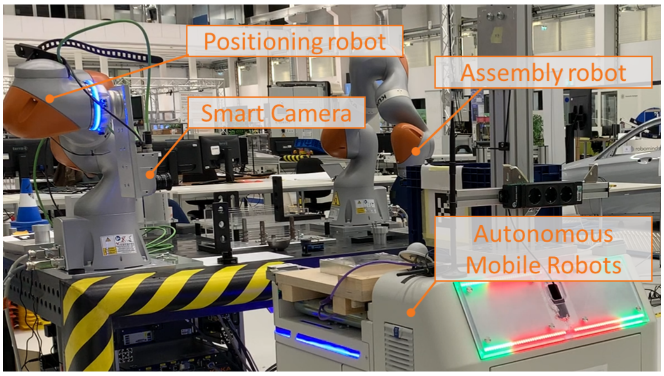

Figure 9: Use-case: accurate positioning for the assembly station, Bär AMR and Balluff Smart Camera.

Rough positioning: An ARUCO marker is attached to the carrier on the AMR. This enables the alignment and the distance of the carrier and AMR to be determined. Since the camera does not directly support ARUCO marker detection, only the raw images from the camera are used and processed for this use case. Figure 10 provides an overview of the individual AAS assets and the communication channel. Data from the evaluation of the ARUCO marker are output via the AAS to the MQTT rough_position topic. The AMRs subscribe to this topic and derive the necessary driving command from it. The X-position (displacement right/left in the image) and the Y-position (distance camera - AMR) are used here, each specified in meters. Furthermore, the theta angle, which indicates the rotation of the AMR in the image, can be used to derive the driving command. The camera and the AMR use different coordinate systems, so a transformation of the data is necessary. This transformation is performed before transmission via the AAS and allows the AMR to use the data directly for the driving commands. Once the AMR has arrived at the rough target position, the position of the camera is changed using the positioning robot. The following fine positioning is performed by positioning the camera directly vertically above the AMR with the workpiece.

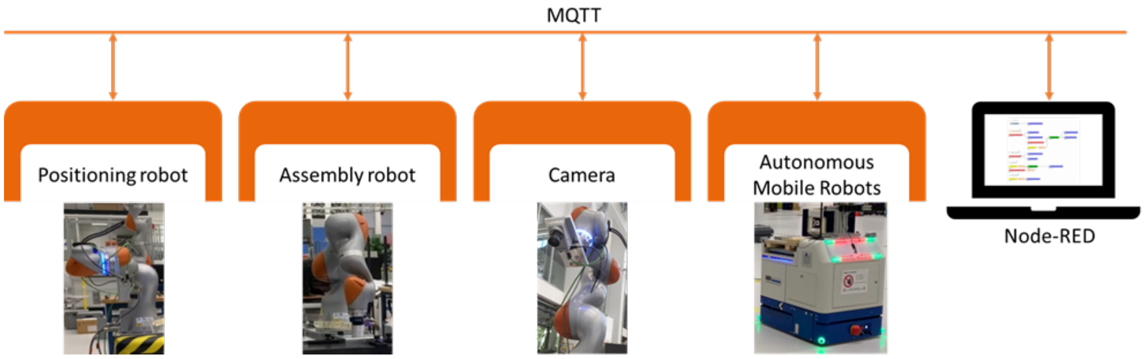

Figure 10: Overview of the asset administration shell for the use case.

Fine positioning: As soon as the robot with the camera has reached the new position, then the inspection program on the camera is switched over to an operation of the AAS. For fine positioning, the image processing algorithms running directly on the camera can be used. This is possible since the distance between the camera and the workpiece does not change during fine positioning. In order to perform fine positioning, the current position of the workpiece must be determined. The first step is to search for the workpiece in the image and then calculate the deviation from the center of the image. This results in the x and y deviations as well as the theta deviation from the learned target state in the center of the image. Driving commands for the AMR are derived from these deviations. The AMR receives the movement commands for the fine positioning via the call for operations of the Raspberry Pi of the camera. This directly addresses the operations of the AMR with the current data. The AMR attempts to minimize these deviations as far as possible by means of driving maneuvers. If the positioning robot with the mounted camera moves in the direction of the table, these deviations become larger, and the AMR must readjust by following the movement of the positioning robot. As soon as the positioning robot reaches its final position, this is reported via an event. The AMR drives the remaining distance to the desired final position and remains there for further assembly.

4.3 Use Case – Decentralized Material Flow

The aim of the logistics use cases is to demonstrate an event-based decentralized material flow-control via the interaction of several CPS. A decentralized material flow control is the capability of system elements to interact with each other and make autonomous decisions [24, 28]. In an FLMS, the material flow can be triggered by different events [29]. In the first use case, the smart load carrier triggers the material flow on a pull principle like the e-Kanban concept. If the material is removed from the smart load carrier, the time-of-flight sensors initiate the "material reorder" event followed by the "transportation" operation for the AMR. In the next step, the empty smart load carrier will be transported [24]. In the second use case, the material flow is trigged by a condition-monitoring event. If a sensor detects a deviation in temperature, humidity or a high acceleration, it publishes an event. Afterwards, the "transportation order" operations are published and the defective material is transported away [24]. In third use cases, the material flow is triggered by the BMS. The BMS uses an infrared interface to transmit information about the condition of the product to the Raspberry Pi installed in the battery case. Subsequently, the information is transmitted via AAS to the MQTT broker. If the BMS is completely assembled on the battery case and connected, it triggers the "connected" event, followed by the "material reorder" operation and "transportation order". In the last use case, the material flow is triggered by a condition-monitoring event of the BMS, similar to the second use case. Then, the product is transported via an AMR either for rework or quality inspection.

5. Conclusion and Outlook

In this paper, the development of CPS for FLMS is presented and tested on a defined product. The various CPS are elements of the FLMS, without rigid coupling of stations, routing and location flexibility. In order to ensure the scalability and technological adaptability of the production system, a planning logic for the design and development of a production system consisting of flexibly linked process modules were implemented. The interoperability of the CPS, fast, intuitive and the ad-hoc creation of process and assembly modules are supported by plug-and-produce approaches. Further, the presented approach will help to master a change in automotive production especially on the human work force in production. The separation between production and logistics and also between product and production will be further eliminated due to the increasing merging of systems. Value-adding processes will take place in all areas of production.

In the next step, to fulfil the premises of the FLMS, the CPS will be reconfigured for a second product, which is unknown at the start of the production. It represents the core point of the validation of versatility in FLMS, since it will show that a second product, which is not known at the time of planning, can be included in production. In addition, the presented concepts and logics in logistics and human-centric production will also be tested and validated on the second product. Moreover, the efforts on the reconfiguration of CPS in an FLMS will be measured and evaluated for future research.

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References

[1] Abele, E., Wörn, A., Martin, P., Klöpper, R., 2006. Performance evaluation methods for mechanical interfaces in reconfigurable machine tools, in: International Symposium on Flexible Automation, Osaka, Japan.

[2] Buzacott, J.A., Yao, D.D., 1986. Flexible Manufacturing Systems: A Review of Analytical Models. Management Science 32 (7), 890–905.

[3] ElMaraghy, H.A., 2007. Reconfigurable Process Plans For Responsive Manufacturing Systems, in: Cunha, P.F., Maropoulos, P.G. (Eds.), Digital Enterprise Technology. Springer US, Boston, MA, pp. 35–44.

[4] Heisel, U., Meitzner, M., 2004. Progress in Reconfigurable Manufacturing Systems. Journal for Manufacturing Science and Production 6 (1-2), 1–8.

[5] Katz, R., 2007. Design principles of reconfigurable machines. Int J Adv. Manuf Technol 34 (5-6), 430–439.

[6] Landers, R.G., Ruan, J., Liou, F., 2006. Reconfigurable Manufacturing Equipment, in: Dashchenko, A.I. (Ed.), Reconfigurable Manufacturing Systems and Transformable Factories, vol. 40. Springer, Berlin, pp. 79–110.

[7] Sethi, A., Sethi, S., 1990. Flexibility in manufacturing: A survey. Int J Flex Manuf Syst 2 (4).

[8] ElMaraghy, H.A., 2009. Changeable and Reconfigurable Manufacturing Systems. Springer, London.

[9] Koren, Y., Heisel, U., Jovane, F., Moriwaki, T., Pritschow, G., Ulsoy, G., van Brussel, H., 1999. Reconfigurable Manufacturing Systems. CIRP Annals 48 (2), 527–540.

[10] Koren, Y., 2010. The Global Manufacturing Revolution. John Wiley & Sons, Inc, Hoboken, NJ, USA.

[11] Koren, Y., Gu, X., Guo, W., 2018. Reconfigurable manufacturing systems: Principles, design, and future trends. Front. Mech. Eng. 13 (2), 121–136.

[12] Mehrabi, M.G., Ulsoy, A.G., Koren, Y., 2000. Reconfigurable manufacturing systems: Key to future manufacturing. Journal of Intelligent Manufacturing 11 (4), 403–419.

[13] Foith-Förster, P., Bauernhansl, T., 2016. Changeable Assembly Systems Through Flexibly Linked Process Modules. Procedia CIRP 41, 230–235.

[14] Greschke, P., 2015. Matrix-Produktion als Konzept einer taktunabhängigen Fließfertigung. Dissertation.

[15] Fries, C., Wiendahl, H.-H., Foith-Förster, P., 2020. Planung zukünftiger Automobilproduktionen, in: Bauernhansl, T., Fechter, M., Dietz, T. (Eds.), Entwicklung, Aufbau und Demonstration einer wandlungsfähigen (Fahrzeug-) Forschungsproduktion. Springer, Berlin, Heidelberg, pp. 19–43.

[16] Bauernhansl, T., Hompel, M. ten, Vogel-Heuser, B., 2014. Industrie 4.0 in Produktion, Automatisierung und Logistik: Anwendung, Technologien, Migration. Springer Fachmedien, Wiesbaden, pages.

[17] Monostori, L., 2014. Cyber-physical Production Systems: Roots, Expectations and R&D Challenges. Procedia CIRP 17, 9–13.

[18] Fries, C., Al Assadi, A., Fechter, M., Bauernhansl, T., Bozkurt, A., Schulz, R., Grimm, S., 2019. Fluide Fahrzeugproduktion.: BMBF-geförderter Forschungscampus für die Mobilität der Zukunft 161 (12), 78–81.

[19] Wiendahl, H.-H., 2002. Situative Konfiguration des Auftragsmanagements im turbulenten Umfeld. Dissertation, 234 pp.

[20] Schuh, G., Schmidt, C. (Eds.), 2014. Produktionsmanagement, 2., vollst. neu bearb. und erw. Aufl. ed. Springer Vieweg, Berlin, 382 pp.

[21] Wiendahl, H.-H., 2020. Auftragsmanagement, in: Bauernhansl, T. (Ed.), Fabrikbetriebslehre 1. Springer, Berlin, Heidelberg, pp. 193–294.

[22] Lee, J., Bagheri, B., Kao, H.-A., 2015. A Cyber-Physical Systems architecture for Industry 4.0-based manufacturing systems. Manufacturing Letters 3, 18–23.

[23] Liao, Y., Deschamps, F., Loures, E.d.F.R., Ramos, L.F.P., 2017. Past, present and future of Industry 4.0 - a systematic literature review and research agenda proposal. International Journal of Production Research 55 (12), 3609–3629.

[24] Bozkurt, A., Tasci, T., Schulz, R., Verl, A., 2021. Designing of Smart Logistics Modules as Cyber-physical systems for Load carriers.

[25] Svetlík, J., 2020. Modularity of Production Systems, in: Machine Tools [Working Title]. IntechOpen.

[26] Ewert, D., Jung, T., Tasci, T., Stiedl, T., 2021. Assets2036 – Lightweight Implementation of the Asset Administration Shell Concept for Practical Use and Easy Adaptation, in: Weißgraeber, P., Heieck, F., Ackermann, C. (Eds.), Advances in Automotive Production Technology – Theory and Application. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 153–161.

[27] Association of the Automotive Industry (VDA), 2019. VDA 5050 – Interface for communication between automated guided vehicles (AGVs) and a master controller. Association of the Automotive Industry (VDA), Berlin.

[28] Hülsmann, M.; Windt, K. Eds., 2010. Understanding autonomous cooperation and control in logistics. The impact of autonomy on management, information, communication and material flow. Springer, Berlin Heidelberg.

[29] Hagg, M., Schulz, R., 2022. Concept for material supply in fluid manufacturing systems. epubli. https://doi.org/10.15480/882.4685.

Biography

Ali Bozkurt (*1991) has been working as a research associate for the Institute of Material Handling and Logistics at the University of Stuttgart since 2018. He studied Industrial Engineering and Management at the University of Erlangen-Nuremberg.

Christian Fries (*1992) has been working as a research associate in the Factory Planning and Production Management department at Fraunhofer IPA since October 2018.

Timur Tasci (*1991) has been working as a research associate for the Institute for Control Engineering of Machine Tools and Manufacturing Units, University of Stuttgart, since 2016. He studied mechatronics and software engineering at the University of Stuttgart.

Dr. Urs Leberle (*1982) worked as a research associate at the wbk Institute of Production Science at the Karlsruhe Institute for Technology (KIT) from 2009 until 2014. Since 2015, he has been working as a project manager at Robert Bosch GmbH. He studied mechanical engineering at the KIT.

Daniel Kessler (*1992) has been working as a data scientist for the innovation group of Balluff GmbH. He studied electrical engineering at the University of Stuttgart.

Markus Joos (*1993) has been working as an automation engineer in the research and development group of Baer Automation GmbH. He studied mechatronics and robotics at the Heilbronn University of Applied Sciences.

Manuel Hagg (*1990) has been working as a research associate for the Institute of Material Handling and Logistics at the University of Stuttgart since 2017. He studied technically-oriented business administration at the University of Stuttgart.

Bernd Neuschwander (*1982) has been working as an advanced development research engineer for Pilz since 2008. He studied electrical engineering and information technologies at the University of Stuttgart. He is now team manager of the Technology Watch and Projects department.

Moritz Hinderer (*1996) has been working as a development engineer at Bosch Research for versatile assembly and industrial robotics since 2022. He studied Mechatronics at Reutlingen University.

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Synthesis of Artificial Coating Images and Parameter Data Sets in Electrode Manufacturing

Achim Kampker[1], Heiner Heimes[1], Benjamin Dorn[1],
Henning Clever[1], Marcel Drescher[1], Robert Ludwigs[1]
[1]Production Engineering of E-Mobility Components (PEM), RWTH Aachen University, Aachen, Germany

Abstract

Driven by continuous cost pressure and increasing market requirements, the optimization of lithium-ion battery production is the focus of attention. To save time and costs, machine learning represents a promising tool. But a considerable amount of training data is needed. Since data is not always available to the required extent, approaches for synthesizing artificial data were investigated. In this study, the quality and corresponding measurement parameters in electrode production were assessed and selected. Based on this selection, coating trials have been conducted and the corresponding data set collected. The data set forms the basis for the synthesis of artificial coating images and parameters. The selection and design of the synthesis models were divided into two sub-steps. First, the synthesis of artificial coating images was investigated. A promising method for the data synthesis of (coating) images is Generative Adversarial Networks (GAN). The basic idea of GANs is to oppose two models: a discriminator and a generator. The generator generates artificial data samples that match the input of the training data set. Afterward, those data samples (both input and artificial data) are introduced to the discriminator. The discriminator's function is to identify whether the data presented originates from the training data set or whether it is a counterfeit (artificial data) of the generator. In a second step, the synthesis of new parameter sets in the form of tabular data is investigated. The requirements for the synthesis of tabular data sets correspond in principle to those for multivariate regression analysis. The combination of the models resulted in a method that allows the prediction of the corresponding measured quality values for arbitrarily selected process parameters, as well as the visualization of the associated coating result in the form of an artificial image.

Keywords: Machine Learning; Generative Adversarial Networks; Data Synthesis; Electrode Manufacturing

1. Introduction

Due to their various properties, lithium-ion batteries have come to the fore as an energy source for mobile applications. As demand increases, so do the demands on their quality, performance, and service life, coupled with steadily growing cost pressure. To meet these requirements, not only further technological development and research in the field of cell technology is needed, but also continuous optimization of the production processes. In this context, the production of electrodes in particular represents a complex sub-step in cell manufacturing. [1] It has a large number of adjustable production parameters with complex influences on the quality characteristics of the electrodes. [2,3] This complexity makes it difficult to analyze the interrelationships and thus to find suitable parameter combinations for the desired production results.

Data-driven approaches are becoming increasingly important for such use cases. For example, image recognition processes trained by means of artificial intelligence can be used to detect production defects and thus

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help in the automated optimization and control of production processes. [4] Just as the development of human intelligence requires a large number of experiences and perceptions over the course of a lifetime, machine learning algorithms must generally be confronted with many observations in order to make accurate predictions. For this reason, machine learning algorithms usually require large amounts of data for their training. In many areas, however, these are not available in the required amount and can only be obtained with difficulty, for example at enormous expense in terms of time and money. [5] In the production of electrodes for lithium-ion cells, for example, the large number of production parameters and their complex interrelationships regarding the production result makes it very difficult to collect large amounts of data for process optimization supported by machine learning methods. Synthetically generated data sets represent an economically interesting alternative to obtaining real test data.

For this reason, an approach to synthesizing artificial electrode coating test data was investigated. Both structured (tabular) and unstructured data (image data) were artificially generated. As a data basis, a reference data set was first created experimentally. For this purpose, tests were carried out on a pilot production line and corresponding quality parameters were measured. The basics of electrode production as well as the models and machine learning algorithms used are introduced in chapter 2. The experimental setup and data preparation, as well as the design of the models for data generation, are described in chapter 3. An overview of the achieved results is given in chapter 4, while chapter 5 summarizes the main conclusions. This study demonstrates that synthetic coating images and their associated process data can be generated using artificial intelligence. However, it is necessary to conduct further research to assess the suitability of this approach as a standalone data source, rather than relying on real data.

2. Fundamentals

In the following chapter, the technical principles of electrode manufacturing and relevance of surface inspection as well as the fundamentals of applying GANs and regression using multilayer perceptron networks (MLP) are established.

2.1 Electrode manufacturing for lithium-ion batteries

Figure 1 shows an overview of the manufacturing processes of electrode manufacturing for lithium-ion battery cells. First, the active material for the electrodes is mixed from several powder components and the solvent to produce the so-called slurry. In the coating step, the slurry is coated onto a metal foil as a thin film and dried afterwards. During calendering, the film is compressed by applying a line load over a roller arrangement to reduce the porosity of the coated material. The electrodes are then cut or punched into the desired shape. This marks the end of electrode manufacturing, which is followed by cell assembly. [6] The work of this paper is focused in particular on the front-end processes from weigh-in of materials, over mixing, to coating and drying.

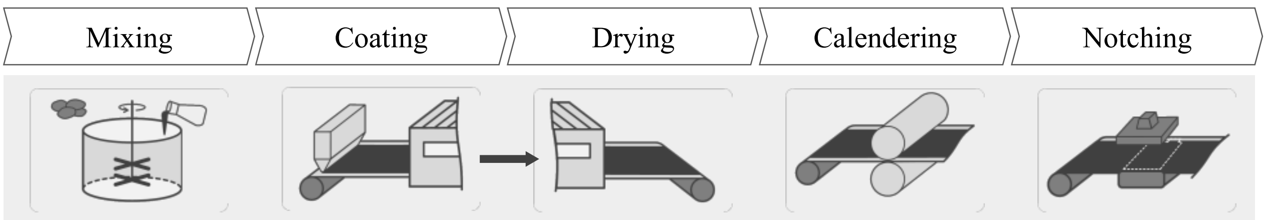

Figure 1: Schematic view of the steps in electrode production [4]

Surface inspection during electrode manufacturing is critical for process control and minimizing scrap rates. By carefully examining the surface of the electrodes, manufacturers can identify and address any defects or irregularities that may affect the performance of the final product. This helps to ensure that the electrodes meet the required specifications and are of high quality. In addition, surface inspection can help identify potential issues early in the manufacturing process, allowing manufacturers to take corrective action (e.g. based on machine learning algorithms) and prevent defective electrodes from being produced. This ultimately leads to lower scrap rates, as fewer defective electrodes need to be discarded, and helps to reduce costs and improve overall efficiency in the manufacturing process. Optical imaging of electrode coatings thereby presents a consistent and automatable solution for the detection of defects. [7]

Choudhary et al. present a promising approach to detect and classify mechanical defects in real time [4]. Also, in other research areas, especially in the medical field, image analysis by means of artificial intelligence have been widely explored in recent years. [8,9] Since the problem of lack of data also exists in the medical setting, Kanayama et al. developed a GAN-based model for the synthesis of endoscopic images for gastric cancer detection [10]. Also, Sedigh et al. used a GAN to generate synthetic skin cancer images to compensate for insufficient data for training a proposed CNN algorithm. [11] Generally, GANs are capable of generating very realistic high-resolution images [12], which make them a viable solution for the presented use case. However, no work could yet be found on image generation in the context of electrode coating. The experimental setup and data basis will be explained in chapter 3.

2.2 Generating synthetic images using generative adversarial networks

The basic idea of GANs is to introduce two opposing models: A discriminative model and a generative model. The generator receives random noise (training data) as input and generates data samples (matching the form of the training data), that are later presented to the discriminator. The task of the discriminator is to identify whether the given sample originated from the training dataset or whether it is a "fake" of the generative model. Mutual competition drives both models to keep improving their methods until the counterfeits are so similar to the originals, that it is no longer possible to distinguish them. Both the generator and the discriminator are typically constructed as deep neural networks and use the binary cross entropy for optimization. [13] When a GAN-trained generator is used to synthesize data, the output cannot be precisely controlled. For example, if the training data set includes data that can be categorized, the classic GAN method cannot be used to specify which category the generated data should come from. Depending on the application, it may be necessary to control the output of the generator. In this case, conditional generative adversarial networks (CGAN) as shown in Figure 2 represent an alternative.

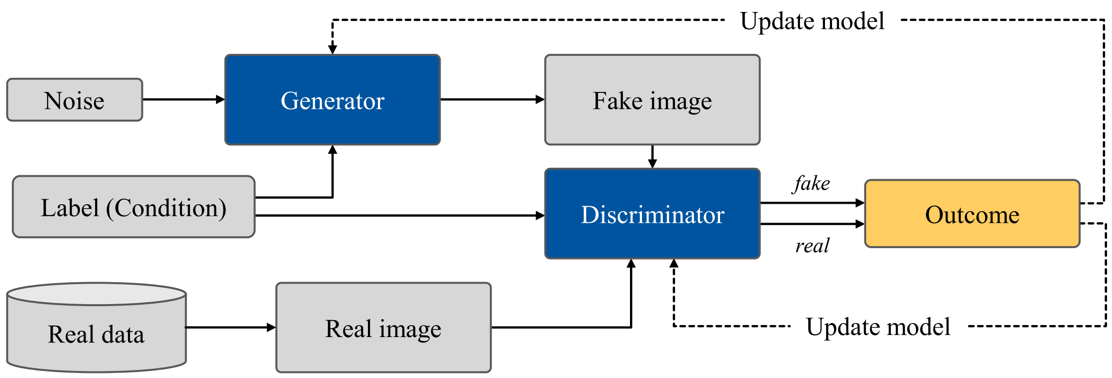

Figure 2: Schematic structure of a Conditional Generative Adversarial Networks (CGAN) [14]

In this case, in addition to the latent vector, a label expressing the membership to a class is passed to the generator and discriminator. The training data set, which is used to train the model must also be labelled. The information of the label is linked with the random signal noise and thus serves as input signal for the data synthesis. In addition to the data point to be evaluated, the discriminator is also provided with the label, which is linked with the input data point (image). [15]

2.3 Regression using multilayer perceptron networks

MLPs are a type of feedforward neural network, that can be used as universal approximators and represent any continuous function. As the name suggests, an MLP is composed of several layers. Between the input layer and the output layer, there is any number of hidden layers. The number of neurons in the input layer is equal to the number of input values. Since in this work three parameters are varied, this also corresponds to the number of input neurons. Analogously the number of neurons in the output layer corresponds to the number of output values. The definition of the number of hidden layers and neurons in each hidden layer are hyperparameters that can be tuned during the optimization process. [5]

3. Methods

The following chapter introduces the experimental design used to generate the data basis as well as the data preprocessing and model design for data synthesis of electrode coating images.

3.1 Experimental design and data acquisition

In order to investigate the coating process, electrodes with different process parameters are produced. For this purpose, three sets of trials are conducted using graphite slurries with different material ratios for the production of anodes. Regarding the processability of the slurry, its viscosity plays a major role. [16] For this reason, the proportion of carboxymethyl cellulose binder (CMC), which significantly controls the viscosity properties, is slightly varied for each test series. Table 1 shows the formulations of the test series for three different slurries. Starting from the basic formulation (Slurry 1), which is based on industrial experience [17], the mass fraction of the CMC binder is slightly increased and reduced. The mass ratios of the other components remain the same relative to each other, resulting in their quantities.

Table 1: Slurry formulations for graphite anodes

Material	Slurry 1	Slurry 2	Slurry 3
Graphite (SG3)	564,00 g	562,30 g	565,70 g
CMC binder	12,00 g	16,00 g	8,00 g
Carbon black	6,00 g	5,98 g	6,02 g
SBR binder	45,00 g	44,87 g	45,14 g
Dist. Water	706,00 g	703,85 g	708,14 g

The electrodes are coated in a roll-to-roll coating line with a slot die for single-sided coating and two drying units. The adjustable parameters of the system are the distance between the slot die and the metal film (which is kept constant at 200 µm), the web speed, and the speed of the feed pump. Table 2 shows the abbreviated representation with the indication of the respective value ranges. To be able to map the influences of the individual parameters, a full factorial experimental design is conducted.

Table 2: Varied test parameters during the full factorial coating trials

Parameter	Value settings
Formulation	Slurry 1; Slurry 2; Slurry 3
Web speed	0.5 m/min; 1.0 m/min; 1.5 m/min
Pump speed	100 rpm; 125 rpm; 150 rpm; 200 rpm

Figure 3 shows extracts of the recorded coating images showing different coating patterns. It is striking that in many cases there is no continuous film. Rather, the coating patterns show defects or line or grid patterns. Also, drying flaws can be observed at high pump speeds and low web speeds. In addition to the images, quality characteristics such as wet film thickness and viscosity of the slurries are recorded. The coating images reveal a strong correlation to the wet film thickness. The ideal wet film thickness is in the range of

120 µm to approx. 200 µm for the defined drying parameters from a process engineering point of view, at which neither coating nor drying defects occur.

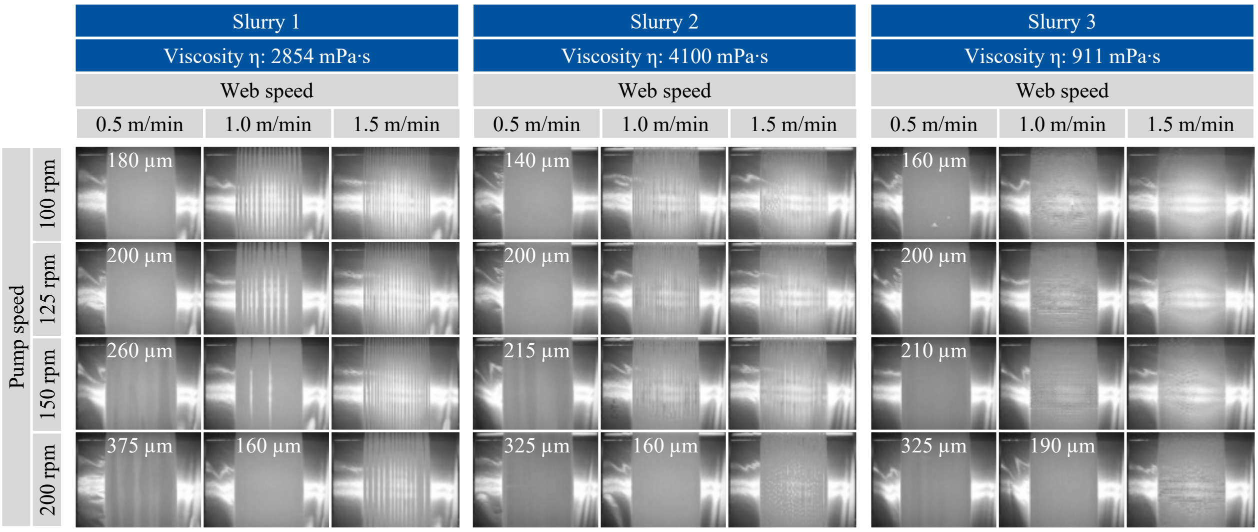

Figure 3: Extract of characteristic images of electrode coatings from the experimental test series

3.2 Data preparation and pre-processing

As previously described, about half of the coating runs do not show a continuous coating film. Rather, line or grid patterns appear. Since in this case there is no wet film thickness to be measured for the respective coatings, a new parameter is introduced to evaluate the test results. The aim is to show what percentage of the film is coated (coating area). For this purpose, the coating images are imported and processed in Python with the help of the scikit-image software library. By applying a grayscale filter, each pixel of the image is assigned a value between 0 and 255 depending on the brightness of the pixel. The values are stored in a matrix with the resolution of the original images (2448x2046).

In the next step, the images are cropped to the coating area, removing the remaining film areas on both sides that do not contain coating. Afterward, a threshold is set for the pixel values above which all values are raised to 255 (white) and set to 0 (black) below. The result is a binary image consisting only of black and white pixels. Dynamic adjustment of the threshold value ensures that, regardless of the exposure of the image, the coated areas appear black and the uncoated areas appear white. Based on the binary image, the proportion of black pixels and thus the proportion of coated area can be calculated for each coating image.

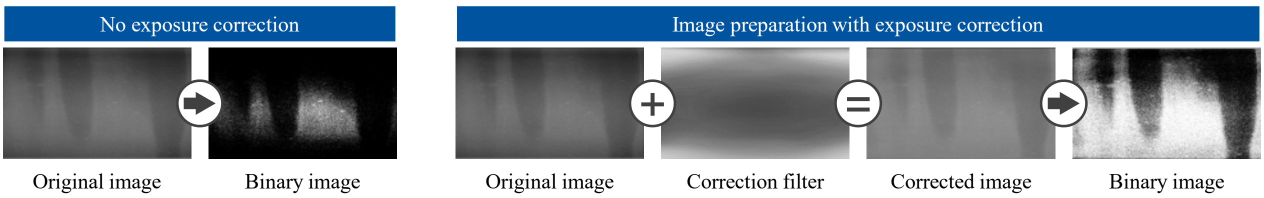

Figure 4: Conversion of the input coating images to binary images including exposure correction

The same principle is used to analyze the images of the coatings that have not fully dried. Since the pixel values (gray levels) of the dry and wet areas are closer together, the determination of the limit value must be much more precise. Another complicating factor is that the images are not evenly illuminated by the camera's flash. Pixel values assigned to the dry state in one image area might describe moist zones in other image areas. In order to compensate for this effect, a brightness filter, as shown in Figure 4, is applied over all images. Since the relative illumination by the flash is almost identical on all images and only the absolute brightness values differ (presumably due to ISO adjustment of the camera), the filter is created manually based on a few images and does not require any dynamic adjustment. Figure 4 shows an example of the binary distribution with and without the filter.

By additionally determining the coating and drying area, a label is assigned to each image. If the edge at the start or end of a coating or bare copper foil is visible on the image, the label *foil edge* is assigned. All other labels are assigned depending on the fraction of coated or dried area. Coating images with a line or grid pattern are considered partly coated and receive values as *coated40*, [...], *coated100*, which indicate the percentage of coated (in increments of ten). The label *coated50* for example describes a coating image, with which the fraction of the coated area accounts for 50-59 %. Complete coatings are labeled as *coated100*. Furthermore, fully coated but not fully dried images are labelled likewise as *dried20*, *dried30*, [...], *dried90*. If the image showed a flawless, fully dried, and continuous coating, the label *OK* was assigned.

To reduce the demand for data storage the image areas of lesser interest (uncoated edges) were cropped and the images were scaled down from their original format of 2448x2046 pixels to 205x128. Furthermore, the pixel values of the images were normalized between -1 and +1 using *MinMax*-normalization.

3.3 Design of the Conditional Generative Adversarial Network

Since the aim of this paper is to generate data points representing different coating patterns according to the labeling logic mentioned above, a CGAN was chosen for image generation. The generator and discriminator were designed as fully interconnected neural networks. The dimension of the latent vector was set to 100. Its values are random but constrained between 0 and 1. The first level of the generator, therefore, comprised 100 neurons. Since the scaled coating images have a resolution of 205x128 pixels, the input level of the discriminator has 26,240 neurons. This also corresponds to the number of neurons in the output layer of the generator. The labels were numbered and embedded into the input layers of each model. As the discriminator returns only one value, it also has only one neuron in the output layer. The models are trained in 50,000 epochs with a batch size of 128. The Adam algorithm [18] is chosen as the optimizer with a learning rate of 0.0002 and a momentum of 0.5.

3.4 Regression of coating parameters

The first modeling approach investigated uses linear regression. The assumption was made that the relationships between the dependent and independent variables are linear. This assumption represents a simplification that can be justified on the basis of the course of the measured data.

The second modeling approach investigated is realized by the construction of an MLP network that contained two hidden layers with 64 neurons each. Rectified linear unit functions (ReLU) are chosen as activations with the exemption of the output layer for the parameters that represent the fractions of coated and dried areas, as they are limited between 0 and 1. Therefore a sigmoid function was used. The chosen error function is the mean squared error and optimization uses the Adam algorithm with a learning rate of 0.001.

4. Results

In this chapter, the results from the synthesis of the coating images are discussed and the application of a combined model to synthesize tabular data sets is validated.

4.1 Synthesis of the coating images

As can be seen in Figure 5, the developed CGAN is capable of generating coating images that are very realistic to human perception, representing all types of defects that occur in the training data set. For some predefined categories, the generated images show great similarity to the corresponding real images (e.g. *coated70*). This can be attributed to little variation in the images of the affected categories of the training dataset. In addition, the generated images show minor distortions in the form of noise.

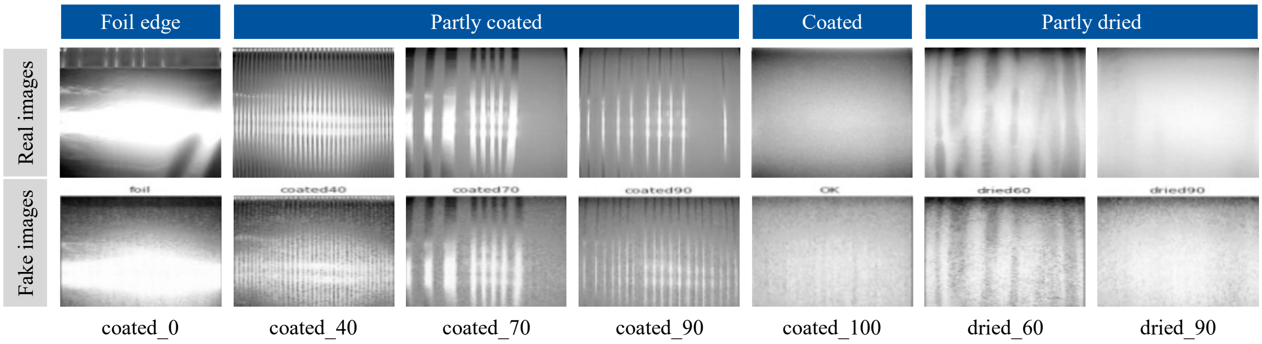

Figure 5: Coating images generated by CGAN

The validation of the “computational” quality of synthetic images remains a focus of current research. The most commonly used quantitative metric for evaluating artificially generated images is the *Fréchet Inception Distance* (FID). [19] The goal of this is not to analyze the generator or discriminator, but rather to take a more outcome-based approach in which generated images are compared to real images and a similarity score between them is determined. [20] The score is calculated by using the *Inception-v3* model. [21] Table 3 shows the results for comparisons of randomly selected batches of 500 images each.

Table 3: FID-Scores for batches of 500 images

Compared batches	Real-1, Real-1	Real-1, Real-2	Real-1, Artificial
FID score	0	70	220

As expected, the FID score for the comparison of two identical batches is 0. The FID score of two batches of real images represents the reference score to aim for. The comparison of real and artificial images shows FID scores about three times higher value than the desired reference score. [19]

4.2 Synthesis of tabular data set

For the synthesis of the tabular process parameter data sets, a simple linear regression model and a more generalizable MLP regression model were applied and evaluated. Figure 6 shows the results of the linear regression (top) and MLP regression analysis (bottom) for the dependent variable wet film thickness. For this parameter, the linear model shows a better fit toward the measured data. The error was quantified using the mean squared error, which reached values of 29.23 for the MLP model and 15.09 for the linear model.

The results for the regression of the fraction of coated area can be seen in Figure 7. Here the MLP regression (bottom) shows a slightly better fit toward the measured data, than the linear model (top). In this case in particular, it is evident that the linear regression produces counterintuitive results (i.e. fraction of coated area greater than 100 %). This prediction requirement is addressed by the MLP. The mean squared error for the MLP model was calculated at 0.10, whereas the error for the linear model is 0.13. In order to achieve the best possible results and generate a fully synthesized dataset, the constructed models of the CGAN and MLP were combined. The structure of the combined models is shown in Figure 8.

For the approximation of the wet film thickness the linear model is used and the fractions of coated and dried areas are calculated by the MLP regression, since these models show the smallest errors as shown in Figure 6 and Figure 7. The values for the fraction of coated and dried areas represent the type and severity of the examined error and thus are transformed into the label that serves as input for image generation.

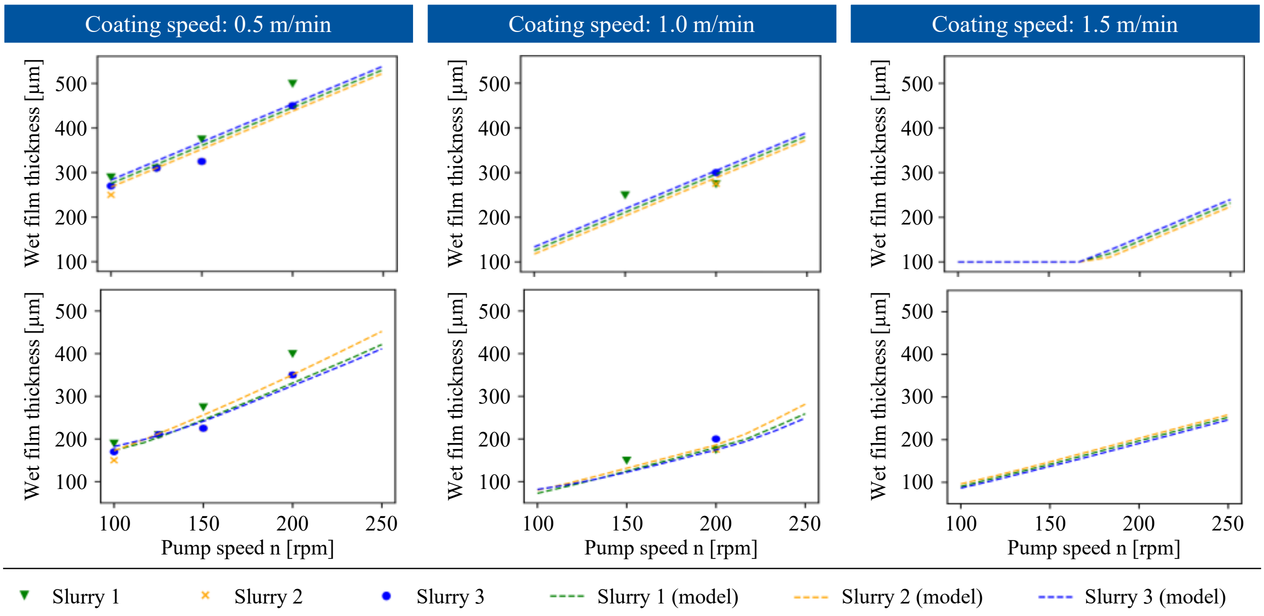

Figure 6: Prediction of the wet film thickness using linear regression (top) and MLP-regression (bottom)

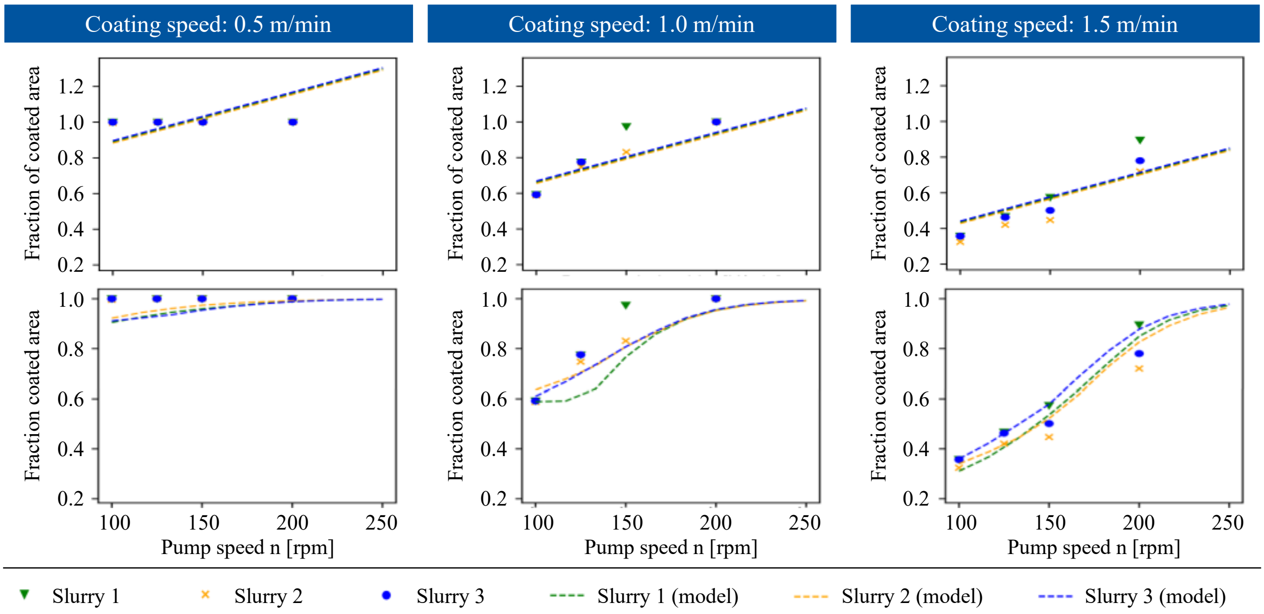

Figure 7: Prediction of the fraction of coated area using linear regression (top) and MLP-regression (bottom)

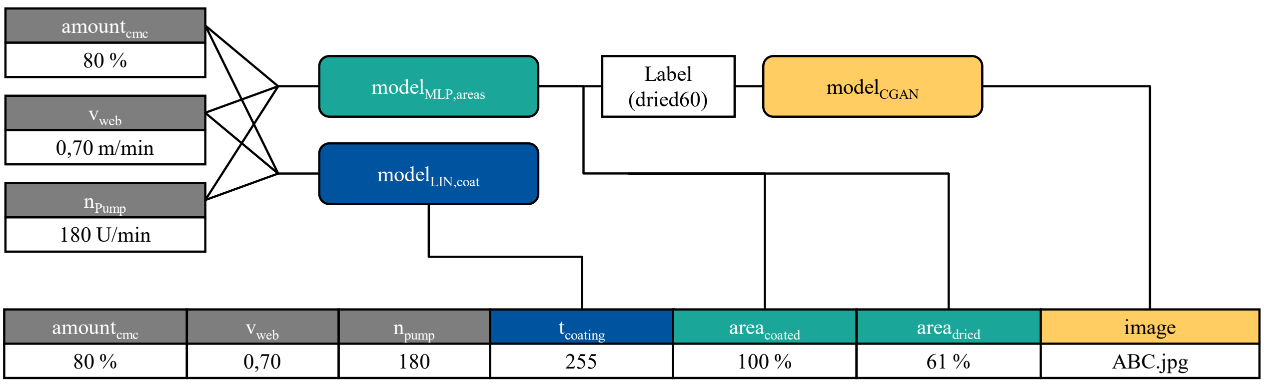

Figure 8: Structure of the combined overall model for data synthesis of electrode coating images

5. Conclusion

The production of electrodes for lithium-ion cells represents a complex manufacturing process with strong influences on the quality of the battery cells. To save time and costs, machine learning methods can provide helpful support for ensuring the quality of the coating process. They are capable of analysing and evaluating complex correlations and abstract data spaces, for which, however, they require a great amount of training data. To provide this amount of input even with limited availability of real test data, an approach to synthesizing artificial coating data by using a CGAN was proposed. The results show that the combination of a linear regression model and an MLP regression model for synthesizing structured data together with a CGAN for synthesizing coating images is capable of generating an artificial data set. The computational quality of the artificial data was evaluated using the Fréchet Inception Distance and could be sufficiently confirmed. However, the commonly applied evaluation metrics are still part of current research. When viewed with the human eye, the quality of the generated images can be considered good. Only a pixel-like noise is visible on many artificially generated images. In summary, this study shows that synthetic coating images and the associated process data can be generated using artificial intelligence. However, further research is needed to evaluate the viability of the artificially generated images and datasets as a stand-alone data source, rather than relying on real data.

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References

[1] Hawley, W.B., Li, J., 2019. Electrode manufacturing for lithium-ion batteries—Analysis of current and next generation processing. Journal of Energy Storage 25, 100862.

[2] Mohanty, D., Hockaday, E., Li, J., Hensley, D.K., Daniel, C., Wood, D.L., 2016. Effect of electrode manufacturing defects on electrochemical performance of lithium-ion batteries: Cognizance of the battery failure sources. Journal of Power Sources 312, 70–79.

[3] Smekens, J., Gopalakrishnan, R., Steen, N., Omar, N., Hegazy, O., Hubin, A., van Mierlo, J., 2016. Influence of Electrode Density on the Performance of Li-Ion Batteries: Experimental and Simulation Results. Energies 9 (2)

[4] Choudhary, N., Clever, H., Ludwigs, R., Rath, M., Gannouni, A., Schmetz, A., Hülsmann, T., Sawodny, J., Fischer, L., Kampker, A., Fleischer, J., Stein, H.S., 2022. Autonomous Visual Detection of Defects from Battery Electrode Manufacturing. Advanced Intelligent Systems 6, 2200142.

[5] Hagan, M.T., Demuth, H.B., Beale, M.H., Jesus, O. de, 2014. Neural network design, 2nd edition ed. Amazon Fulfillment Poland Sp. z o.o, Wrocław, Amazon, Wrocław, 800 pp.

[6] Heimes, H.H., Kampker, A., Lienemann, C., Locke, M., Offermanns, C., Michaelis, S., Rahimzei, E., 2018. Produktionsprozess einer Lithium-Ionen-Batteriezelle, 3. Auflage, [revidierte Ausgabe] ed. PEM der RWTH Aachen; VDMA, Aachen, Frankfurt am Main, circa 24 ungezählte Seiten.

[7] Reynolds, C.D., Slater, P.R., Hare, S.D., Simmons, M.J.H., Kendrick, E., 2021. A review of metrology in lithium-ion electrode coating processes. Materials & Design 209, 109971.

[8] Hirasawa, T., Aoyama, K., Tanimoto, T., Ishihara, S., Shichijo, S., Ozawa, T., Ohnishi, T., Fujishiro, M., Matsuo, K., Fujisaki, J., Tada, T., 2018. Application of artificial intelligence using a convolutional neural network for detecting gastric cancer in endoscopic images. Gastric cancer : official journal of the International Gastric Cancer Association and the Japanese Gastric Cancer Association 21 (4), 653–660.

[9] Liu, W., Anguelov, D., Erhan, D., Szegedy, C., Reed, S., Fu, C.-Y., Berg, A.C., 2016. SSD: Single Shot MultiBox Detector, in: Leibe, B., Matas, J., Sebe, N., Welling, M. (Eds.), Computer Vision – ECCV 2016, vol. 9905. Springer International Publishing, Cham, pp. 21–37.

[10] Kanayama, T., Kurose, Y., Tanaka, K., Aida, K., Satoh, S.'i., Kitsuregawa, M., Harada, T., 2019. Gastric Cancer Detection from Endoscopic Images Using Synthesis by GAN, in: Shen, D., Liu, T., Peters, T.M., Staib, L.H., Essert, C., Zhou, S., Yap, P.-T., Khan, A. (Eds.), Medical Image Computing and Computer Assisted Intervention – MICCAI 2019, vol. 11768. Springer International Publishing, Cham, pp. 530–538.

[11] Sedigh, P., Sadeghian, R., Masouleh, M.T., 2019 - 2019. Generating Synthetic Medical Images by Using GAN to Improve CNN Performance in Skin Cancer Classification, in: 2019 7th International Conference on Robotics and Mechatronics (ICRoM). 2019 7th International Conference on Robotics and Mechatronics (ICRoM), Tehran, Iran. 20.11.2019 - 21.11.2019. IEEE, pp. 497–502.

[12] Zhang, B., Gu, S., Zhang, B., Bao, J., Chen, D., Wen, F., Wang, Y., Guo, B., 2021. StyleSwin: Transformer-based GAN for High-resolution Image Generation.

[13] Goodfellow, I.J., Pouget-Abadie, J., Mirza, M., Xu, B., Warde-Farley, D., Ozair, S., Courville, A., Bengio, Y., 2014. Generative Adversarial Networks.

[14] MathWorks Inc. Train Generative Adversarial Network (GAN). https://de.mathworks.com/help/deeplearning/ug/train-generative-adversarial-network.html. Accessed 30 October 2022.

[15] Mirza, M., Osindero, S., 2014. Conditional Generative Adversarial Nets.

[16] Schmitt, M., Baunach, M., Wengeler, L., Peters, K., Junges, P., Scharfer, P., Schabel, W., 2013. Slot-die processing of lithium-ion battery electrodes—Coating window characterization. Chemical Engineering and Processing: Process Intensification 68 (4–5), 32–37.

[17] Wentker, M., Greenwood, M., Leker, J., 2019. A Bottom-Up Approach to Lithium-Ion Battery Cost Modeling with a Focus on Cathode Active Materials. Energies 12 (3), 504.

[18] Kingma, D.P., Ba, J., 2014. Adam: A Method for Stochastic Optimization.

[19] Borji, A., 2022. Pros and cons of GAN evaluation measures: New developments. Computer Vision and Image Understanding 215 (4), 103329.

[20] Heusel, M., Ramsauer, H., Unterthiner, T., Nessler, B., Hochreiter, S., 2017. GANs Trained by a Two Time-Scale Update Rule Converge to a Local Nash Equilibrium.

[21] Szegedy, C., Vanhoucke, V., Ioffe, S., Shlens, J., Wojna, Z., 2015. Rethinking the Inception Architecture for Computer Vision.

Biography

Henning Clever (*1992) is research associate at the Chair of Production Engineering of E-Mobility Components (PEM) at the RWTH Aachen University since 2019 and group lead for the research group Battery Production Management since 2021. He studied mechanical engineering specializing in production engineering at the RWTH Aachen University.

Marcel Drescher (*1994) is research associate at the Chair of Production Engineering of E-Mobility Components (PEM) at the RWTH Aachen University since 2022. He studied mechanical engineering at the RWTH Aachen University with a focus on automotive engineering.

Robert Ludwigs (*1993) is research assistant at the Chair of Production Engineering of E-Mobility Components (PEM) at RWTH Aachen University. He studied mechanical engineering with a specialization in production technology at RWTH Aachen University.

Benjamin Dorn (*1990) is research associate at the Chair of Production Engineering of E-Mobility Components (PEM) at the RWTH Aachen University since 2018 and chief engineer for Production Technology & Organization since 2021. He studied business administration and engineering specializing in mechanical engineering at the RWTH Aachen University.

Dr.-Ing. Heiner Hans Heimes (*1983) is executive chief engineer of the Chair of Production Engineering of E-Mobility Components (PEM) at the RWTH Aachen University since 2019. He studied mechanical engineering with a focus on production engineering at RWTH Aachen University. From 2015 to 2019, he was head of the Electromobility Laboratory (eLab) of RWTH Aachen University.

Prof. Dr.-Ing. Achim Kampker (*1976) is head of the chair "Production Engineering of E-Mobility Components" (PEM) of RWTH Aachen University. Prof. Dr. Kampker also acts as member of the executive board of the "Fraunhofer Research Institution for Battery Cell Production FFB" in Münster. He is involved in various expert groups of the federal and state governments.

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Categorizing Challenges And Potentials Of Digital Industrial Platforms

Jonas Eichholz[1], Michael Baumeister[1], Alexander Kreyenborg[1], Daniel Hefft[1], Nick Große[1], Michael Henke[1]

[1] *Chair of Enterprise Logistics, TU Dortmund, Dortmund, Germany*

Abstract

In complex supply chains, digital platforms play an emerging role as an infrastructure for network-based collaboration of industrial companies to stay competitive. Participating in a platform business offers a range of new potentials, while also introducing new challenges. Awareness of these is crucial for both users and providers to make informed decisions. Thus, this paper provides an overview about typical challenges and potentials from the perspective of potential or actual digital industrial platform users to support decision making processes. Against that backdrop, a descriptive study is conducted in the field of industrial service platforms motivated from two sides. Expert workshops are held to examine the practical opportunities and hurdles. The findings are then compared to those identified in literature. Then, the results are organized into a category system that highlights the key challenges and potentials for users as well as providers of digital industrial platforms.

Keywords

Digital Platform; Industrial Service; B2B; Literature Review; Expert Workshop; Category System

1. Introduction

The increased use of information and communication technologies as well as advancing digitalization is affecting industrial companies and its value chains. Thus, significantly more data is gathered, making it an economic resource critical for success [1]. However, enhanced networking of the partners simplifies the exchange between them and thus facilitating interaction. Digital platforms play an important role as the predominant marketplace for exchanging data. [2] At the same time, the industrial service sector gains importance, leading to a transformation of the industry into a service society, forcing companies to secure their competitiveness by offering additional services to their existing products [3]. This so-called servitization [4] enables companies to develop unique selling propositions by offering services individually tailored to various customers' demands. The expansion of the value-added spectrum further enables new sales and profit potentials. [5] Furthermore, the interplay of services with platform economies opens the scope for completely new disruptive business models [6]. Low entry barriers initially stimulated the platform market in the business-to-consumer (B2C) area and platforms such as Amazon or Netflix changed the competitive market dramatically. This trend is also increasingly observable in the business-to-business (B2B) area, but challenges slow down business transformation. [7] Research on the fundamental requirements for digital platforms has progressed significantly in recent years [8–10]. Nevertheless, it is still unclear for many companies, particularly small and medium-sized enterprises (SMEs), whether it is beneficial for them to enter the platform business, which is of great interest due to its current relevance for optimizing processes in

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industrial service industry. While actual research focuses on specific aspects and components of digital platforms [11–13], there is a lack of a comprehensive view in the targeted domain. To address this gap, this paper aims to answer the following research question: ***What are companies' challenges and potentials using digital platforms for industrial services?*** The paper addresses both users considering participating in platform businesses, as well as platform providers seeking to design and operate successful platforms. For this, we conducted a two-stage mixed inductive and deductive approach. We first analyzed practice-led knowledge obtained from expert workshops and compared this to theoretical insights gained through a systematic literature review. By combining the results from these two sources, we develop a category system that we utilize to present the implementations of identified challenges and potentials. Finally, the paper concludes with a summary of the results, an assessment of limitations and a subsequent outlook for future research.

2. Related Background

In order to understand the research, we explain basics about the related topics digital platforms and industrial services. It is worth noting that while platforms can also have a physical presence, we narrow our focus to digital platforms for the purposes of this investigation. Additionally, we consider industrial services as the use case for these digital platforms, taking into account the background and expertise of the practitioners involved.

2.1 Digital Platforms

Digital platforms are two-sided or even multi-sided markets that facilitate transactions between different costumer groups or consumers [14,15]. The most important assets of digital platforms are information and interactions, which boosts the interplay by far-reaching developments in Information and Communication Technology that made computing power cheaper and allowed the homogenization of huge amounts of data. Those digital platforms scale well due to the fact that no physical structure has to be owned, which make network effects as their key characteristic easier to exploit. [16,17] The activity of many users on a platform encourages new users to join the platform, which results in scale effects [18]. Those digital platforms consist of two main elements: the actual core with its technological infrastructure, dominated by the platform owner, and the periphery with complementary apps of third parties. Combined, these serve as a base for externals to build their products or services on. [19,6] The owners of the platform control the intellectual property and the dynamic interactions between various roles of participants, also called governance. Providers operate as intermediary to the user, whereas producers offer something on the platform and consumers take up those offerings. [20] After all, platforms can create value in two different ways or a combination of them. On transaction platforms individuals are brought together to interact with each other. Besides, innovation platforms offer a technological infrastructure for innovators to develop new services or products. [21]

2.2 Industrial Services

Due to the heterogeneity of industrial services, no common accepted definition has been found yet. DONABEDIAN [22] provides an integrative definition that divides services into three phases: potential orientation, process orientation and result orientation [23]. Other approaches focus on specific attributes, but there is no consensus about which these are exactly [24]. In this context, services are often characterized by their intangibility, heterogeneity, inseparability and perishability [25]. Other authors mention attributes like lack of transfer of ownership, non-storage capability and simultaneity of production and consumption. In general, services can be defined by two characteristics: the immateriality of services and the external integrity in the service creation process. [26] Addressing customer needs, the industrial sector often combines service-based offerings with tangible goods. Thus, TUKKER distinct between eight different types of product-service systems, each with a different degree of material goods and services [27]. In summary, industrial services have a wide range of manifestations, from basic transactional services, e.g. maintenance or repair, to more complex relational offerings, e.g. plant operating or full service contracts [28,29].

3. Research approach

To gain a comprehensive and rigorous understanding of challenges and opportunities of digital industrial platforms, the authors utilize a two-stage mixed inductive and deductive approach is conducted. First, we analyzed practice-led knowledge from expert workshops, highlighting the topic by both users and providers. In order to further expand our understanding, we conducted a systematic literature review to gather additional theoretical insights. The results from these two stages were then combined and organized into a category system to provide a structured, easily understandable overview.

3.1 Focus Group Workshops

To get a broad range of different views of the examined topic and to start with understanding the meanings behind this as well as efficiently use the group dynamics arising from that method [30,31], focus group interviews according to MISOCH have been conducted [32]. The underlying design is presented in Table 1.

Table 1: Research design for the focus group interviews

Date	Length	Number of groups	Number of participants	Composition of groups
07.05.2021	10 + 35 + 10 min	3	14	Mostly practitioners
25.06.2021	10 + 30 + 20 min	2	10	Mostly researchers

We conducted a total of five focus group interviews with 24 participants (4-6 per group) on two different occasions. These interviews took place in the context of a workshop during a conference on maintenance and service, as well as a webinar featuring different research projects in the field of digital platforms. The groups were divided in a manner that ensured the best possible mix of different backgrounds. For the first iteration, a surplus of practitioners was noted, for the second one more researchers were involved. The given stimulus was a 10 minutes' presentation with basic information about industrial services and digital platforms. Within the 30 respectively 35 minutes the groups had to answer four different questions, whereof two referred to the current processes and the other two explicitly to the challenges and potentials of platforms ("Where are you seeing the greatest potentials of platforms?" and "Which problems arise using platforms?"). We conducted the workshop with an online collaboration whiteboard, where the participants formulate their ideas under moderation. For a better structure, we used relevant modules of a reference process for industrial services according to [33], which contained an exemplary process. After, the participants presented and summarized their results within 10 respectively 20 minutes to the other groups. To complement and cross-validate the findings from the expert workshop, the authors conducted a systematic literature review.

3.2 Systematic Literature Review (SLR)

To also build upon existing knowledge from academic research and enhance that knowledge through the given input from the practical side, an exhaustive systematic literature review has been conducted [34,35]. This is based on the methodological guidelines proposed of WEBSTER & WATSON [36] and VOM BROCKE ET AL. [37]. To ensure a broad base of literature, the authors used a selection of well-known databases (Scopus, Web of Science, IEEE Xplore). Within those, we applied the searchstring '(challenge OR barrier OR hurdle) AND (opportunity OR chance OR potential) AND platform AND industrial AND service'. The use of three operators regarding challenges and potentials helped us including publications in which synonyms of these appear. The terms 'platform', 'industrial' and 'service' derive directly from the research question. As a result, he literature search provided a total of 595 publications identified in October 2022. In the first iteration we excluded 157 duplicates and non-available papers. Afterwards, the authors examined the papers in context of content, only including papers dealing with digital industrial platforms with reference to engineering. Papers dealing with physical platforms, such as those used in automotive, were excluded.

Similarly, papers from other domains such as healthcare where the term platform is widely used in context of service robots or in the IT sector where programming units are often referred to as services, were not taken into account. Applying this, the remaining 438 publications were reviewed based on their titles, abstracts and keywords. If that was not enough to define the specific topic and thus determine relevance, we scanned the papers, resulting in 31 relevant publications. Following, the authors conducted a forward- and backward-search using Google Scholar, identifying additional relevant papers, resulting in 4 further publications. To ensure the reliability of the results, two of the authors independently carried out the process of identifying relevant publications. If there was any uncertainty about the relevance of a publication, a discussion followed until we reached a consensus. As a result, the authors identified a total of 35 publications (see Figure 1).

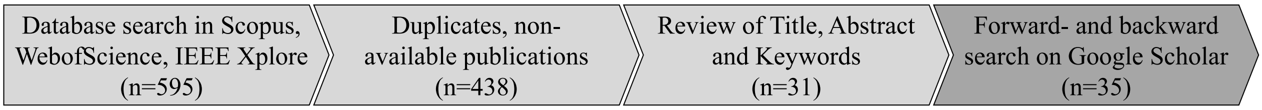

Figure 1: Process of the structured literature review

3.3 Categorization

In order to structure the findings and derive a category system out of this, the authors conducted a qualitative content analysis in the form of an inductive categorization according to MAYRING & FENZL [38]. Complementary to this, the structural framework proposed by GIOIA ET AL., a three-level classification consisting of so-called 1st-order terms and 2nd-order themes as well as the aggregate dimensions (which correspond to the term "categories" used in this paper) to make the process more understandable and resilient [39]. To ensure the comprehensiveness and relevance of our category system, we paid close attention to the completeness and selectivity of the categories, only including relevant issues [40]. In total, we collected 189 1st-order terms out of the focus group workshops (86) and SLR (103), including 83 challenges and 106 potentials. First, the authors derived seven categories (standardization, technology, co-creation, resources, governance, communication and security) from the 1st-order terms. Following, we found 26 variant 2nd-order attributes for the 1st-order terms and assigned these to the categories. The categorization process was carried out in multiple iterations by three different researchers, ensuring reliability [41]. Considering completeness and selectivity, this results in a structured and easily understandable overview of the challenges and potential benefits of digital industrial platforms.

4. Challenges and Potentials

To structure and summarize the results with its categorization, we propose the following Table 2. The 2nd-order attributes from the categorization are referred to as 'Attributes' and assigned to the respective 'Category'. The terms 'Challenge/ Potential' and 'Workshop/ Literature' show how often the respective 1st-order terms are mentioned. If there were identical statements within the literature, we removed these – if two different points are addressed, we integrated both.

Table 2: Categorized Challenges and Potentials of digital industrial platforms

Category	Attribute	Challenge/ Potential	Workshop/ Literature	References
Standardization	Interfaces	13 / 1	2 / 12	[44,43,50,42,48,52,47,49,45, 51,13,46]
	Specification clarification	3 / 8	10 / 1	[46]
	Data structure	2 / 4	5 / 1	[42]
	Maturity level	2 / 1	1 / 2	[53,45]
	Customizability	2 / 1	3 / 0	-

Technology	Data management	4 / 9	9 / 4	[44,47,45,46]
	Additional services	2 / 9	2 / 9	[54,57,53,47,56,12,45,51,55]
	Dependency	5 / 0	3 / 2	[52,58]
	Scalability	2 / 3	1 / 4	[59,42,53,47]
Co-Creation	Mergers	0 / 16	0 / 16	[54,42,60,65,64,62,11,12,63, 61,13]
	Network effect	1 / 8	4 / 5	[58,11,46,66]
	Partner management	4 / 3	1 / 6	[12,51,55,61,13]
Resources	Know-how	11 / 0	6 / 5	[58,11,51,13,67]
	Process modifications	1 / 6	3 / 4	[68,12,61,13]
	Portfolio	0 / 6	2 / 4	[69,11,13]
	Financial	1 / 1	0 / 2	[54,13]
Governance	Transparency	5 / 3	7 / 1	[52]
	Roles	4 / 3	5 / 2	[70,13]
	Trust	2 / 3	3 / 2	[42,13]
	Sovereignty	2 / 1	3 / 0	-
Communication	Customer relations	1 / 9	3 / 7	[70,47,11,51,61,13]
	Networking	0 / 6	5 / 1	[71]
	Unified language	2 / 2	3 / 1	[60]
Security	Data security	8 / 0	2 / 6	[52,47,45,46]
	Counterfeit protection	2 / 3	3 / 2	[47]
	Attacks from outside	4 / 0	0 / 4	[42,47,73,72]

Subsequently, the authors explain and discuss the attributes, including the challenges and potentials per category. This is done based on the 2nd-order attributes, referenced from both the focus group workshop as well as the SLR, to deduce further implications for practitioners and researchers. Since the authors mention all references within the table, the following statements only include an excerpt of the most relevant thus representative literature. If all challenges and potentials derive from the workshops (‘Customizability’ and ‘Sovereignty’), there is no further reference to literature.

4.1 Standardization

Standards can help simplify many processes by providing predefined building blocks, but they can also restrict *customizability*, making it harder to react to unexpected situations or deviations from the standard. Finding the right balance is not trivial and many stakeholders may be included, which is why standardization may often not reach the needed *maturity level* [53]. For example, in the industrial sector, it can be challenging to find a common language for *specification clarification* at the beginning of an order [46]. Especially, introducing standards within companies might lead to problems with physical and digital *interfaces* due to heterogeneous system landscapes and *data structures* [44,42,51].

4.2 Technology

Digital platforms have the potential for *scalability* due to their digital structure, but this requires a corresponding architecture [53,47]. A major issue is the technical *dependency* that users may have on a platform. For example, the need to build platform-specific interfaces can make it difficult or even prevent users to change systems. [58] Additionally, platforms often allow the incorporation of external parties for *additional services*. If these parties can be easily integrated into the platform, it can provide added value for all users. [54,57] However, to fully realize this value, functioning *data management* is essential above all. Since many companies do not even have most of their data in a digital way, this is both a challenge and a potential. By using platforms, they may be forced to digitize further, potentially leading to improvements in internal processes. [44,46]

4.3 Co-Creation

Co-Creation between platform users is a central aspect of digital platforms. Accordingly, digital platforms provide *mergers* by entering cooperation with other participants, expand the customer base, exchange knowledge, services and values, and reduce initiation costs [11–13]. It can also facilitate *partner management* by providing a common place to find suitable partners and to communicate and exchange data [51,55]. These increases with the number of users, a phenomena known as the *network effect*, which is the core benefit of platforms [46]. However, it can fail to materialize if not enough active users on the platform.

4.4 Resources

Platforms can disrupt the internal structures of companies, presenting both potentials and challenges. For many companies, platforms are new and unfamiliar due to a lack of *know-how* and commitment among employees [58]. This can require significant efforts and *financial* investments at the beginning due to training, knowledge generation and internal changes, leading to uncertainties according the benefits of the platform [54]. At the same time, breaking up traditional structures can offer new opportunities, such as *process modifications* or the ability to expand the *portfolio* due to platform-based optimizations [68,11,13].

4.5 Governance

Trust, *sovereignty* and *transparency* are crucial considerations for companies when connecting to a platform. Potential users must trust the platform, especially with regard to data sovereignty. In addition to the platform owner, companies must also trust other third-party providers. At the same time, companies can benefit being transparent in some situations, such as allowing them to present their processes openly and disclose their capabilities to potential customers. [42,52,13] To ensure necessary hierarchies and associated rights and obligations, clear *roles* must be defined to prevent unauthorized transactions or data manipulation [70].

4.6 Communication

One of the main advantages of digital platforms is their ability to facilitate the exchange and *networking* of a broad range of users. Companies can present themselves to a large number of other users and easily connect with target groups. [71] Doing so, platforms can help with *customer relations*, allowing to establish new or maintain existing contacts and increase customer loyalty. This can be achieved through optimal in-service feedback and constant exchange. [70,47,13] However, to bring the diverse target groups and their ways of thinking together and support their common understanding, a *unified language* is necessary [60].

4.7 Security

Data and the related know-how are valuable resource for companies. Therefore, *data security* of platforms is of particular importance, especially in the B2B sector [52,47,45]. Companies fear the loss their data sovereignty, which can increase their vulnerability to *attacks from outside* [42,73]. *Counterfeit protection* is also important, as companies may worry about losing their data integrity. However, a platform as an intermediary for data exchange can use appropriate technologies to meet these requirements and enable a secure and regulated exchange. [47]

5. Conclusion, Limitations and Outlook

By examining the topic from both practical and literature-based perspectives, this study provides a broad overview of emerging challenges and potentials for companies using digital platforms for industrial services. The findings serve as a foundation for further research and help practitioners make informed decisions and assess their own situation. We reveal that there are categories in which challenges arise above all, such as security, and there are also categories that offer more potentials, such as co-creation. Overall, the number of identified challenges (83) and potentials (106) are nearly balanced, indicating a degree of skepticism but also recognition of the significant potential of digital platforms. To fully realize this potential, however, there are still several steps to be taken, including standardization for a better communication and the use of appropriate technologies to reduce interface problems. Education and training for users and providers of platforms on the use of digital technologies are also important factors.

This paper also has underlying limitations. The evaluation shows that there was bias in the workshops, with certain topics receiving more attention than others through discussions during the implementation. Additionally, participating in the workshops was voluntary, which attracted people with a general positive and open attitude towards digital platforms. Furthermore, a large part of the literature deals with the operator side, which created a certain gap between the mentions from the focus group workshops and the literature, but at the same time broadened the scope of consideration. During the selection of literature during the SLR, we noticed that both terms 'service' and 'platforms' were broadly used and not clearly characterized, posing a challenge in the context of our research topic as well as in terms of clearly differentiating different research streams.

As previously noted, the user side of platforms has not been extensively studied in the research field. However, this study has specifically identified significant challenges faced by companies in participating in the platform business, while they generally have a positive attitude. Further research should aim to address this gap and provide support to companies during the implementation process. This could be achieved through practical access to identify the most important factors for companies and developing a structured process model with clear recommendations for both users and providers to address the challenges and take advantage of the opportunities presented by the platform business.

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References

[1] Porter, M.E., Heppelmann, J.E., 2014. How smart, connected products are transforming competition. Harvard Business Review 92 (11), 64–88.

[2] Leimeister, J.M., 2020. Dienstleistungsengineering und -management: Data-driven Service Innovation, 2., vollständig aktualisierte und erweiterte Auflage ed. Springer Gabler, Berlin, Heidelberg, 463 pp.

[3] Schwahn, F., Mai, C.-M., Braig, M., 2018. Arbeitsmarkt im Wandel - Wirtschaftsstrukturen, Erwerbsformen und Digitalisierung. Statistisches Bundesamt, Wiesbaden, 156 pp.

[4] Vandermerwe, S., Rada, J., 1988. Servitization of business: Adding value by adding services. European Management Journal 6 (4), 314–324.

[5] West, S., Gaiardelli, P., Saccani, N., 2022. Modern Industrial Services. Springer International Publishing, Cham.

[6] Tiwana, A., 2014. Platform ecosystems: Aligning architecture, governance, and strategy. Morgan Kaufmann, Waltham, MA.

[7] Haucap, J., Kehder, C., Loebert, I., 2021. B2B-Plattformen. Nomos Verlagsgesellschaft mbH & Co. KG.

[8] Gawer, A., 2021. Digital platforms' boundaries: The interplay of firm scope, platform sides, and digital interfaces. Long Range Planning 54 (5), 102045.

[9] Hein, A., Schreieck, M., Riasanow, T., Setzke, D.S., Wiesche, M., Böhm, M., Krcmar, H., 2020. Digital platform ecosystems. Electron Markets 30 (1), 87–98.

[10] Stallkamp, M., Schotter, A.P.J., 2021. Platforms without borders? The international strategies of digital platform firms. Global Strategy Journal 11 (1), 58–80.

[11] Korhonen, H.M.E., Still, K., Seppanen, M., Kumpulainen, M., Suominen, A., Valkokari, K., 2017. The Core Interaction of Platforms: How Startups Connect Users and Producers. Technology Innovation Management Review 7 (9), 17–29.

[12] Li, P., Cheng, Y., Song, W., Tao, F., 2020. Manufacturing services collaboration: connotation, framework, key technologies, and research issues. Int J Adv Manuf Technol 110 (9-10), 2573–2589.

[13] Suuronen, S., Ukko, J., Eskola, R., Semken, R.S., Rantanen, H., 2022. A systematic literature review for digital business ecosystems in the manufacturing industry: Prerequisites, challenges, and benefits. CIRP Journal of Manufacturing Science and Technology 37, 414–426.

[14] Gawer, A., 2014. Bridging differing perspectives on technological platforms: Toward an integrative framework. Research Policy 43 (7), 1239–1249.

[15] Reuver, M. de, Sørensen, C., Basole, R.C., 2018. The Digital Platform: A Research Agenda. Journal of Information Technology 33 (2), 124–135.

[16] Bruhn, M., Hadwich, K., 2017. Dienstleistungen 4.0: Geschäftsmodelle - Wertschöpfung - Transformation. Springer Fachmedien Wiesbaden, Wiesbaden.

[17] Marshall W. van Astyne, Geoffrey G. Parker, Sangeet Paul Choudary, 2016. Pipelines, platforms, and the new rules of strategy. Harvard Business Review 94, 16.

[18] Evans, P.C., Gawer, A., 2016. The rise of the platform enterprise: A global survey.

[19] Parker, G., van Alstyne, M., Choudary, S.P., 2016. Platform revolution: How networked markets are transforming the economy - and how to make them work for you, New York, London, 336 pp.

[20] Jaekel, M., 2017. Die Macht der digitalen Plattformen. Springer Fachmedien Wiesbaden, Wiesbaden.

[21] Gawer, A., Cusumano, M.A., 2014. Industry Platforms and Ecosystem Innovation. J Prod Innov Manag 31 (3), 417–433.

[22] Donabedian, A., 1980. Explorations in Quality Assessment and Monitoring: The Definition of Quality and Approaches to its Assessment. Ache Management.

[23] Schuh, G., Gudergan, G., Kampker, A., 2016. Management industrieller Dienstleistungen. Springer Berlin Heidelberg, Berlin, Heidelberg.

[24] Haller, S., Wissing, C., 2020. Dienstleistungsmanagement. Springer Fachmedien Wiesbaden, Wiesbaden.

[25] Zeithaml, V.A., Parasuraman, A., Berry, L.L., 1985. Problems and Strategies in Services Marketing. Journal of Marketing 49 (2), 33–46.

[26] Fließ, S., 2009. Dienstleistungsmanagement: Kundenintegration gestalten und steuern. Gabler, Wiesbaden.

[27] Tukker, A., 2004. Eight types of product–service system: eight ways to sustainability? Experiences from SusProNet. Bus. Strat. Env. 13 (4), 246–260.

[28] Gebauer, H., Paiola, M., Edvardsson, B., 2010. Service business development in small and medium capital goods manufacturing companies. Managing Service Quality, 123–139.

[29] Gitzel, R., Schmitz, B., Fromm, H., Isaksson, A., Setzer, T., 2016. Industrial Services as a Research Discipline. 4:1-22 Pages / Enterprise Modelling and Information Systems Architectures, Vol 11 (2016).

[30] Gill, P., Stewart, K., Treasure, E., Chadwick, B., 2008. Methods of data collection in qualitative research: interviews and focus groups. British dental journal 204 (6), 291–295.

[31] Rabiee, F., 2004. Focus-group interview and data analysis. The Proceedings of the Nutrition Society 63 (4), 655–660.

[32] Misoch, S., 2015. Qualitative Interviews. Walter de Gruyter GmbH, Berlin, München, Boston, 373 pp.

[33] Kallenberg, R., 2002. Ein Referenzmodell für den Service in Unternehmen des Maschinenbaus. Zugl.: Aachen, Techn. Hochsch., Diss., 2002. Shaker, Aachen, 248 pp.

[34] Harris Cooper, 1988. Organizing knowledge syntheses: A taxonomy of literature reviews. Knowledge in Society 1, 104–126.

[35] Snyder, H., 2019. Literature review as a research methodology: An overview and guidelines. Journal of Business Research 104 (5), 333–339.

[36] Jane Webster, Richard T. Watson, 2002. Analyzing the Past to Prepare for the Future: Writing a Literature Review. MIS Quarterly 26 (2), xiii–xxiii.

[37] Vom Brocke, J., Simons, A., Niehaves, B., Riemer, K., Plattfaut, R., Cleven, A., 2009. Reconstructing the Giant: On the Importance of Rigour in Documenting the Literature Search Process.

[38] Mayring, P., Fenzl, T., 2019. Qualitative Inhaltsanalyse, in: Baur, N., Blasius, J. (Eds.), Handbuch Methoden der empirischen Sozialforschung, vol. 3, Wiesbaden, pp. 633–648.

[39] Gioia, D.A., Corley, K.G., Hamilton, A.L., 2013. Seeking Qualitative Rigor in Inductive Research. Organizational Research Methods 16 (1), 15–31.

[40] Rössler, P., 2017. Inhaltsanalyse, 3. überarbeitete Auflage, Online-Ausgabe ed. UVK Verlagsgesellschaft mbH; UVK/Lucius, Konstanz, München, 292 pp.

[41] Tranfield, D., Denyer, D., Smart, P., 2003. Towards a Methodology for Developing Evidence-Informed Management Knowledge by Means of Systematic Review. Br J Management 14, 207–222.

[42] Barenji, A.V., Li, Z., Wang, W.M., Huang, G.Q., Guerra-Zubiaga, D.A., 2020. Blockchain-based ubiquitous manufacturing: a secure and reliable cyber-physical system. International Journal of Production Research 58 (7), 2200–2221.

[43] Alberti, A.M., Santos, M.A.S., Souza, R., Lourenco da Silva, Hirley Dayan, Carneiro, J.R., Campos Figueiredo, V.A., Rodrigues, Joel J. P. C., 2019. Platforms for Smart Environments and Future Internet Design: A Survey.

[44] Agostinho, C., Costa, R., Malo, P., Jardim-Goncalves, R., 2006. Product data integration in the demand of interoperability in e-Business, in: 3rd International IEEE Conference, London, UK, pp. 807–812.

[45] Pedrazzoli, P., Sorlini, M., Rovere, D., Lazaro, O., Malò, P., Fiorello, M., 2022. Challenges and Founding Pillars for a Manufacturing Platform to Support Value Networks Operating in a Circular Economy Framework.

[46] Wortmann, F., Joppen, R., Drewel, M., Kühn, A., Dumitrescu, R. Developing and evaluating concepts for a digital platform, in: , Managing Technology for Inclusive and Sustainable Growth, pp. 647–660.

[47] Heiss, M., Oertl, A., Sturm, M., Palensky, P., Vielguth, S., Nadler, F., 2015. Platforms for industrial cyber-physical systems integration: contradicting requirements as drivers for innovation, in: Workshop on Modeling and Simulation of Cyber-Physical Energy Systems (MSCPES), Seattle, WA, USA.

[48] Camargo-Vila, M., Osma-Pinto, G., Ortega-Boada, H., 2020. Enterprise Architecture an Approach to the Development of IoT Services: Oriented to Building Management, in: , Applied Technologies, vol. 1194, Cham, pp. 207–221.

[49] Madhikermi, M., Yousefnezhad, N., Framling, K., 2018. Data Exchange Standard for Industrial Internet of Things, in: 2018 3rd International Conference on System Reliability and Safety (ICSRS), pp. 53–61.

[50] Baig, R., Centelles, R.P., Freitag, F., Navarro, L., 2017. On edge microclouds to provide local container-based services, in: 2017 Global Information Infrastructure and Networking Symposium, GIIS 2017, pp. 31–36.

[51] Petrik, D., Straub, D., Herzwurm, G., 2020. Potentials of platforms for the realization of digital services for component manufacturers. Procedia CIRP 93 (2), 652–657.

[52] Ghomi, E.J., Rahmani, A.M., Qader, N.N., 2019. Cloud manufacturing: challenges, recent advances, open research issues, and future trends. Int J Adv Manuf Technol 102 (9-12), 3613–3639.

[53] G. Di Orio, P. Maló, J. Barata, M. Albano, L. L. Ferreira, 2018. Towards a Framework for Interoperable and Interconnected CPS-populated Systems for Proactive Maintenance, in: 2018 IEEE 16th International Conference on Industrial Informatics (INDIN), pp. 146–151.

[54] Arnold, C., Kiel, D., Voigt, K.-I., 2017. Innovative business models for the industrial internet of things, in: 26th International Association for Management of Technology Conference, IAMOT 2017, pp. 1379–1396.

[55] Popa, L., Popa, V., 2018. Study on a collaborative platform for product development using cloud computing. IOP Conf. Ser.: Mater. Sci. Eng. 400.

[56] Lee, J., Ardakani, H.D., Yang, S., Bagheri, B., 2015. Industrial Big Data Analytics and Cyber-physical Systems for Future Maintenance & Service Innovation. Procedia CIRP 38, 3–7.

[57] Ferrer, B.R., Mohammed, W.M., Martinez Lastra, J.L., Villalonga, A., Beruvides, G., Castano, F., Haber, R.E., 2018. Towards the Adoption of Cyber-Physical Systems of Systems Paradigm in Smart Manufacturing Environments, in: 2018 IEEE 16th International Conference on Industrial Informatics (INDIN), pp. 792–799.

[58] Koren, I., Braun, S., van Dyck, M., Jarke, M., 2021. Dynamic Strategic Modeling for Alliance-Driven Data Platforms: The Case of Smart Farming. Springer Science and Business Media Deutschland GmbH, 92 pp.

[59] A. Pradhan, J. Agwa-Ejon, 2014. Opportunities and Challenges of Embracing Smart Factory in South Africa, in: Proceedings of PICMET '14 Conference, pp. 1–8.

[60] Belkadi, F., Boli, N., Usatorre, L., Maleki, E., Alexopoulos, K., Bernard, A., Mourtzis, D., 2020. A knowledge-based collaborative platform for PSS design and production. CIRP J. Manuf. Sci. Technol. 29, 220–231.

[61] Shamsuzzoha, A., Kankaanpaa, T., Carneiro, L.M., Almeida, R., Chiodi, A., Fornasiero, R., 2013. Dynamic and collaborative business networks in the fashion industry. International Journal of Computer Integrated Manufacturing 26, 125–139.

[62] Gong, X., Jiao, R., Jariwala, A., Morkos, B., 2021. Crowdsourced Manufacturing for Delivery of Manufacturing as a Service, in: 2021 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), Singapore, Singapore, pp. 1617–1621.

[63] Mao, Z., Zhang, W., Yang, B., Zhang, T., 2021. Impact of coronavirus pandemic on sharing mode of manufacturer. Computers and Industrial Engineering 158.

[64] Fechtelpeter, C., Kuehn, A., Dumitrescu, R., Ebbesmeyer, P., 2017. Integrated technology transfer concept for fostering innovation in SMEs, in: IAMOT 2017, pp. 1028–1048.

[65] Camarinha-Matos, L.M., Fornasiero, R., Afsarmanesh, H., 2017. Collaborative Networks as a Core Enabler of Industry 4.0, in: Collaboration in a Data-Rich World, vol. 506. Springer International Publishing, pp. 3–17.

[66] Zhang, W., 2020. Analysis of Cooperation Decision between Small and Medium-sized Manufacturing Enterprises and Cross-border E-commerce Platform Based on Evolutionary Game, in: 2020 The 6th International Conference on Industrial and Business Engineering, pp. 45–48.

[67] Yang, S., Bagheri, B., Kao, H.-A., Lee, J., 2015. A Unified Framework and Platform for Designing of Cloud-Based Machine Health Monitoring and Manufacturing Systems. J Manuf Sci Eng Trans ASME 137 (4).

[68] Coreynen, W., Matthyssens, P., Vanderstraeten, J., van Witteloostuijn, A., 2020. Unravelling the internal and external drivers of digital servitization: A dynamic capabilities and contingency perspective on firm strategy. Industrial Marketing Management 89 (1), 265–277.

[69] Chen, J., Mo, R., Chu, J., Yu, S., Fan, J., Cheng, F., 2019. Research on the optimal combination and scheduling method of crowdsourcing members in a cloud design platform. Proceedings of the Institution of mechanical Engineers Part B-Journal of Engineering Manufacture, 2196–2209.

[70] Cantu, C.L., Schepis, D., Minunno, R., Morrison, G., 2021. The role of relational governance in innovation platform growth: the context of living labs. Journal of Business and Industrial Marketing 36, 236–249.

[71] Camarinha-Matos, L.M., Fornasiero, R., Ramezani, J., Ferrada, F., 2019. Collaborative Networks: A Pillar of Digital Transformation. Applied Sciences (Switzerland) 9 (24), 5431.

[72] Raes, V., Vossaert, J., Naessens, V., 2018. Development of an embedded platform for secure CPS services. Springer Verlag, 19 pp.

[73] K. Tabassum, A. Ibrahim, S. A. El Rahman, 2019. Security Issues and Challenges in IoT, in: 2019 International Conference on Computer and Information Sciences (ICCIS), pp. 1–5.

Biography

Jonas Eichholz (*1996) is a research assistant at the Chair of Enterprise Logistics, TU Dortmund University since 2020 and works in the department of maintenance- and service-management. His research focuses on co-creation, services and data management.

Michael Baumeister (*1998) is a student assistant at the Chair of Enterprise Logistics, TU Dortmund University since 2022 and works in the department of Blockchain Europe.

Alexander Kreyenborg (*1988) is a research assistant at the Chair of Enterprise Logistics, TU Dortmund University since 2016 and works in the department of maintenance- and service-management. His research focuses on servitization and product-service-systems.

Daniel Hefft (*1989) is a research assistant at the Chair of Enterprise Logistics, TU Dortmund University since 2020 and works in the department of maintenance- and service-management. His research focuses on new development methods for data-driven services.

Nick Große (*1992) is a research assistant at the Chair of Enterprise Logistics, TU Dortmund University and since 2019 and works in the department of maintenance- and service-management. His research focuses on blockchain-enabled trust in networks.

Prof. Dr. Dr. h. c. Michael Henke (*1971) has been in the leadership of the Chair of Enterprise Logistics, TU Dortmund University and institute director of the Fraunhofer Institute of Material Flow and Logistics (IML) since 2013. He is also an adjunct professor for Supply Chain Management at the School of Business and Management at the Lappeenranta University of Technology in Finland since 2015.

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Anticipatory Inventory Management For Realizing Robust Production Processes In Engineer-To-Order Manufacturing: A Modeling Approach

Alexander Wenzel[1], Lennart Hingst[1], Peter Nyhuis[1]

[1]*Institute of Production Systems and Logistics, Leibniz Universität Hannover, An der Universität 2, 30823 Garbsen, Germany*

Abstract

At ever shorter intervals, manufacturing and processing companies of all industries are confronted with external or internal disruptions and crises that need to be managed. Consequently, a corporate focus on robust supply chains and processes is essential. At the same time, crises and their impact on supply chains cannot be predicted. To be able to act anticipatively, it is necessary to link product and production system design to take suitable measures to safeguard production at an early stage. In this context, a monetary conflict of objectives arises concerning when a company should position itself robustly and when it is sufficient to react flexibly to disruptions. The production planning and control (PPC) task inventory management is an essential lever for realizing robust order fulfilment processes. Inventory management aims to ensure that production and assembly within the company are supplied in the right quantities and without lateness. In particular, companies that operate according to the engineer-to-order strategy (ETO) face specific challenges in dimensioning stocks for materials or components - for example, due to the low level of standardization or lack of supplier diversity. This paper presents an approach for anticipatory inventory management using product portfolio characteristics. A new modeling approach for dimensioning safety stocks under the increasing influence of crises is also developed and integrated into the process.

Keywords

Production planning and control (PPC), Inventory Management, Safety stock, Robustness, ETO

1. Introduction

Increasing dynamics and volatility in the global business environment lead to rising uncertainties for companies in every sector. As a result, future market developments and resulting supply chain disruptions are more challenging to anticipate and cannot be predicted with sufficiently accurate probability. [1,2] Companies must therefore create robust processes which, despite these developments, enable on-time deliveries to customers and, in turn, sustainable competitiveness. In recent years, the planning and design of supply chains have been primarily characterized by cost optimization and profitability [3]. Current crises (e.g., the COVID-19 pandemic, the Suez Canal blockage, and uncertainty in the financial markets) illustrate how unpredictable the business environment is becoming and how susceptible the widely interlinked supply chains react to such disruptions. Additionally, companies are being affected by crises/disruptions and associated material shortages with increasing frequency and intensity [4]. This poses particular challenges for ETO-manufacturer (e.g., Aircraft or shipbuilders). The high level of customer influence throughout the production process leads to additional uncertainties [5] and requires close cooperation with suppliers. In some cases, joint development and design work is

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carried out with suppliers, which must have appropriate certifications (e.g. regarding safety and quality). In crises, therefore, manufacturers cannot necessarily switch suppliers to counteract supply bottlenecks. At the same time, stocking certain materials or components for complex products is associated with high costs. These constraints require a closer link between the early development phase and production system design, including procurement and production planning and control (PPC). An important task within the PPC is inventory management. The main challenge is dimensioning the safety stock depending on the service level to be realized. Safety stocks are considered suitable for avoiding supply bottlenecks [6]. Since crises/supply chain disruptions cannot be predicted, it is hardly possible for companies to realize necessary inventory increases in time. This paper defines anticipatory inventory management as a link between product and production system design. It enables companies to identify materials/components in early planning phases that require higher risk hedging, e.g., through higher stock levels, due to their high importance regarding complexity, price, or multiple uses. Previous approaches hardly examine how the product structure or standardization characteristics influence the decision regarding safety stock dimensioning [4] and how companies can assess potential delivery quantity deviations logistically and economically during crises [7].

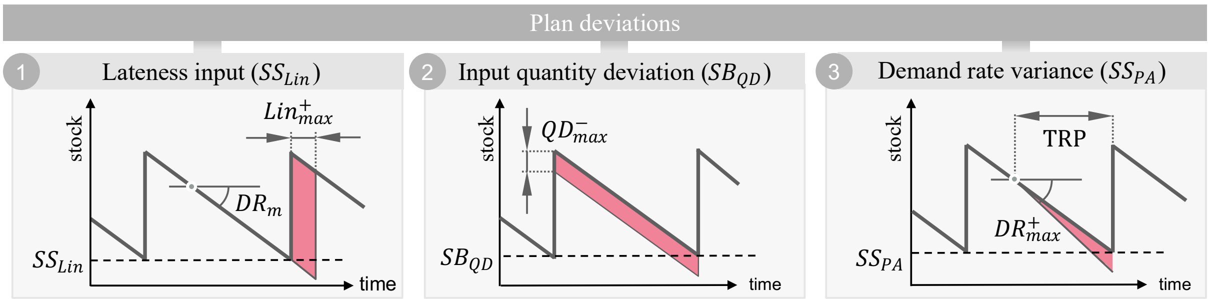
This paper develops an approach to mathematically model delivery quantity deviation as a safety stock component. This model is integrated into an analysis procedure that supports companies in selecting materials for which robust inventory dimensioning is appropriate. Section 2 presents the state of the art for safety stock dimensioning. In Section 3, the research methodology used is described. Section 4 describes the mathematical model for dealing with delivery quantity deviations and the analysis procedure for anticipating inventory management before Section 5 provides a summary and outlook for future research activities.

2. State of the art

2.1 Fundamentals of stock dimensioning to deal with uncertainties

Various properties of production systems for dealing with uncertainties exist. The property of robustness aims to avoid disturbances from the outset. In the case of unexpected disruptions, robustness will minimize the influences in such a way that the functionality of the production system is maintained. [8,9]. In contrast to the reactive resilience strategy, robust stock sizing is a proactive strategy since the system is designed anticipatively - i.e., before a disturbance - so that corresponding properties take effect when the disruption occurs [10]. For example, multiple-sourcing strategies are generally more robust than single-sourcing strategies. In the case of a supplier breakdown, the entire supply chain is not jeopardized since if the other suppliers for this material remain able to deliver, production can continue at least for a certain time without any significant loss of performance [11].

Robust production systems are insensitive to external and internal influences and thus continue to perform in the event of unexpected disruptions [8,12]. One important supply chain element for absorbing these influences are warehouses, which enable decoupling in terms of time and quantity and supply subsequent processes with materials, semi-finished products, or tools. Inventory dimensioning focuses on the trade-off between low inventory costs (e.g., resulting from capital commitment and floor space costs) and a high level of service. The service level indicates the share of demand the available stock can serve in terms of quantity and time [13,14]. The basis for the approaches of stock dimensioning described below is the general REFA inventory model, which represents the stock development of an article or material over time. The safety stock is used to achieve a high level of service despite deviations from the plan concerning dates, quantities, and requirements [7]. The dimensioning of the safety stock is based on three essential components, shown in Figure 1 [15].



Legend
Lin^+_{max} : *max. positive Lateness* — DR^+_{max} : *max. demand rate* — QD^-_{max} : *max. negative quantity deviation*
TRP : *Total replenishment time* — DR_m : *mean demand rate*

Figure 1: Three components for dimensioning the safety stock due to plan deviations

The first component takes into account schedule deviations in stock inbounds. Here, the stock is increased to such an extent that the demand can still be met for the duration of the maximum positive input lateness (Lin^+_{max}). **The second component** focuses on the quantity deviation from the planned input to the warehouse. The safety stock required for this (QD^-_{max}) results from the maximum negative quantity deviation to be assumed. **The third component** of the safety stock represents demand rate deviations that occur within the replenishment time. For this purpose, the difference in the maximum demand rate deviation $DR^+_{max}$and the mean demand rate (DR_m) is formed. Given that the individual components can add up and compensate, which is the case if stochastic independence is assumed, the minimum safety stock is calculated according to formula 1 [7]. BECKER evolves this formula by taking into account seasonal fluctuations in demand or offtake rates [16] so that a time-dynamic calculation of the safety stock is possible.

$$SS_{\min} = \sqrt{(Lin^+_{max} \cdot DR_m)^2 + (QD^-_{max})^2 + ((DR_{max} - DR_m) \cdot TRP)^2} \quad (1)$$

$$SS_{min,i} = \sqrt{\left(\sum_{t=i+1+TRP}^{i+TRP+Lin^+_{max}} DF_t\right)^2 + \left(QD^-_{max}\right)^2 + \left(FD^+_{max} \sum_{t=i}^{i+TRP} DF_t\right)^2} \quad (2)$$

with
$SS_{min,i}$ Minimum safety stock at the time i / QTY
Lin^+_{max} Maximum positive lateness to be assumed / SCD
QD^-_{max} Maximum negative delivery quantity deviation to be assumed / QTY
FD^+_{max} Maximum positive forecast deviation to be assumed / %.
DF_t Demand forecast for the time t / QTY
TRP Total Replenishment time / SCD

2.2 Approaches to take into account product structure properties in safety stock dimensioning

The literature review by GONÇALVES ET AL. shows that only a few relatively old papers deal with how product structures and standardization affect the dimensioning of stock [4]. COLLIER develops a formula for safety stock calculation that considers an analytical metric based on the bill of materials (BOM) to measure the degree of commonality in a product family. This formula was validated using simulation. The results indicate that increasing the degree of component commonality leads to lower safety stocks while maintaining the same service level [17]. GRUBBSTRÖM'S approach aims to determine a safety stock in the case of demand uncertainty for planned production flows in single-stage product structure systems. The annuity flow is used as the evaluation criterion instead of the usual average cost approach [18]. CARLSON AND YANO calculate a heuristic upper bound for safety stock dimensioning for each component of a product structure with periodic and replanned production schedules under stochastic demands. Using simulation, the authors demonstrate the approach's potential by comparatively evaluating different stock levels using the inventory cost criterion. In another paper, the authors investigate how the frequency of replanning affects safety stock decisions for a single product and its product structure. [19,20] In developing their solution, PERSONA ET AL. consider the benefits of modular product design and Super-BOMs, which were created by combining multiple BOMs of similar products. In the paper, cost-based analytical models are developed, evaluated, and applied to quantify the optimal safety stock for modular subassemblies and components. In doing so, the authors focus on the requirements of a make-to-order and assemble-to-order strategy [21]. The approach developed by HERNÁNDEZ ET. AL. also deals with calculating and reducing safety stocks for modular product structures in the context of make-to-order strategies. In addition to safety stock reduction by commonality in modules and components, a substitution factor revised from group technology theory is also considered. Using fictitious examples, different scenarios for inventory dimensioning are tested (e.g. with and without high commodity), and it is shown that safety stocks could be reduced by applying the developed model [22]. The literature analysis shows that only a few approaches deal with the interface of product and production system design. None of the methods considers the three components of the safety stock (cf. section 2.1) and focuses on modeling quantity deviations due to increasing disruptions.

3. Research Methodology

The variety of interdependencies and the technical and organizational influencing factors that must be considered while integrating predictive inventory management into ETO production require a model-based approach to structure and solve the problem. A deductive-experimental research approach was chosen to develop a generally applicable model for inventory dimensioning. In doing so, argumentative-deductive analysis achieves inferences from issues or facts through reasoned argumentation. The research is construction-oriented and qualitative. The hypotheses created about specific real-world points using deduction will then be examined by observations and experimentations to confirm or disprove them. (cf. [7]). If the limits of analytical methods have been reached, if complex cause-effect relationships are involved, or if experiments on the real object of investigation are challenging to perform, experiments can be carried out with the help of simulations. The results presented in this paper are based on the deductive modeling approach. An experimental investigation of the interrelationships is focused on in following papers.

4. Anticipatory inventory management for ETO processes

4.1 Modeling assumptions

Section 2 shows the components of the safety stock for static and dynamic cases. The impact of delivery date variances is related to inventory inputs, and the effect of demand rate or forecast variances is connected to inventory outputs. Quantity deviations as an additional safety stock component should only be considered if the replenishment time is higher than the period between two planned deliveries. [7] The modeling approach presented in this paper is based on the assumption that if a crisis occurs, the availability of certain materials is abruptly reduced while demand remains constant. If the availability of materials decreases, suppliers may no longer be able to deliver the contracted quantity of materials within a specified replenishment time. As a result, at certain measurement times after the crisis has occurred, there are deviations in the delivery quantities of materials that are affected by the corresponding bottleneck situation and, therefore, cannot easily be compensated by subsequent deliveries, e.g. from other suppliers. In that case, companies whose safety stocks were already replenished in adequate quantities before the first signs of demand availability problems will realize a higher service level for a more extended period in the event of supply shortfalls. For anticipatory dimensioning of safety stocks, business parameters such as increased storage costs or loss of revenues due to opportunity costs must be considered when determining the added value of an early increase in safety stock.

4.2 A mathematical model for robust dimensioning of safety stock as a result of crises

To make crisis-related inventory adjustments, it is generally not necessary to anticipate the exact time a crisis will occur. Instead, it should be determined how many and which deliveries (cf. section 4.2) could be affected by the availability problems. Therefore, it is essential to make accurate predictions about the length of the crisis and the number of deliveries that occur during the crisis. Furthermore, similar to the demand forecast from BECKER'S approach (see section 2.2), it must be predicted how significant the quantity deviations of the deliveries will be during the crisis. If this can be estimated separately for each delivery, a more accurate calculation of the costs arising from the safety stock increase can be made. However, the method is only effective if the average deviation values in delivery quantity are calculated. If the crisis impacts many deliveries, an average value simplifies the calculations significantly.

The number of affected deliveries is calculated from the estimated duration of the crisis and the time between two deliveries or the original replenishment time. All deliveries between the last complete delivery before the occurrence of the crisis and the first full delivery after the occurrence of the crisis are considered affected deliveries:

$$n_c = \left\lceil \frac{D_c}{TRP} \right\rceil \quad (3)$$

With	n_c	Number of deliveries affected by crisis *c*
	D_c	Expected duration of the crisis *c* / SCD (supply calendar days)
	TRP	Replenishment time / SCD

The minimum theoretical safety stock level is the cumulative shortfall forecast over the crisis duration. These can be determined both via the averaged forecast quantity deviations of individual deliveries and via the forecast availability level:

$$SS_{QD,c} = \sum_{l=1}^{n_c} p_{QD^-,l} \quad = D_c \cdot DR_m \cdot (1 - p_{a,c}) \quad (4)$$

With	$SS_{QD,c}$	Component of safety stock due to quantity deviations resulting from crisis k / QTY
	DR_m	Mean demand rate / QTY per SCD
	$p_{QD^-,l}$	Predicted negative quantity deviation from delivery l / QTY
	n_c	Number of deliveries affected by crisis c
	D_c	Expected duration of the crisis c / SCD
	$p_{a,c}$	Mean availability forecast of the affected item for crisis c / %.

The safety stock component calculated in this way represents the quantity of a material/article by which the safety stock must be increased before the crisis occurs to survive the crisis without reducing the service level. The safety stock component calculated in equation (3) considers the shock's intensity and duration of the availability crisis. In principle, it can be assumed that no two crises are alike. Furthermore, a crisis does not necessarily have identical effects on companies. For example, particularly cooperative relationships with a supplier can mean that a company can better overcome a crisis than other competitors. The impact of crises on the procurement situation of a company must be understood as a multi-factorial result, which must be analyzed separately for each crisis. Therefore, the theoretically necessary safety stock component $SS_{QD,c}$ (see formula 3) is extended by four additional factors. The **adjusted** safety stock component is calculated with consideration of all factors as follows:

$$\widetilde{SS}_{QD,c} = SS_{QD,c} \cdot F_O \cdot \frac{F_R}{F_I} \cdot F_A \tag{5}$$

With

$\widetilde{SS}_{QD,c}$	Adjusted component of safety stock due to quantity deviations resulting from crisis k / QTY
$SS_{QD,c}$	Unadjusted component of safety stock due to quantity deviations resulting from crisis k / QTY
F_O	Factor for the probability of occurrence
F_R	Factor for the relative order quantity
F_I	Factor for the importance of the order/customer
F_A	Factor for alternative procurement options and the procurement strategy

The **factor probability of occurrence** of the crisis indicates the extent to which the forecast delivery quantity deviations are actually to be expected. The second factor is the **size of the order quantity**. The larger the order quantity, the greater the probability that delivery will not be complete in the event of availability problems. In this context, **the customer's economic or strategic importance or the supplier's order** must be considered as a factor, too: As a rule, customers who regularly purchase large quantities are of greater importance than customers whose order quantity is significantly smaller. The supplier, therefore, endeavours to serve large orders as fully as possible to ensure the satisfaction of essential customers. Given the factor described above, customers whose vast order quantities should receive as complete deliveries as possible. However, this isn't easy to achieve precisely because of the large quantities involved. In times of availability problems, other customers may no longer be able to be supplied. In contrast, smaller purchase orders from customers of lesser economic importance can be served more readily. It can therefore be assumed that these effects offset each other to a certain extent (see formula 4).

In addition to the factors already mentioned, it must be examined **which procurement strategy** is being pursued and to what time alternative procurement options can be activated for the article concerned. In the most unfavourable scenario for the company F_O, F_A and the ratio $\frac{F_R}{F_I}$ assumes the value 1. In this case, the necessary adjusted safety stock ratio $\widetilde{SS}_{QD,c}$ corresponds precisely to the forecast shortfall $SS_{QD,c}$. accumulated throughout the entire crisis. The necessary safety stock component is reduced if at least one factor is smaller than 1. As a result, the theoretically required safety stock percentage calculated based on intensity and duration cannot increase any further, taking equation (4) into account. In order to determine these factors for the respective (crisis) situation, an evaluation table can be used as a decision-making aid based on the factor evaluation within the framework of a Failure Mode and Effects Analysis (FMEA).

To integrate the determined safety stock component $\widetilde{SS}_{QD,c}$ into equation (2), it must first be noted that the forecast and delivery date deviations components refer to the following replenishment time. $\widetilde{SS}_{QD,c}$, on the other hand, refers to a crisis that occurs within the following replenishment time. However, the determined inventory share refers to the duration of this crisis, which can cover several replenishment times. If $\widetilde{SS}_{QD,c}$ should be used for QD^{-}_{max} in equation (2), this would result in the compensation effects of geometric addition only acting on the additional quantity deviation-related safety stock level required in the first replenishment time, so an excessively high safety stock level would be calculated. Therefore, it is necessary to consider the compensation effects for the entire crisis period. If it were possible to replenish the safety stock during the crisis, the safety stock required at the beginning of each replenishment period would be calculated according to equation (5). This requires demand forecasts for the entire crisis period. These are then assumed to remain constant during the crisis period.

$$SS_{min,i} = \frac{1}{n_c}\sqrt{(n_c \cdot \sum_{t=i+1+TRP}^{i+TRP+Lin_{max}^{+}} DF_t)^2 + (\widetilde{SS}_{QD,c})^2 + (n_c \cdot FD_{max}^{+} \sum_{t=i}^{i+TRP} DF_t)^2} \quad (6)$$

With $SS_{min,i}$ Minimum safety stock at the time i / QTY

Lin_{max}^{+} Maximum positive lateness to be assumed / SCD

$\widetilde{SS}_{QD,c}$ Adjusted component of safety stock due to quantity deviations resulting from crisis c / QTY

DF_t Demand forecast for the time t / QTY

FD_{max}^{+} Maximum positive forecast deviation to be assumed / %.

TRP Total Replenishment time / SCD

n_c Number of deliveries affected by crisis *c*

4.3 Procedure for anticipatory inventory management

In designing, planning, and controlling production systems, ETO manufacturing focuses mainly on the product. Decisions in the context of product development are primarily made for design- or customer-oriented reasons. The challenges this creates in the individual production stages, assembly, or procurement and provision are only considered to a limited extent. The realization of a high logistic performance (e.g. a high service level in the warehouse) is thus made more difficult. The three-stage procedure developed here (see figure 2) starts at this point and focuses on the interface between driver variables of the product structure and inventory dimensioning.

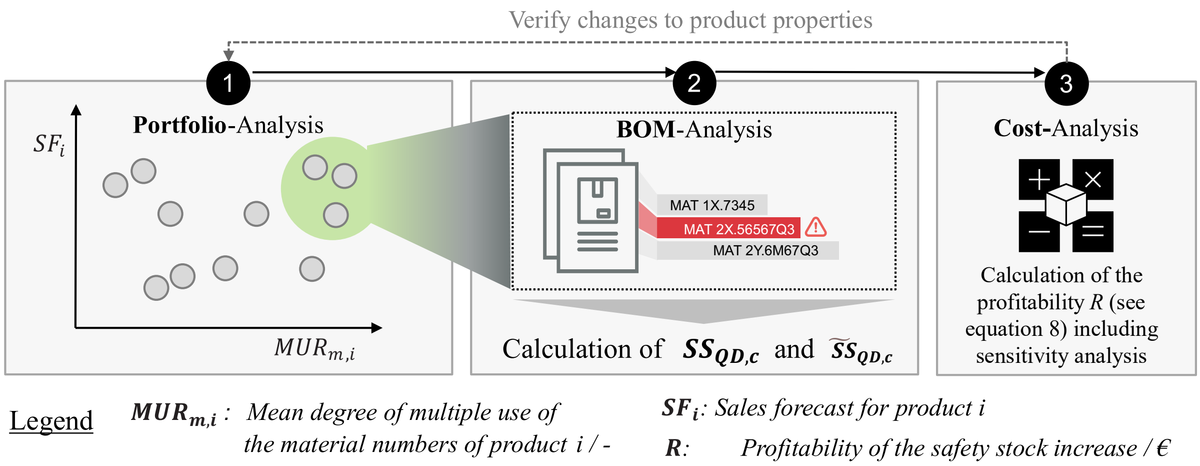


Figure 2. Approach for anticipatory inventory management

In the first step, the product portfolio is analyzed about the driver parameter of the degree of multiple uses of the material numbers[23].

$$MUR_{m,p} = \frac{1}{n_{Prod}} \cdot \frac{\sum_{j=1}^{n_{Mat,p}} MU_j}{n_{Mat.p}} \quad (7)$$

With $MUR_{m,p}$ Mean degree of multiple uses of the material numbers of product p / -

n_{Prod} Number of all products in portfolio / -

p Product *p* / -

$n_{Mat.p}$ Number of all material numbers of product p (j = 1, ... J) / -

MU_j Number of products in which material number j is used / -

As stated by KÄMPFER & NYHUIS [23], the frequency of usage can be utilized to calculate the proportion of the portfolio in which the material numbers of a product are used on average. If the information on the multiple usage levels within the (future) portfolio is linked with corresponding key figures on the sales forecasts per product p, a description matrix can be created (cf. Figure 2; left block). This makes it possible to identify materials in the early development phases for which robust safety stock dimensioning appears worthwhile from an economic and logistical point of view. This form of product representation allows materials to be identified for which robust inventory dimensioning offers a powerful lever for safeguarding production against potential disruptions. **The second step of the procedure** involves the application of the modeled formula presented in the previous chapter (see formula 5 in section 4.1.) for the robust dimensioning of safety stock, which takes into account delivery quantity deviations depending on crises at the time i. The first step is selecting materials for which robust stock dimensioning is a significant lever for safeguarding production against potential disruptions. After selecting materials suitable for robust stock dimensioning, this approach phase assists with the question of "how robust should the company set itself up to be". After dimensioning has been carried out for one material or component, the profitability (R) of the safety stock increase due to quantity deviations should be finally evaluated. For this purpose, the following calculation logic is integrated into the **third step of the procedure**:

$$P = S - \Delta C_l - \Delta C_{exp} = (P_c - P_b) \cdot \widetilde{SS}_{QD,c} - \frac{P_v \cdot \Delta {SS_m}^2 \cdot (z_{IR} + k_{CW})}{DR_m \cdot 36000} \quad (8)$$

With
P Profitability of the safety stock increase / €
S Savings of the safety stock increase / €
ΔC_I Additional inventory costs / €
ΔC_{exp} Additional costs due to interest expenses / € (opportunity costs)
P_c Price level during the crisis / € per QTY
P_b Price level before the crisis / € per QTY
$\widetilde{SS}_{QD,c}$ Adjusted component of safety stock due to quantity deviations resulting from crisis c / QTY
ΔSS_m Mean additional safety stock throughout the crisis / QTY
DR_m Mean demand rate / ME per SCD
z_{IR} Opportunity interest rate p.a. / %
k_{CW} Warehousing costs p.a. / %

It is assumed that although it is possible to purchase a required quantity at a higher price during the crisis, this should be avoided by adjusting the safety stock beforehand. It is also assumed that the relationship between the price level during and before the crisis is equivalent to the balance of the material availability level before the crisis (around 100%) and during the crisis. The price difference multiplied by the amount of additional safety stock $\widetilde{SS}_{QD,c}$ represents the savings S that the anticipatory stock increase can achieve. Additional inventory costs and opportunity costs reduce this saving. The additional inventory cost is obtained by multiplying the value per item, the average additional safety stock, the storage period, and the storage cost rate per day. Other costs that must be considered are interest expenses arising from the additional capital.

5. Conclusion

In this paper, a procedure for anticipatory inventory management was developed to link product and production system properties. The modeling approach integrated into the process can be used to quantify how robustly a company should position itself concerning relevant materials/components, depending on the predicted duration and intensity of a crisis. Future research could address determining factors to adjust the safety stock level due to quantity deviation. As indicated in section 3, testing and validating the modeling approach presented here is necessary using, e.g. simulation experiments to meet the requirements of the deductive-experimental research approach. The extent to which a rating scale for the factors and their mathematical modeling is meaningful must be answered in future research based on simulation studies. The mathematical model assumes that reordering in increasingly volatile environments cannot cover the quantity deviations. The developed model-theoretical representation of several successive supply quantity deviations during a crisis can be a starting point for further research. For example, future approaches should address the adjustment of safety stock levels in simultaneous uncertain replenishment times and demand rates. Here, it is essential to investigate how the compensation effects behave. Converting the model presented here into a model-based systems engineering approach would enable a systematic representation and interdisciplinary use of the information in product development and production system design. Stock dimensioning is one possible measure to realize robust production systems. Different properties, such as resilience, are also available for designing and planning production systems. Depending on the evaluation of the given uncertainty, it needs further research activities to identify the right combination of measures.

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References

[1] Gupta, A., Maranas, C.D., 2003. Managing demand uncertainty in supply chain planning. Computers & Chemical Engineering 27 (8-9), 1219–1227.

[2] Handfield, R., Straube, F., Pfohl, H.-C., Wieland, A., 2013. Trends and Strategies in Logistics and Supply Chain Management.: Embracing global logistics complexity to drive market advantage.

[3] Lariviere, M.A., 2020. Supply Chains, in: Vernengo, M., Caldentey, E.P., Rosser Jr, B.J. (Eds.), The New Palgrave Dictionary of Economics. Palgrave Macmillan UK, London.

[4] Gonçalves, J.N.C., Sameiro Carvalho, M., Cortez, P., 2020. Operations research models and methods for safety stock determination: A review. Operations Research Perspectives 7, 100164.

[5] Tu, Y., 1997. Real-time scheduling and control of one-of-a-kind production. Production Planning & Control 8 (7), 701–710.

[6] Eruguz, A.S., Sahin, E., Jemai, Z., Dallery, Y., 2016. A comprehensive survey of guaranteed-service models for multi-echelon inventory optimization. International Journal of Production Economics 172, 110–125.

[7] Nyhuis, P., Wiendahl, H.-P., 2009. Fundamentals of Production Logistics: Theory, Tools and Applications, 1st ed. Springer-Verlag Berlin Heidelberg, 332 pp.

[8] Hingst, L., Park, Y.-B., Nyhuis, P., 2021. Life Cycle Oriented Planning Of Changeability In Factory Planning Under Uncertainty. Hannover : publish-Ing, Garbsen.

[9] Vlajic, J.V., van der Vorst, J.G.A.J., Haijema, R., 2012. A framework for designing robust food supply chains. International Journal of Production Economics 137 (1), 176–189.

[10] Hingst, L., Wecken, L., Brunotte, E., Nyhuis, P., 2022. Einordnung der Robustheit und Resilienz in die Veränderungsfähigkeit. Hannover : publish-Ing, Garbsen.

[11] Tang, C.S., 2006. Robust strategies for mitigating supply chain disruptions. International Journal of Logistics Research and Applications 9 (1), 33–45.

[12] Klibi, W., Martel, A., Guitouni, A., 2010. The design of robust value-creating supply chain networks: A critical review. European Journal of Operational Research 203 (2), 283–293.

[13] Lutz, S., 2002. Kennliniengestütztes Lagermanagement. Zugl.: Hannover, Univ., Diss., 2002, Als Ms. gedr ed. VDI-Verl., 159 pp.

[14] Schönsleben, P., 2008. Integrales Logistikmanagement, 8th ed. Springer Berlin Heidelberg, Berlin, Heidelberg.

[15] Lutz, S., Lödding, H., Wiendahl, H.-P., 2003. Logistics-oriented inventory analysis. International Journal of Production Economics 85 (2), 217–231.

[16] Becker, J., 2016. Dynamisches kennliniengestütztes Bestandsmanagement. PZH Verlag, Garbsen, 152 pp.

[17] Collier, D.A. Aggregate Safety Stock Levels and Component Part Commonality. Management Science 1982, 1296–1303.

[18] Grubbström, R.W., 1998. A net present value approach to safety stocks in planned production. International Journal of Production Economics 56-57, 213–229.

[19] Candace, A.Y., Carlson, R.C., 2007. Interaction between frequency of rescheduling and the role of safety stock in material requirements planning systems. International Journal of Production Research (25), 221–232.

[20] Carlson, R.C., Candace, A.Y., 1986. Safety Stocks in MRP—Systems with Emergency Setups for Components. Management Science (32), 403–412.

[21] Persona, A., Battini, D., Manzini, R., Pareschi, A., 2007. Optimal safety stock levels of subassemblies and manufacturing components. International Journal of Production Economics 110 (1-2), 147–159.

[22] Hernández, K.E., Olivares-Benítez, E., Zuniga, C.A., 2015. Safety stock levels in modular product system using commonality and part families. IFAC-PapersOnLine 48 (3), 1387–1392.

[23] Kämpfer, T., Nyhuis, P., 2022. Logistische Ansätze zur Produktklassifizierung. WT Werkstatttechnik 112 (4), 227–231.

Biography

Alexander Wenzel, M.Sc. (*1992), studied industrial engineering with a focus on production and systems engineering at Technical University Braunschweig. Since 2020, he has been a research associate in production management at the Institute of Production Systems and Logistics (IFA) at the Leibniz University Hannover.

Lennart Hingst, M.Sc. (*1989) has been a research associate in the factory planning group at the Institute of Production Systems and Logistics (IFA) at the Leibniz University Hanover since 2019. He studied technical logistics at the University of Duisburg-Essen (M.Sc.) and has years of industry expertise.

Prof. Dr.-Ing. habil. Peter Nyhuis (*1957) studied mechanical engineering at Leibniz University Hannover and subsequently worked as a research assistant at the Institute of Production Systems and Logistics (IFA). After completing his doctorate in engineering, he received his habilitation before working as a manager in the field of supply chain management in the electronics and mechanical engineering industry. He is heading the IFA since 2003. In 2008 he became the managing partner of the IPH - Institut für Integrierte Produktion Hannover GmbH.

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Bridging Data Gaps In The Food Industry – Sensor-Equipped Metal Food Containers As An Enabler For Sustainability

Peter Burggräf[1, 2], Fabian Steinberg[1], Tobias Adlon[2], Philipp Nettesheim[1], Jan Salzwedel[2]
[1]*Chair for International Production Engineering and Management, University of Siegen, Siegener Straße 152, 57223 Kreuztal, Germany*
[2]*Laboratory for Machine Tools and Production Engineering (WZL), RWTH Aachen, Campus-Boulevard 30, 52074 Aachen, Germany*

Abstract

In recent years, Machine Learning (ML) applications for manufacturing have reached a high degree of maturity and can be considered a suitable tool for improving production performance. In addition, ML applications can be used in many other production areas to enhance sustainability within the manufacturing process. One area is storing and transporting bulk materials in metal Intermediate Bulk Containers (IBC). These IBCs are currently used solely for their primary purpose of storage and transportation of raw and finished goods. Hence, while in use, IBCs are often a black box, not providing additional value to manufacturers. Equipping IBCs with sensor technology can provide such value: new data can be generated along the entire supply chain and production processes, taking the sustainability of production to a new level. Within the research project smart.CONSERVE, we use this additional data, for example, to monitor the stored food's critical characteristics or to establish predictive maintenance for IBCs. Thus, storing produced goods in defective IBCs can be avoided, and wasting resources can be prevented. This publication describes how smart IBCs in the food industry can increase supply chain visibility and reduce food waste. To illustrate this, we present possible data-related use cases enabled by smart IBCs, provide insights into how these use cases can be transferred to other industries, and exemplify the many opportunities for manufacturers to develop new smart services and ML applications based on the collected data – and how this can support manufacturers in achieving higher levels of sustainability.

Keywords

Artificial Intelligence; Supply Chain; Sustainability; Smart Solutions; Smart Services; Machine Learning Applications

1. Introduction

In 2008, the global financial and economic crisis strongly impacted industries and supply chain. Despite the economy's recovery in the following years, manufacturing companies in the European Union are still under high competitive pressure [1]. In addition, new products are being launched onto the market with increasing frequency and product life cycles are becoming shorter. This further increases the market pressure on companies [2]. To remain competitive, they have to reduce their production costs [3]. Due to the crises in the food industry over the past decade, such as bovine spongiform encephalopathy, dioxin contamination, rotten meat, classical swine fever, and avian influenza, customers have become increasingly concerned with the quality, origin, and preservation of food [4,5]. Therefore, companies need to regain customers trust. Through a data-transparent supply chain, clients can accurately be informed about product-related information when purchasing food [6]. To gain customers' trust, food enterprises need to increase transparency along the supply chain, as trust is a crucial factor in the food industry [7].

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Nowadays, manufacturing industries face different challenges in the competitive environment – for example, the problems of scheduling and order release – i.e. caused by complex production processes –, inaccurate demand forecasting, and inefficient production. The economic activity of a manufacturing enterprise is to process, refine, and produce raw materials and semi-finished goods [8]. Since food-producing companies fulfill the mentioned factors, they can be considered to belong to the manufacturing industry [9]. We address these challenges in the BMLE-funded joint project "smart.CONSERVE - Smart Container Services for Food Industries". Afterwards the developed smart Intermediate Bulk Containers (IBCs) can be retransferred to other manufacturing branches – as a solution for more data-transparency and enabler for Machine Learning (ML) approaches to increase economic and ecological sustainability within the supply chain.

In recent years, ML applications have become a powerful tool for optimizing performance in various production areas [10]. For example, assisted by ML, decisions or suggestions can be made automatically. Moreover, ML can be used to optimize the scheduling and order release to provide load- and demand-oriented scheduling proposals for production [11]. Furthermore, ML algorithms have been developed for numerous use cases to improve demand forecasting. An example of the relevance of a versatile data basis is the research of [12], proved that the integration of weather forecast data can optimize the demand forecasting for beer. As numerous decisions within the supply chain depend on demand forecasting, more accurate demand forecasts with ML, based on a solid database, can not only decrease the logistic costs but also strengthen customer satisfaction [2,13,14]. Additionally, a suitable forecasting algorithm is an essential element for effective logistic management to maximize the utilization of trucks [1].

In summary, a high level of data availability is the basis for raising the sustainability of many processes connected to the supply chain, by providing smart services that give useful supply chain information based on product- and container-data. In the research project smart.CONSERVE, sensor technology to create data related to stainless steel food IBCs has already been developed but has not been applied in industrial practice, yet. Therefore, this paper aims to answer the following research questions:

- How can existing container fleets be retrofitted with the developed smart technology to provide a sufficient data basis for smart services and advanced ML applications, using various data sources, to increase sustainability in the (food) supply chain?
- How can retrofit scenarios for existing fleets of IBCs be designed without restricting the producer's ability to deliver reliably?
- What are possible ideas for smart services and ML applications to increase sustainability in the food industry by using data collected by smart IBCs?

The remaining parts of this article are structured as follows: section 2 briefly introduces the current use of IBCs for storing and transporting goods, the effects of increasing sustainability requirements, the lack of data, and the challenges for a smart solution in food industries. Section 3 gives an overview of ideas for smart services and ML applications to increase sustainability and reduce food wastage. Section 4 summarizes the technical solution developed in the research project smart.CONSERVE and describes scenarios and challenges for its implementation in existing container fleets. Section 5 offers a conclusion.

2. Initial Situation

The following chapter provides an overview of the initial situation regarding using IBCs within the supply chain and existing ML approaches to increase sustainability within the supply chain in food industries.

2.1 Machine Learning

As in other industries, ML approaches have been developed for the food industry to increase sustainability and competitiveness in various areas of the supply-chain. For example, ML is used to predict the harvest of the coming years [15]. This enables wholesalers to prepare for poor harvests early to gain an advantage over competitors. One approach for reducing food waste is to monitor the evolution of fruit quality in the supply chain after the fruit is harvested. Researchers have developed a method in which a digital twin of the fruit is created at the time of harvest and thermal imaging technologies with ML algorithms are used to monitor the quality of the fruit during storage using the digital twin [16]. In the food industry, ML algorithms are utilized in production planning to minimize overproduction, which often occurs due to process uncertainties that lead to larger production quantities being planned than actual customer demand. To improve production planning, which was previously based on the experience of operators, GARRE et al. developed algorithms that support production planning to minimize the delta and thus reduce the wastage of raw materials [17].

2.2 IBCs in Food Industries

In the industry, reusable IBCs play an essential role. They are suitable for many sectors to transport and store goods, such as beverages, foodstuff, chemicals, or hazardous goods [18]. To meet the diverse requirements, various types of IBCs exist, such as composite, plastic, foldable, heated, and metal IBCs. Because of hygiene, flavor stability, and other food-safety-related reasons, the most common IBC within the food industry is the stainless-steel IBC. For beverages and foodstuff, it is designed to meet the standards of hygiene and flavor stability, to protect the stored goods from being affected by other external factors (i.e. UV radiation) and guarantees the quality of beverages and foodstuffs during transport and storage. Depending on the goods, the IBC can be equipped with additional systems, such as heating or cooling systems [19].

Today, these IBCs are only used to transport and store product materials. There is no collection of product- and container-specific data via sensors in the spirit of a smart IBC. This is due to the strict micro-bacterial safety requirements of the food industry: To avoid product contamination, IBCs have to be completely sealed; hence, no sensor data can be transmitted from the inside via cables. On the other hand, the steel IBC shields the mobile signals to such an extent that direct transmission via mobile network is challenging. As a result, manufacturers have no real-time information about their IBCs and products after leaving the company's warehouse. Consequently, various issues along the supply chain have to be addressed manually by the involved partners, e.g., by phone or email. Following are some examples of these issues identified during guided qualitative interviews with several experts [20]:

- Where are the IBCs and which ones are ready for collection?
- What are the current stock levels of the customers?
- Does the container allow all product-specific storage conditions to be continuously met?

However, with increasing automation in production and logistics planning as well as end consumer demands for a transparent supply chain, the collection of product- and container-specific data are of great importance. The end consumer's need for transparency is underlined by the smart container eZaar, developed for at-home food storage, food stock monitoring, and food wastage prevention [21]. Another call for transparency lies in the fact that IBCs are reused several times. Therefore, IBC owners strive to achieve the highest possible utilization of containers to minimize fleet size and, thus, their capital commitment. However, IBCs are often not immediately reported to the supplier as empty and remain unused in warehouses instead of being reused.

Different from other industries, an essential factor in the food industry is the best-before-date of products, which may not be exceeded and, thus, influences production and warehouse planning [22]. Because of the perishable nature of food, the long lead times for food production, the seasonal variations in production and consumption, and the variability in product quality and yield, the food supply chain has an increased level of complexity [23]. To provide consumers with high-quality fresh products, the planning process for the availability of production capacity and material requirements, the production process, and the distribution planning process must be integrated to ensure on-time product availability [24].

Besides, the strive for ecological and economic sustainability in production is a priority for more and more enterprises [25]. This is motivated by both investor and customer expectations, as well as national and international legislation: In 2015, the Paris Agreement was completed, a treaty under international law with the goal of global climate protection. The adhering countries regularly derive new Nationally Determined Contributions (NDCs) to concretize these goals. [26] As a tool for their implementation, e.g., Germany has been using CO_2 pricing since 2021: This involves pricing CO_2 emissions induced to the use of fossil fuels via a national emissions trading system, currently at 25 euros per ton emitted. Until 2026, the fixed price will gradually rise to 65 euros per ton. After that, the volume of the allowances issued will be limited in line with climate targets, and an auction process will be introduced. [27] This primarily affects industry, which, in Germany, emits 3.5 times more CO_2 than private households [28]. Consequently, the German industry has great potential to reduce CO_2 emissions, but it also faces significant challenges in securing its profitability. The literature describes various starting points for initiating such transformations in production [29]. The highly price-sensitive food industry can address both issues using smart metal IBCs: container fleet sizes and food waste can be reduced. At the same time, transport routes and production processes can be optimized – thus, both economic and ecological benefits for manufacturers and customers can be realized.

To solve these problems, the enterprise Packwise developed a “smart cap” that can be mounted onto plastic IBCs. Through this smart cap, information about the location, fill level, and temperature will be collected, transferred via mobile network, and provided to users via a cloud application. This information can help to track the IBCs, reorder products, and guarantee the quality of the goods. For example, monitoring is required when transporting liquids sensitive to temperature- and pressure- fluctuations and vibrations.

In the research project smart.CONSERVE, this tracking solution for plastic IBCs has been applied to metal IBCs. Several challenges had to be addressed to allow this: Micro-bacterial safety is affected by sensors mounted on the inside of food IBCs; however, outside-mounted sensors can neither measure inside temperature and pressure nor can the steel surface be penetrated by radar to measure the fill level. Besides, mounting the smart cap on the inner side of the lid weakens the mobile signal and, thus, hinders the transfer of the data to the cloud application. The research consortium already elaborated a tracking system solution for metal IBCs to measure the mentioned product-related data [30]. To benefit from these results in industrial practice, metal IBCs have to be equipped with the necessary sensor technology – either involving the container manufacturers during production or by converting existing IBCs. Therefore, the paper outlines approaches and challenges for implementing this sensor technology in industrial practice.

3. Enabling Sustainability with Smart Containers

Smart IBCs can enhance resource usage and sustainability in the food industry, and provide manufacturing companies with the ability to remain competitive during shortages of raw materials and rising energy costs in Europe. As part of the research project, we conducted interviews with various supply chain stakeholders in order to identify innovative use cases. The following is a selection of ideas for smart services and ML applications enabled by container data collection for further research:

- Shelf life monitoring:

  Digital twins can track the product's best-before date in industries with perishable products. On the one hand, this allows customers to be warned in good time before the product's expiration date and to adjust the production schedule. On the other hand, it can also provide complete and secure proof of the shelf life of the ingredients used in production [31]. This way, supply chain partners can optimize resource use and increase end customers' confidence in product quality through traceability.

- Energy optimized storage:

  As described in many publications, the storage temperature significantly influences quality and shelf life [32]. The use of a digital twin combined with a temperature-based best-before profile offers companies the possibility to coordinate storage temperature and production schedule in such a way that the product is consumed strictly within the shelf life. This way, companies can optimize the energy used to cool the products and increase sustainability.

– Automated routing for container collection:

Tracking location, fill level, and shelf life makes it possible to automate the routing for collecting IBCs. There are two input factors for planning the IBCs to be collected. On the one hand, the expiration date can be used to anticipate how many IBCs can be collected on a given day due to an exceeded expiration date. On the other hand, fill level monitoring data (e.g., current fill level and current filling behavior) can be combined with historical data to calculate empty IBCs on a given day using ML. This data can be used with the location of the IBCs to determine the optimal route to pick up the IBCs on a given day using hybrid heuristic algorithms [33]. By improving the capacity utilization of the trucks and optimizing the pick-up route, a reduction in CO2 emissions can be achieved. In addition, the IBC fleet size can be reduced, so less IBCs must be produced and raw materials as well as energy for production can be saved.

– Optimized production planning:

Production planning is essential, regardless of the industry, to produce efficiently, meet customer needs at the right time and be competitive. One key factor in production planning is demand forecasting. For this reason, researchers have been working on optimizing demand forecasting and have developed various heuristic methods and ML algorithms. However, all of these methods rely on data from the supply chain, which is why companies have started to exchange data [34]. The introduction of the developed smart IBCs offers the possibility to implement these new data in ML-based forecasts. Overproduction and, thus, a waste of resources and capital commitment due to planning inaccuracies can be reduced.

Due to the versatile applications for stainless steel IBCs, most of these use cases can be transferred to other industries where IBCs are used to store and transport products (i. e., fluids and granulated substances).

4. Technical approach and practical implementation

In smart.CONSERVE, sensor technology, already used in many applications, has been applied for the first time in stainless steel IBCs, cf. [30]. For example, this involves a pressure sensor, thermometer, accelerometer, brightness sensor, and radar sensor, as well as RFID and GPS. These sensors and technologies allow early warnings in case of temperature- and pressure-related issues, identification of mishandling or improper use, fill-level and thus stock-level monitoring, automatic bookings in ERP systems, location tracking and hence automatic notification of deliveries, inventory tracking as well as route optimization. This technical solution has not been implemented in industrial practice, yet. However, its implementation is necessary to enable the data-related use cases described above.

To enable this implementation in industrial practice, we focused on the development of a concept to equip existing steel IBC fleets of food manufacturers with the developed sensor technologies. This can be part of the production of steel IBCs, which means that food manufacturers can chose between traditional IBCs and smart-enabled food containers. These smart-enabled containers can be used to build up new container management systems or to be embedded into existing ones.

However, qualitative guided expert interviews [20] conducted during the research project suggest that modifying existing steel IBCs and equipping them with smart sensor technology – referred to as “retrofitting” – is the more relevant case for industrial practice and will therefore be focused upon in this paper. Steel IBCs can easily be used for more than 30 years, and food manufacturers usually have a relatively large fleet of containers due to high turnaround times. For individual container fleets, the most feasible retrofitting approach is determined by how many containers are to be equipped with smart technology. Therefore, we explored different retrofitting volumes.

The exploration aimed to define intervals for possible container retrofitting volumes that do not negatively affect process stability and delivery reliability of food manufacturers. These intervals are based on scenarios derived from an ABC analysis on typical order volumes of food manufacturers' customers. This data was generated in the research project smart.CONSERVE. After a manual alignment of the data from different sources, data quality was sufficient to perform an ABC analysis. Based on the results of this analysis and the assumption of a container rotation period of three months per customer, five scenarios could be distinguished. The scenarios can feature full (one scenario) or partial retrofitting (four scenarios) of a container fleet. The partial retrofitting scenarios can be described according to the reference object: On the one hand, partial retrofitting can cover the orders of one or more specific customers ordering from one food manufacturer; on the other hand, partial retrofitting can cover one or more specific products or groups of products, e. g., products sharing one main ingredient. In our ABC analysis, we decided to focus on the "A" category of customers and/ or product orders, i. e., all customers or products needed to reach 80 per cent of the ordered quantity in one representative quarter. In this way, a significant share of customers or product orders can be covered by smart IBCs without the necessity to retrofit entire IBC fleets.

In scenario (1), all IBCs used for supplying one or a small number of customers of a typical food manufacturer are retrofitted. Necessary fleet sizes to cover a "A" customer (as identified in the previous analysis) range from 3,000 to 5,000 containers. To cover the largest customers, fleet sizes of up to 10,000 IBCs would be necessary. Similarly, scenario (2) focuses on the product perspective. To cover the typical "A" product orders from all customers, necessary smart IBC fleet sizes range from 1,500 to 7,000. To cover the most frequently ordered products, fleet sizes of up to 10,000 IBCs would be required. Scenario (3) represents a variation of scenario (2): Retrofitting is limited to the "A" products ordered by "A" customers, requiring the retrofitting of around 2,000 IBCs per "A" customer. In scenario (4), a single product for one "A" customer is chosen, and typically about 1,000 IBCs are equipped. Scenario (5) describes retrofitting an entire fleet of approximately 30,000 containers. Since the above quantities overlap, the described scenarios were synthesized into volume intervals for retrofitting (cf. Table 2). This synthesis was based on one specific finding of our research: If food manufacturers cannot equip their entire IBC fleet with smart technology, it can still be beneficial to either focus on a very specific product and customer, an "A" product and/ or customer, or on one of the three most important products or customers. In the following, the retrofitting process is described and the implications and characteristics of the different volume intervals are derived.

Table 1: Scenarios for retrofitting volumes based on an ABC analysis of customer orders

Scenario	**(1) by customers**	**(2) by products**	**(3) by "A" products**	**(4) one chosen "A" product**	**(5) entire fleet**
Number of retrofitted IBCs	Per "A" customer: 3,000 - 5,000 Total of Top 3 Customers: ~10,000	Per "A" product: 1,500 -7,000 Total of Top 3 Customers: ~10,000	Per "A" customer: ~2,000	Per "A" customer: ~1,000	~30,000

For retrofitting, it is necessary to modify the existing containers: The pre-assembled smart cap has to be mounted on the outer surface of the container lid, the internal sensors on the inner surface. For this purpose, a metal plate is welded to the top to create a flat surface for installing the smart cap. Hooks are welded to the bottom of the lid to hold the sensor package in place. After cooling, a holder for the smart cap is glued to the metal plate. The adhesive has to cure for 24 hours. Metal plates, hooks, and adhesive plates are prefabricated. Hence, in retrofitting, only the lids are modified; the IBCs themselves are not used in this process.

By analyzing typical food production processes during our research, it became evident that all food manufacturers using IBCs must clean and sterilize them before refilling. Usually, the IBCs and the lids are washed separately. This separation during the cleaning process offers easy access to the lids for retrofitting purposes. However, the quantity of available lids for retrofitting is limited by the container rotation period of three months and the characteristics of the washing process itself: as the lids can be washed faster than the IBCs, a possible source for the lids in the washing process is the buffer at the end of the washing line. Lids can be taken from this buffer, retrofitted, and returned to begin the washing process after around two days – due to the necessary curing times of the adhesive. However, only a limited volume of lids can be taken from this buffer without compromising the stability of the washing process and, thus, delivery reliability of a food manufacturer. Based on the conducted interviews with different food manufacturers, we assume this volume to be limited to ca. 50 lids per day. This results in different retrofitting times depending on the quantity category chosen from Table 2. As a result, either internal retrofitting in existing internal maintenance workshops or external retrofitting by a subcontractor or container manufacturer is most feasible. For a small number of containers, an internal retrofit can be carried out in short time. On the contrary, retrofitting 10,000 or more containers requires the contracting of an external company as well as changes to the washing process to increase the daily quantity of modifiable lids – to be able to realize the data-use-related advantages of smart IBCs in a reasonable time frame and to permit internal maintenance workshops to focus on their core tasks. However, these process changes are yet to be determined.

Table 2: Volume intervals for retrofitting

Number of retrofitted IBCs	**< 1,000**	**2000 - 5,000**	**8,000 - 12,000**	**30,000**
(Partly) attainable scenarios	4	(1), (2), 3, 4	1, 2, 3, 4	1, 2, 3, 4, 5
Time for internal retrofitting (days)	< 20	60 - 100	160 - 240	600
External retrofitting	No	No	Optional	Yes

But it is not only the number of removable container lids that is a challenge in the retrofit process. Further challenges in the retrofitting process arise from the different manhole closure types of the IBCs: screw-on lids and bayonet lids. During the filling process of IBCs with bayonet lids, a bell-shaped cover has to be lowered onto the lid for closure. Therefore, the available area for welding the supports for the smart cap and the internal sensors onto the bayonet lids is smaller compared to screw-on lids. This requires a more careful positioning of the supports and the smart cap and makes the retrofitting of bayonet lids more demanding and therefore even more time-consuming. In consequence, this reduces the number of retrofits per day and extends the conversion time of a fleet.

Similarly, not only the retrofitting of the container lids poses a challenge to the stability of the container cycle. Retrofitted containers also require adjustments to their washing process. Additional steps in the disassembly of the containers are the removal of the smart cap and internal sensor package. Extra cleaning is required for the sensor package. After washing, these disassembled parts must be reassembled. While adding new washing process steps is simple in a fully converted fleet, challenges for the washing process arise when it becomes necessary to implement two different washing process variants running in parallel. This can be the case during the retrofitting phase or if a food manufacturer chooses a partial retrofit of its IBC fleet. However, these challenges are not limited to differentiating between two types of containers: partial retrofitting also requires that the washing process allows for order-related washing and buffering at the end of the washing process within the limited space of existing washing facilities. In order to ensure the necessary process stability and thus delivery reliability with smart containers, it is therefore necessary to take into account an exact allocation of the smart containers to the orders in production planning.

Besides, the use of the collected data for food production processes is limited by the percentage of converted containers. Only if a significant part of the fleet is retrofitted, adjustments based on these data can be made in production and supply chain processes. Thus, developing dedicated retrofitting processes for different retrofitting volume intervals is crucial to enable data-related use cases of smart IBCs.

5. Conclusion

Smart metal IBCs have the potential to enable sustainability use cases and ML applications within the supply chain. This work gives some examples for smart services and ML applications enabled by smart metal IBCs. In the smart.CONSERVE research project, a technical solution has already been developed to create the necessary data: the smart cap and the networked sensor package. However, to enable the data-related use cases it is necessary to equip a sufficient number of IBCs with this technical solution. Therefore, the implementation of the developed technical solution in existing container fleets and a retrofit of IBCs is necessary. Our work describes various retrofit scenarios for existing container fleets. Furthermore, the paper highlights the long retrofit time of an entire container fleet as the key problem for enabling smart services and ML applications. It is critical to address this problem to increase sustainability and fill data gaps in the food industry. Therefore, further activities in the current research project will focus on developing a retrofit process in detail, implementing it in a pilot phase and validating the mentioned use cases for data utilization.

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References

[1] Hart, M., Tomastik, M., Heinzova, R., 2015. The methodology of demand forecasting system creation in an industrial company, in: 4th International Conference on Advanced Logistics and Transport (ICALT). IEEE, pp. 12–17.

[2] Afifi, A.A., 2020. Demand Forecasting of Short Life Cycle Products Using Data Mining Techniques, in: Maglogiannis, I., Iliadis, L., Pimenidis, E. (Eds.), Artificial Intelligence Applications and Innovations, vol. 583. Springer International Publishing, Cham, pp. 151–162.

[3] Cheng, Y.-H., Hai-Wei, L., Chen, Y.-S., 2006. Implementation of a Back-Propagation Neural Network for Demand Forecasting in a Supply Chain - A Practical Case Study, in: IEEE International Conference on Service Operations and Logistics, and Informatics. IEEE, pp. 1036–1041.

[4] Bastian, J., Zentes, J., 2013. Supply chain transparency as a key prerequisite for sustainable agri-food supply chain management. The International Review of Retail, Distribution and Consumer Research 23 (5), pp. 553–570.

[5] Turi, A., Goncalves, G., Mocan, M., 2014. Challenges and Competitiveness Indicators for the Sustainable Development of the Supply Chain in Food Industry. Procedia - Social and Behavioral Sciences 124, pp. 133–141.

[6] Wognum, P.M., Bremmers, H., Trienekens, J.H., van der Vorst, J.G., Bloemhof, J.M., 2011. Systems for sustainability and transparency of food supply chains – Current status and challenges. Advanced Engineering Informatics 25 (1), pp. 65–76.

[7] Astill, J., Dara, R.A., Campbell, M., Farber, J.M., Fraser, E.D., Sharif, S., Yada, R.Y., 2019. Transparency in food supply chains: A review of enabling technology solutions. Trends in Food Science & Technology 91, pp. 240–247.

[8] Pollert, A., Kirchner, B., Polzin, J.M., 2008. Duden - Wirtschaft von A bis Z: Grundlagenwissen für Schule und Studium, Beruf und Alltag, 3rd ed. Duden, Mannheim, Leipzig, Wien, Zürich.

[9] Huang, Y., Wang, L., Liang, S.Y. (Eds.), 2019. Handbook of manufacturing. World Scientific, New Jersey, London, Singapore, Beijing, Shanghai, Hongkong, Taipei, Chennai, Tokyo.

[10] Kumar, S., Gopi, T., Harikeerthana, N., Gupta, M.K., Gaur, V., Krolczyk, G.M., Wu, C., 2023. Machine learning techniques in additive manufacturing: a state of the art review on design, processes and production control. J Intell Manuf 34, pp. 21–55.

[11] Thorben Jensen, 2020. Artificial Intelligence: Use Cases for Industry. https://www.messe.de/apollo/hannover_messe_2020/obs/Binary/A1021863/Whitepaper%20Use%20Cases%20for%20Industry.pdf.

[12] Nikolopoulos, K., Fildes, R., 2013. Adjusting supply chain forecasts for short-term temperature estimates: a case study in a Brewing company. IMA Journal of Management Mathematics 24 (1), pp. 79–88.

[13] Mircetic, D., Nikolicic, S., Maslaric, M., Ralevic, N., Debelic, B., 2016. Development of S-ARIMA Model for Forecasting Demand in a Beverage Supply Chain. Open Engineering 6 (1), pp. 407–411.

[14] Zhu, X., Ninh, A., Zhao, H., Liu, Z., 2021. Demand Forecasting with Supply - Chain Information and Machine Learning: Evidence in the Pharmaceutical Industry. Prod Oper Manag 30 (9), pp. 3231 - 3252.

[15] Balducci, F., Impedovo, D., Pirlo, G., 2018. Machine Learning Applications on Agricultural Datasets for Smart Farm Enhancement. Machines 6 (3), pp. 38.

[16] Melesse, T.Y., Bollo, M., Di Pasquale, V., Centro, F., Riemma, S., 2022. Machine Learning-Based Digital Twin for Monitoring Fruit Quality Evolution. Procedia Computer Science 200, pp. 13–20.

[17] Garre, A., Ruiz, M.C., Hontoria, E., 2020. Application of Machine Learning to support production planning of a food industry in the context of waste generation under uncertainty. Operations Research Perspectives 7 (100147), pp. 1–8.

[18] Biganzoli, L., Rigamonti, L., Grosso, M., 2018. Intermediate Bulk Containers Re-use in the Circular Economy: An LCA Evaluation. Procedia CIRP 69, pp. 827–832.

[19] Saha, N.C., Ghosh, A.K., Garg, M., Sadhu, S.D., 2022. Food packaging: Materials, techniques and environmental issues. Springer, Singapore.

[20] Helfferich, C., 2019. Leitfaden- und Experteninterviews, in: Baur, N., Blasius, J. (Eds.), Handbuch Methoden der empirischen Sozialforschung, pp. 669–686.

[21] Pila, R., Rawat, S., Singhal, I.P., 2017. eZaar, the smart container, in: 2nd International Conference on Telecommunication and Networks - TEL-NET 2017. IEEE, pp. 1–5.

[22] Prusa, P., Chocholac, J., 2015. Demand Forecasting in Production Logistics of Food Industry. AMM 803, pp. 63–68.

[23] Krishnan, R., Yen, P., Agarwal, R., Arshinder, K., Bajada, C., 2021. Collaborative innovation and sustainability in the food supply chain - evidence from farmer producer organisations. Resources, Conservation and Recycling 168 (105253).

[24] Zhao, M.A., Setyawan, B., 2020. Sales Forecasting for Fresh Foods: A study in Indonesian FMCG, in: International Conference on Information Science and Communications Technologies (ICISCT). IEEE, pp. 1–9.

[25] Küpper, D., Kuhlmann, K., Pieper, C., Burchardt, J., Schlageter, J., 2020. The Green Factory of the Future, pp. 1–20.

[26] Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit (BMUB), 2015. Übereinkommen von Paris: Deutsche Übersetzung der Urschrift von 2015. UNFCCC. www.bmu.de/fileadmin/Daten_BMU/Download_PDF/Klimaschutz/paris_abkommen_bf.pdf. Accessed 16 March 2022.

[27] Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit (BMU), 2021. Klimaschutzbericht 2021. www.bmu.de/fileadmin/Daten_BMU/Download_PDF/Klimaschutz/klimaschutzbericht_2021_bf.pdf. Accessed 16 March 2022.

[28] Statistisches Bundesamt, 2019. Umweltökonomische Gesamtrechnungen: Direkte und indirekte CO2-Emissionen in Deutschland 2010-2015. https://www.destatis.de/DE/Themen/Gesellschaft-Umwelt/Umwelt/UGR/energiefluesse-emissionen/Publikationen/Downloads/co2-emissionen-pdf-5851305.html. Accessed 16 March 2022.

[29] Burggräf, P., Adlon, T., Salzwedel, J., Ebade Esfahani, M., Weiler, C., Paßlick, F., 2022. Green factories: Measures for a new direction – How the drive for enhanced sustainability is changing factory planning - part 2. wt Werkstattstechnik online 112 (05), pp. 348–353.

[30] Burggräf, P., Steinberg, F., Adlon, T., Nettesheim, P., Kahmann, H., Wu, L., 2023. Smart Containers -Enabler for More Sustainability in Food Industries?, in: Liewald, M., Verl, A., Bauernhansl, T., Möhring, H.-C. (Eds.), Production at the Leading Edge of Technology. Springer International Publishing, Cham, pp. 416–426.

[31] Bakalis, S., Gerogiorgis, D., Argyropoulos, D., Emmanoulidis, C., 2022. Food Industry 4.0: Opportunities for a digital future, in: , Food Engineering Innovations Across the Food Supply Chain. Elsevier, pp. 357–368.

[32] Perveen, K., 2011. Effect of temperature on shelf life, chemical and microbial properties of cream cheese. Afr. J. Biotechnol. 10 (74), pp. 16929–16936.

[33] Wang, Y., Zhang, S., Guan, X., Peng, S., Wang, H., Liu, Y., Xu, M., 2020. Collaborative multi-depot logistics network design with time window assignment. Expert Systems with Applications 140 (112910).

[34] Li, T., Zhang, H., 2015. Information sharing in a supply chain with a make-to-stock manufacturer. Omega 50, pp. 115–125.

Biography

Univ.-Prof. Dr.-Ing. Peter Burggräf (*1980) studied mechanical engineering in Aachen and London. He wrote his Ph.D. thesis in factory planning at the Laboratory for Machine Tools and Production Engineering, WZL of RWTH Aachen University. He is the scientific head of the Department of Factory Planning at the Laboratory of Machine Tools and Production Engineering WZL of RWTH Aachen University. He has been, since 2017, head of the Institute of International Production Engineering and Management (IPEM) at the University of Siegen, Germany.

Fabian Steinberg, M.Sc. (*1992), studied production engineering at the RWTH Aachen University, Germany. He is pursuing a Ph.D. with the Chair of International Production Engineering and Management (IPEM) at the University of Siegen, Germany, focusing on predicting missing parts for the assembly start in an engineer-to-order environment based on artificial intelligence. Since 2018, he has been working with the Chair IPEM, where, since 2022, he has been the Chief Engineer.

Tobias Adlon, M.Sc. (*1989), studied industrial engineering at RWTH Aachen University, Germany, and Imperial College London, UK. After working in two management consultancies and the manufacturing industry, in 2015, he joined the Chair of Production Systems at the Laboratory for Machine Tools and Production Engineering, WZL of RWTH Aachen University, as a research associate. Since 2020. he has been the Chief Engineer of the Factory Planning Department.

Philipp Nettesheim, M.Sc. (*1995), studied industrial engineering at the University of Siegen, Germany, and the University of Tulsa, US. He graduated from RWTH Aachen University, Germany, in 2020. Since 2020, he has been working as a research associate with the Chair for International Production Engineering and Management (IPEM) at the University of Siegen, where, since 2022, he has been a group leader. Since October 2020, he has been responsible for the joint project smart.CONSERVE.

Jan Salzwedel, M.Sc. (*1995), studied industrial engineering at RWTH Aachen, Germany, and business administration at Università degli Studi di Torino, Italy. Since 2021, he has worked as a research associate with the WZL of RWTH Aachen. His Ph.D. project focuses on characterizing, measuring, and improving resource efficiency and other ecological and economic sustainability KPIs in factory planning. Since May 2021, he has been responsible for the joint project smart.CONSERVE.

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A Fuzzy Inference System-Based Approach For Assessing Strategic Capabilities In Global Production Networks

Gwen Louis Steier[1], Kevin Gleich[1], Sina Peukert[1], Gisela Lanza[1]
[1]*wbk Institute of Production Science, Karlsruhe Institute of Technology (KIT), Kaiserstr. 12, 76131 Karlsruhe, Germany*

Abstract

Intangible factors, e.g. the availability of infrastructure at a production site, and implicit knowledge, have an essential influence on the decision-making in global production networks. However, the consideration of intangible factors and implicit knowledge, especially in planning the production network configuration and determining the production network strategy, is usually done implicitly or only based on qualitative and subjective estimations. This can cause biased decisions and miscalculations that make additional and expensive adaptions in the global production network necessary. In order to address this challenge, this paper develops a methodology based on fuzzy inference systems (FIS) to enable a more quantitative and objective consideration of strategic network capabilities influenced by intangible factors and implicit knowledge. For this, the strategic network capabilities are described by several criteria aggregated through one or multiple cascading fuzzy inference systems. The resulting metrics for strategic network capabilities as well as intangible factors are normalized and comparable. Transparency about strategic network capabilities allows a focused discussion about the strategic configuration of the production network. Moreover, the metrics can also be used in other quantitative approaches such as mathematical optimization. The proposed methodology is demonstrated with 70 intangible factors, six strategic network capabilities, and 21 sub-capabilities from academic literature. It can be shown that the developed methodology can map intangible factors and implicit knowledge in a very flexible and detailed manner by selecting and weighting the describing criteria within the FIS in order to quantify strategic network capabilities.

Keywords

Global Production; Production Network Configuration; Production Strategy; Fuzzy Inference System; Intangible Factors; Decision-Making

1. Introduction

Today, large corporations as well as medium-sized companies organize their value creation in globally distributed production sites. The drivers of this internationalization are labor cost advantages, access to resources and the development of new sales markets. The results are global production networks (GPNs) [1]. However, current disruptive events such as COVID-19 and related entry regulations, supply shortages for different materials, Ukraine war, energy crisis and political tensions resulting in decoupling scenarios show the complexity and vulnerability of such GPNs. In particular, recent years have shown that the frequency of such disruptive events is steadily increasing, making risk reduction, adaptability and resilience increasingly the key success factor [2]. At the same time, sustainability is also increasingly on the strategic agenda of companies. Both legal regulations and market requirements must be taken into account in the configuration of production networks. In addition to these requirements for sustainability and adaptability, network decisions are also subject to a variety of other overlapping strategic motives. Due to these elusive,

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manifold aspects, a clear alignment of the production network configuration to the production strategy is very difficult. Therefore, the goal of this approach is to develop a method that quantifies network strategic capabilities based on fuzzy inference systems (FIS) in order to create comparability and transparency regarding fit of production strategy and configuration.

2. Global Production Network Configuration And Corresponding Challenges

Global production networks are formally defined as globally distributed production sites that are interconnected via material and information flows [1]. A distinction is made between GPNs, also called international manufacturing networks, which consist of intra-company networks, and inter-company networks, also called supply chains [3]. This paper focuses purely on intra-company networks. The design of production networks is also referred to as network configuration. Here, network configuration involves decisions about network structure including global dispersion of plants, allocation of resources and products as well as the assignment of plant roles including capability building [1].

The goal of the network configuration is to design the network in such a way that it optimally matches the strategic goals of the company as well as its specific environment. This congruence is referred to as strategic fit [4]. As mentioned at the beginning, the strategic motives can be manifold and partly contrary to each other. Strategic motives or capabilities and their interrelationships have already been discussed extensively in the literature. For example, [5] derived the four international manufacturing capabilities *resources accessibility*, *thriftiness ability*, *manufacturing mobility* and *learning ability*. [4], in contrast, differentiates between production strategy and production network strategy. A detailed discussion of strategic capabilities and their interdependencies can be found in [6]. The strategic capabilities differ in terms of their evaluability. For example, capabilities such as access to cheap labor or market proximity are easy to value in monetary terms. Other capabilities, such as access to qualified personnel and reliability of infrastructure, on the other hand, are difficult to quantify [7,8].

This diversity and ambiguity of factors makes network configuration a highly complex management decision. [9] refers to these challenges as *detail complexity* and *hysteresis*. Detail complexity describes the number of influencing factors and strategic motives as well as the interactions between them. Hysteresis, on the other hand, describes the temporal discrepancy between the occurrence of a disruption and the adjustment of the network. Especially against the background of increasing volatility of the environment, short adaptation times are rapidly becoming a success factors [1]. This is counteracted by the rising complexity of details due to the increasing importance of intangible factors. Thus, the detail complexity makes the evaluation of network alternatives and fast decision making more difficult. For this purpose, decision support models are applied in network decision making. These help in structuring the decision problem and create transparency about decision alternatives. A large number of decision support models already exist in the literature. However, the detail complexity and hysteresis make it difficult to adequately model the decision situation [8]. Intangible factors, in particular, pose a major challenge and are therefore usually neglected, although they have a significant influence on the competitiveness in GPNs [7,10]. The following chapter is dedicated to a selection of decision support models and their handling of intangible factors.

3. State Of The Art

In the following chapter, the existing literature regarding the consideration of intangible factors in global production networks is reviewed and research gaps are identified. The found literature can be divided into two areas. The first area consists of more qualitative approaches like management frameworks that identify and describe intangible factors or evaluate intangible factors on a highly aggregated level. The second area contains more quantitative approaches that use intangible factors within multi-criteria decision-making methods as well as optimization or simulation models.

3.1 Qualitative Approaches For Identification Of Intangible Factors Within Production Strategy

The usage of intangible factors within the qualitative approaches varies from a solely identification of factors, e.g. [11], towards a detailed description of single factors by other criteria for performance evaluation, e.g. [12], or complex frameworks for strategy definition, e.g. [13].

[11] and [14] focus on the identification of different factors. [11] perform a literature review and identify 19 potential key factors for allocation and reallocation decisions in production networks. Similar to this, [14] identify 48 different tangible and intangible success factors as a starting point for further research. [15] and [16] identify and analyze different strategic factors for GPNs or reasons for a reallocation of production sites.

In contrast to the solely identification of various factors, [12] develop a framework to evaluate the supply chain performance based on quantitative and qualitative factors. Several approaches use a similar concept, by describing intangible factors through several other measures. They use fuzzy multi-attribute decision making (MADM) methods, such as fuzzy TOPSIS to evaluate a single plant location or a supplier and consider several intangible and tangible factors that are evaluated based on five to seven linguistic variables [17–19]. A more sophisticated use of intangible factors in strategic frameworks can be observed in [13] and [5]. Both focus on GPNs and the production strategy, respective the strategy fulfillment. They describe several network capabilities, competences or the network structure based intangible and tangible factors.

While reviewing the researched qualitative approaches it becomes apparent that one part of the approaches only identifies factors or develop a strategic framework based on the factors in a generic way. However, a systematic methodology to assess the single intangible factors is not developed, leaving the evaluation ultimately up to the subjective estimation of the expert. The other part of the reviewed qualitative approaches uses simple (fuzzy) MADM approaches to quantify the intangible factors, but they lack the complexity since only a few factors are selected. Moreover, they are not developed in a generic way but only for a specific use case, e.g. supplier evaluation. Furthermore, both sub-groups have in common that interdependencies between different factors are usually not considered in the evaluation of the factors or while developing the strategic frameworks.

3.2 Quantitative Approaches With Intangible Factors As Input

In the more quantitative approaches, quantified intangible factors often serve as input for an optimization or simulation model. Within the quantification are large differences and some approaches directly quantify intangible factors to integer-values [20–22]. Other approaches such as [23–25] define a methodology that is based on integer-values and does not consider any subjective estimation or implicit human knowledge. But since the focus of this work is to capture exactly them, these approaches are not considered any further.

[26] quantify intangible factors, such as staff qualification, directly in an optimization model as fuzzy numbers. In contrast, [27] evaluates the intangible factors, similar to the approaches in chapter 3.1, based on several factors and a survey with decision-makers. The evaluation serves as input for an optimization model for GPNs. A combination of [26] and [27] is presented by [28]. [28] use FIS to quantify intangible factors in a first stage. In a second stage, the resulting values are used in an optimization model. Other approaches use a self-developed system based on fuzzy logic to quantify risks and dependencies in GPNs [29] or use PROMETHEE to prioritize and evaluate different factors as input for a simulation model [30].

A detailed comparison of 46 qualitative and quantitative decision support models as well as their addressed objectives, influencing factors, and application areas in network configuration can be found in [8].

While reviewing the more quantitative approaches, it can be observed that they use mostly subjective estimations. Furthermore, the approaches are use-case specific and consider only selected intangible factors and thus usually lack the representation of interdependencies between factors. Therefore, the qualitative approaches do not represent the detail complexity that is inherent to the quantification of intangible factors and their consideration in decision making in GPN, see also [7,10].

3.3 Derivation Of Research Gap

In summary, both literature groups (chapter 3.1 & 3.2) are missing a generic and systematic methodology to quantify or evaluate intangible factors in a way that reduces the influence of subjective estimations and that can represent interdependencies between different intangible factors.

Therefore, especially against the background of the detail complexity mentioned at the beginning, a gap in the systematic and analytical consideration of intangible factors in decision-making becomes apparent [8]. This gap is also reflected in practice. Intangible factors are perceived as relevant for decision-making, but are often only included by gut feeling and managerial judgement due to their difficult assessment [7,10]. However, in order to cope with the detail complexity, new research approaches are required that systematize intangible factors, quantify them and make them comparable with quantitative factors.

Therefore, the approach in this paper addresses the research gap and develops a fuzzy inference-based evaluation methodology for intangible factors. FIS seems appropriate for this problem since they can aggregate qualitative and quantitative metrics as well as additional subjective estimation to one metric. Additionally, they can be combined easily with other FIS to cover interdependencies between factors and represent the inherent detail complexity of the topic.

This method can be applied and adapted for various use-cases and quantifies intangible factors in a less subjective way while considering human-decision knowledge. The generated values for the intangible factors can be used to create transparency and evaluate the strategic fit in production networks as well as in quantitative approaches such as optimization or simulation.

4. Methodology For Assessing Strategic Capabilities In Global Production Networks

To develop the approach for quantification of intangible factors in global production networks, at first the foundations of fuzzy logic are briefly presented (chapter 4.1). Afterwards, the structure of the complete model is presented (chapter 4.2) and the derivation of the causality diagrams is explained (chapter 4.3). Finally, the structure and the definition of the FIS are formulated (chapter 4.4).

4.1 Foundations Of Fuzzy Logic

In contrast to classical crisp sets und numbers, where an object is part of a set or not or a number is a fix value, fuzzy sets and numbers have continuous grades of membership. So, an object can be partially part of several sets or values. The degree of membership is defined by membership function, that can represent linguistic evaluations as "high" or "low". Transferred to intangible factors with no clear metrics, the evaluation of a strategic capability can be "high" or "low" or partially "high" and partially "low", which allows to represent subjective suggestions and uncertainty about the "real" value [31,32]. The most common forms of membership functions are triangular and trapezoid functions (see Figure 1) [31].

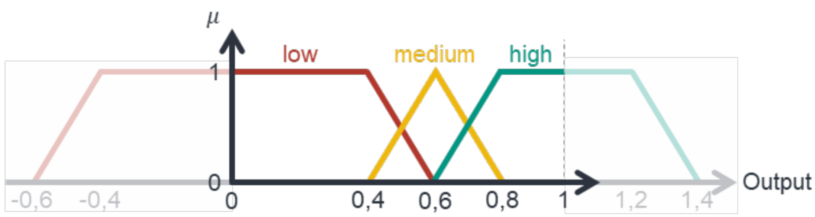

Figure 1: Standardized triangular and trapezoid membership functions for input and output variables

Analogously to classical crisp sets, the logic operations "and", "or", "not", respective "intersection", "union", "complement" can be defined also for fuzzy sets. For further reading see [32].

Based on fuzzy sets, FIS can be defined. A fuzzy rule base allows to map human knowledge whereas the fuzzification imitates human subjective decision making. Basically, they follow a three-step structure of fuzzification, rule-based inference, and defuzzification. In the fuzzification, the input variables, such as the distance to highways, and the output variables, e.g. availability of infrastructure, are selected and formulated as fuzzy numbers. Furthermore, the evaluation in form of linguistic terms, the scales, and the according membership functions are defined by human decision-makers (see Figure 1). In the next step, the decision rules are defined with if-then rules related to the input and output variables in the rule base, such as "if the distance to the next highway is low, the availability of infrastructure is high". These rules are a formal description of implicit expert knowledge by the decision-makers. In addition, the inference method, so how the logical operators within the rules are defined mathematically, is determined [33–35]. There are different possibilities, but the most common one is the max-min inference. In the defuzzification, the resulting fuzzy output of rules is converted into a crisp-value. This can be done by several methods, while the centroid-method is the most common one [36].

4.2 Structure Of The Model For Quantification Of Strategic Network Capabilities

Such FIS are used to quantify strategic capabilities and intangible factors in GPNs based on human knowledge. Figure 2 shows the structure of the model. The strategic capabilities (blue) are quantified based on the network configuration (green) and influencing factors (gray). Influencing factors come from external and internal company environment. External influencing factors are, e.g. wage costs and demand. Internal influencing factors come from the company, but cannot be influenced by the configuration, such as product properties. Some influencing factors (e.g. political stability) are rather general from macro-economic aspects (yellow). Here, indices from databases can be used as metrics. The other influencing factors must be evaluated on a company-specific basis (dark blue). Relevant aspects of the configuration are the geographical distribution or the specialization of production sites. With the help of FIS, the strategic capabilities per plant are quantified based on the influencing factors. These are aggregated to a network score using weighting keys.

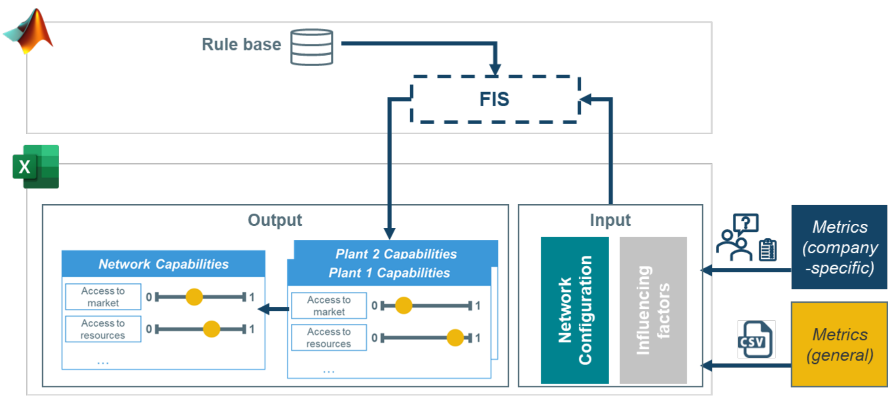

Figure 2: Structure of model for quantification of strategic capabilities in global production networks

4.3 Identification Of Causality Diagrams

Strategic capabilities are determined by a large number of influencing factors, some of which are interlinked in a highly complex manner [12]. But if more metrics are included in the quantification of strategic capabilities, the complexity increases, since in case of FIS, the number of rules increases significantly which makes it hard for human-decision makers to define a complete and consistent rule-base. Therefore, the different input factors that are relevant for the quantification are grouped additionally in different categories to gain causality diagrams for the intangible factors. In order to generate such structured causality diagrams, the method of networked thinking according to [37] was applied. A good size for these categories seems to be three to four factors per category. This aims to define clearly separated and relevant sub-measures for intangible factors. Each category as well as the evaluation of the strategic capability itself is represented by a FIS. So instead of defining one large rule-base, several smaller rule-bases for the categories are defined, which reduces the number of rules and simplifies the consistent and complete definition. An example for such a causality diagram is given by the sub-capabilities *access to cheap labor*, which is part of the strategic network capability *access to resources* in Figure 3. Here, GCR is the global competitiveness report by the world economic forum, which provides different indices for single nations [38].

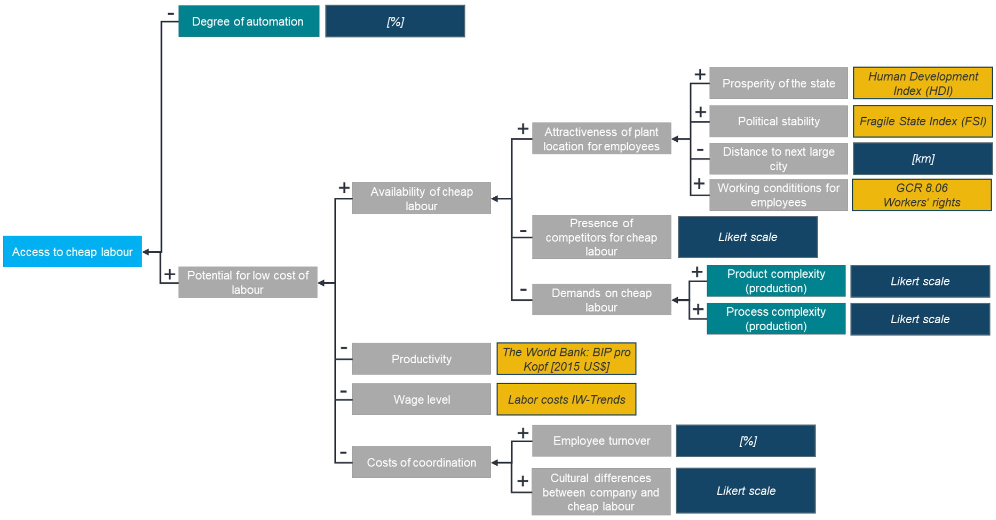

Figure 3: Exemplary causality diagram for the availability of infrastructure at a production site

4.4 Definition Of The Fuzzy Inference Systems

After defining the causality diagrams (see chapter 4.3), they can be transformed into FIS. For this, every category as well as the aggregation to an evaluation for the according intangible factor is modelled as a specific FIS. This allows a detailed representation of the identified causalities and the included human knowledge. To create these FIS the three steps of fuzzification, rule-base inference and defuzzification are performed. Since the selection of the input and output variables is already done, only the scales of them needs to be defined. Since some of the input criteria can be measured directly, such as distances, the scales are fixed. For other criteria that stem from external indices or reports, such as the GCR, or that are estimated directly by decision makers, e.g. product complexity, a standardized scale from 0 to 1 is used. Due to the flexibility of FIS, intangible input factors that can only be approximated with difficult effort can also be integrated as fuzzy variables, thus allowing a feasible application. This is done for example for the cultural distance between the company and cheap labor (see Figure 3). As it can be seen from the causality diagram in Figure 3, the scales of the input variables vary strongly. This is covered by the FIS since they only use the linguistic evaluation of the variables and so the different scales can be considered together in a quantitative way. Therefore, the definition of the membership functions and the linguistic terms is done directly by the decision-makers. However, for most of the input and output variables, standardized triangular and trapezoid functions (see Figure 1), that can be transformed to individual scales, are used in terms of simplicity and comparability. Furthermore, since for the quantification many input variables and criteria can be used, only a few membership functions and linguistic terms are used per FIS, to reduce the complexity of the rule bases. The standardized membership function for the input and output variables is defined on the interval [0;1] and can be adapted for individual variables if necessary (see Figure 1).

Based on the previously defined causality diagrams, for each FIS the rule-base is defined by decision-makers. In these rule-bases the implicit knowledge and the decision base of human decision-makers is modeled. While formulating the rules, it is important that they are as consistent as possible and that they cover all cases of possible input variables' values. Due to the causality diagrams (see chapter 4.3) and the fact that each category respective FIS only have a maximum of four input variables the rules can be formulated very intuitive since every input is fuzzified with intuitive linguistic terms ("high", "medium" and "low"). For sake of simplicity the max-min method is chosen for the inference. For the defuzzification, the centroid method is used. For a better interpretability of the defuzzied values, it is important, that they can assume all values on the interval [0;1], since there is no other metric for evaluating intangible factors. Therefore, the centroid of the memberships for "high" and "low" needs to be 1, respective 0 as depictured in Figure 4. This must be done for all intangible factors and the corresponding categories. The cascading FIS contains the implicit expert knowledge for the evaluation of intangible factors and creates comparability between these factors and production sites and networks, since subjective influences from individual decisions are minimized.

5. Application In The Strategic Network Performance Assessment

Using the approach presented in Chapter 4, a tool for evaluating the strategic capabilities of the network was implemented. The tool allows to evaluate the strategic capabilities of the network based on local tangible and intangible influencing factors as well as configurational network decisions using the presented fuzzy inference systems. In sum, the 6 capabilities *access to market, access to resources, learning capability, efficiency, sustainability* and *changeability* are considered. These in turn are fed from sub-capabilities, as explained in 4.3. The capabilities per plant are then aggregated to a network score using weighting keys. Capability-specific weighting keys are possible. For example, *access to market* is weighted by sales volume and *efficiency* by production volume. Figure 5 shows the dashboard of the tool in the Excel interface using fictive data for illustrative purpose.

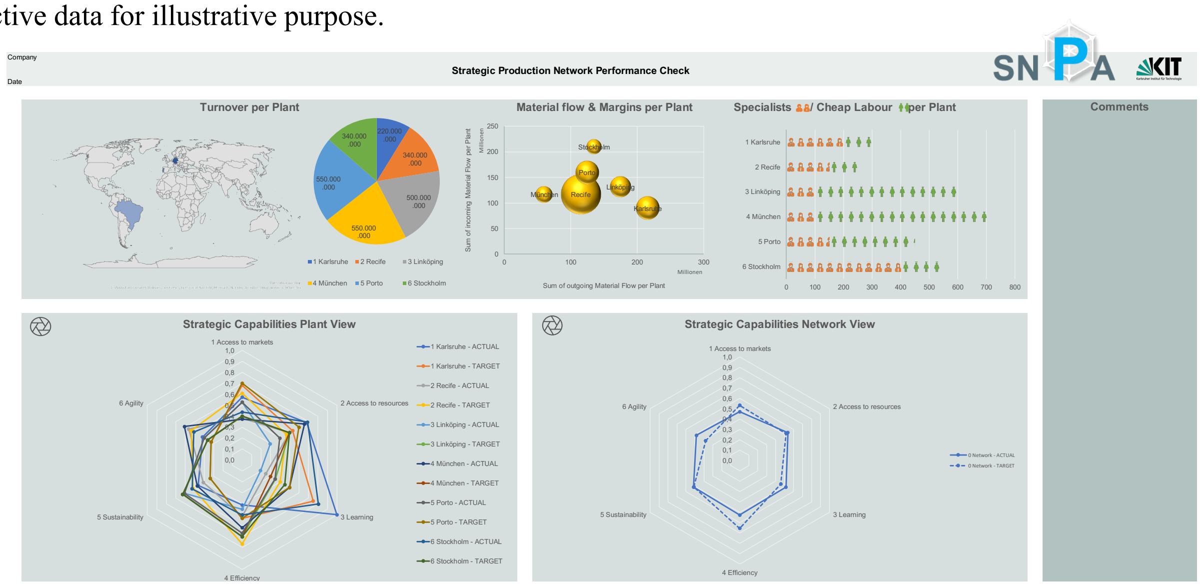

Figure 4: Dashboard of the Strategic Network Performance Assessment

The strategic capabilities per plant are shown on the bottom left, and the strategic capabilities of the network are shown on the right. In addition to the actual capabilities (solid lines), which are determined on the basis of the fuzzy inference system, a target capability (dashed lines) is also shown. The target is to be defined specifically for the company. The discussion of strategic differentiation factors according to [4] can promote the identification of strategic network targets. The direct comparison of target and actual strategic capabilities reveals strategic mis-fits. This enables a goal-oriented discussion of the strategic direction of the network and of potential action measures in the strategic network configuration. In addition to network targets, plant targets can also be defined, thus promoting a strategic focus through plant roles. Moreover, the tool displays further information such as sales and profit distribution. Number of employees and material flows are displayed, which support the manager in the strategic discourse.

6. Conclusion And Outlook

The strategic configuration of global production networks is a highly complex management decision. The multitude of influencing factors as well as their diversity, difficult comparability and mutual relationships influence the performance of the production network. Aligning the production network consistent with the production strategy, which is called strategic fit, requires transparency about these strategic capabilities. Previous approaches have so far insufficiently considered these mostly intangible strategic capabilities. Either models focus only on partial aspects and here especially costs or consider the strategic capabilities in a very aggregated way, so that the informative value and support for decision making remains low.

To this end, this paper presents an approach that quantifies strategic network capabilities based on influencing factors and network configuration. The 6 strategic capabilities are thereby composed of 21 sub-capabilities. The quantification is done via fuzzy inference systems, which in turn uses a rule base obtained by assessing causal relationships and leveraging implicit expert knowledge.

This approach has been implemented prototypically. The fuzzy inference systems have been implemented in MATLAB. MATLAB in turn interfaces with Excel to import the required input and export the quantified capabilities as output to be displayed in a dashboard. The visualization in a dashboard enables a focused discussion about strategic misfits in the network configuration. The input here includes company-specific variables collected in interviews, as well as macroeconomic indices from databases. In the next step, the tool will be applied in workshops with industry partners. The aim is on the one hand to validate the causal relationships found and on the other hand to evaluate the support potential in strategic network configuration.

The approach can be further developed with other methods from data science and artificial intelligence. For example, it would be conceivable to use preference learning to derive membership functions of the fuzzy variables [8]. A major challenge here is the data basis, as network decisions are often very complex and individual, making it difficult to generate a suitable data basis. Approaches with synthetic data could help here. Furthermore, individual strategic capabilities could be linked back to configuration variables and influencing factors in various analyses using e.g. structural equitation models.

Acknowledgements

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References

[1] Lanza, G., Ferdows, K., Kara, S., Mourtzis, D., Schuh, G., Váncza, J., Wang, L., Wiendahl, H.-P., 2019. Global production networks: Design and operation. CIRP Annals 68 (2), 823–841.

[2] Lanza, G., Schuh, G., Friedli, T., Verhaelen, B., Rodemann, N., Remling, D., 2020. Transformation globaler Produktionsnetzwerke. Zeitschrift für wirtschaftlichen Fabrikbetrieb 115 (4), 196–199.

[3] Rudberg, M., Olhager, J., 2003. Manufacturing networks and supply chains: an operations strategy perspective. Omega 31 (1), 29–39.

[4] Friedli, T., Mundt, A., Thomas, S., 2014. Strategic Management of Global Manufacturing Networks. Springer Berlin Heidelberg, Berlin, Heidelberg.

[5] Shi, Y., Gregory, M., 1998. International manufacturing networks-to develop global competitive capabilities. Journal of Operations Management 16 (2-3), 195–214.

[6] Netland, T.H., Frick, J., 2017. Trends in Manufacturing Strategies: A Longitudinal Investigation of the International Manufacturing Strategy Survey, in: , International Manufacturing Strategy in a Time of Great Flux. Springer, Cham, pp. 1–16.

[7] Kaiser, J., Steier, G.L., Seeger, T., Friedli, T., 1117. Entscheidungsfindung in der Gestaltung und Koordination von globalen Produktionsnetzwerken. Zeitschrift für wirtschaftlichen Fabrikbetrieb (9), 522–527.

[8] Steier, G.L., Benfer, M., Werz, P., Ziora, M., Lanza, G., 2022. Decision support models for strategic production network configuration – A systematic literature analysis.

[9] Ferdows, K., 2014. Relating the Firm's Global Production Network to Its Strategy, in: , International Operations Networks. Springer, London, pp. 1–11.

[10] Steier, G.L., Silbernagel, R., Maier, T., Peukert, S.K., Lanza, G., 2022. The Role of Intangible Influencing Factors in Strategic Network Decision-Making [in press], in: 29th EurOMA Conference, July 1 - 6, 2022. Book of Proceedings, Berlin, Deutschland, 01.07.2022 – 06.07.2022.

[11] Balbontin, C., Hensher, D.A., 2019. Firm-specific and location-specific drivers of business location and relocation decisions. Transport Reviews 39 (5), 569–588.

[12] Bhatnagar, R., Sohal, A.S., 2005. Supply chain competitiveness: measuring the impact of location factors, uncertainty and manufacturing practices. Technovation 25 (5), 443–456.

[13] Scherrer, M., Deflorin, P., 2017. Linking QFD and the manufacturing network strategy. International Journal of Operations & Production Management 37 (2), 226–255.

[14] Ng, H.S., Kee, D.M.H., 2012. Development of Intangible Factors for SME Success in a Developing Country. International Journal of Academic Research in Business and Social Sciences 2 (12), 198–213.

[15] Mishra, S., Singh, S.P., Johansen, J., Cheng, Y., Farooq, S., 2019. Evaluating indicators for international manufacturing network under circular economy. MD 57 (4), 811–839.

[16] Vanchan, V., Mulhall, R., Bryson, J., 2018. Repatriation or Reshoring of Manufacturing to the U.S. and UK: Dynamics and Global Production Networks or from Here to There and Back Again. Growth and Change 49 (1), 97–121.

[17] Awasthi, A., Chauhan, S.S., Goyal, S.K., 2010. A fuzzy multicriteria approach for evaluating environmental performance of suppliers. International Journal of Production Economics 126 (2), 370–378.

[18] Chu, T.-C., 2002. Selecting Plant Location via a Fuzzy TOPSIS Approach. The International Journal of Advanced Manufacturing Technology 20 (11), 859–864.

[19] Govindan, K., Khodaverdi, R., Jafarian, A., 2013. A fuzzy multi criteria approach for measuring sustainability performance of a supplier based on triple bottom line approach. Journal of Cleaner Production 47, 345–354.

[20] Becker, A., Stolletz, R., Stäblein, T., 2017. Strategic ramp-up planning in automotive production networks. International Journal of Production Research 55 (1), 59–78.

[21] Bihlmaier, R., Koberstein, A., Obst, R., 2009. Modeling and optimizing of strategic and tactical production planning in the automotive industry under uncertainty. OR Spectrum 31 (2), 311–336.

[22] Hochdörffer, J., Klenk, F., Fusen, T., Häfner, B., Lanza, G., 2021. Approach for integrated product variant allocation and configuration adaption of global production networks featuring post-optimality analysis. International Journal of Production Research, 1–25.

[23] Brintrup, A., Puchkova, A., 2018. Multi-objective optimisation of reliable product-plant network configuration. Applied network science 3 (1), 1.

[24] Moser, R., 2014. Strategische Planung globaler Produktionsnetzwerke: Bestimmung von Wandlungsbedarf und Wandlungszeitpunkt mittels multikriterieller Optimierung. Zugl.: Karlsruhe, Karlsruhe Inst. für Technologie, Diss., 2014. Shaker, Aachen, XII, 139, XX S.

[25] Paquet, M., Martel, A., Montreuil, B., 2008. A manufacturing network design model based on processor and worker capabilities. International Journal of Production Research 46 (7), 2009–2030.

[26] Ozgen, D., Gulsun, B., 2014. Combining possibilistic linear programming and fuzzy AHP for solving the multi-objective capacitated multi-facility location problem. Information Sciences 268, 185–201.

[27] Prinz, A., 2016. Mathematische Modellierung zur Optimierung der Wertschöpfungsverteilung nach quantitativen und qualitativen Kriterien in Produktionsnetzwerken der diskreten Fertigung. Dissertation. Universität Stuttgart.

[28] Sadic, S., Sousa, J.P. de, Crispim, J.A., 2018. A two-phase MILP approach to integrate order, customer and manufacturer characteristics into Dynamic Manufacturing Network formation and operational planning. Expert Systems with Applications 96, 462–478.

[29] Niknejad, A., Petrovic, D., 2016. A fuzzy dynamic Inoperability Input–output Model for strategic risk management in Global Production Networks. International Journal of Production Economics 179, 44–58.

[30] Ude, J., 2010. Entscheidungsunterstützung für die Konfiguration globaler Wertschöpfungsnetzwerke: Ein Bewertungsansatz unter Berücksichtigung multikriterieller Zielsysteme, Dynamik und Unsicherheit. Zugl.: Karlsruhe, Karlsruher Institut für Technologie, Diss., 2010. Shaker; Wbk Inst. für Produktionstechnik, Aachen, Karlsruhe, III, 154, XXXIII S.

[31] Klir, G.J., Yuan, B., 1995. Fuzzy sets and fuzzy logic: Theory and applications. Prentice Hall PTR, Upper Saddle River, New Jersey, 574 pp.

[32] Zadeh, L.A., 1965. Fuzzy sets. Information and Control 8 (3), 338–353.

[33] Deb, S.K., Bhattacharyya, B., 2005. Fuzzy decision support system for manufacturing facilities layout planning. Decision Support Systems 40 (2), 305–314.

[34] Frank, H., 2002. Fuzzy Methoden in der Wirtschaftsmathematik: Eine Einführung, 1. Aufl. ed. Vieweg, Braunschweig, Wiesbaden, 241 pp.

[35] Mamdani, E.H., 1976. Advances in the linguistic synthesis of fuzzy controllers. International Journal of Man-Machine Studies 8 (6), 669–678.

[36] Tanaka, Y., 1993. An overview of fuzzy logic, in: Proceedings of WESCON '93. WESCON '93, San Francisco, CA, USA. 28-30 Sept. 1993. IEEE, pp. 446–450.

[37] Gomez, P., Probst, G.J.B., 1995. Die Praxis des ganzheitlichen Problemlösens: Vernetzt denken, unternehmerisch handeln, persönlich überzeugen. Haupt, Bern, Stuttgart, 301 pp.

[38] Schwab, K., 2019. The Global Competitiveness Report 2019. World Economic Forum. https://www.weforum.org/reports/global-competitiveness-report-2019. Accessed 24 March 2022.

Biography

Gwen Louis Steier, M.Sc. studied industrial engineering at the TU Darmstadt and the Karlsruhe Institute of Technology (KIT). He is a research associate at the wbk Institute of Production Science of KIT in the department of Production Systems with a focus on Global Production Strategies.

Kevin Gleich, M.Sc. studied industrial engineering at the Karlsruhe Institute of Technology (KIT). He is a research associate at the wbk Institute of Production Science of KIT in the department of Production Systems with a focus on Global Production Strategies.

Dr.-Ing. **Sina Peukert** did her PhD at the Institute of Production Science in the field of robustness enhancement in production networks. Since 2020, she leads the research group Global Production Strategies.

Prof. Dr.-Ing. **Gisela Lanza** studied industrial engineering at the Karlsruhe Institute of Technology (KIT) and held the first shared professorship "Global Production Engineering and Quality" at KIT in cooperation with Daimler AG. Ms. Since 2003, she has been head of the Production Systems Department at the wbk Institute of Production Science of KIT.

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Approach For Data-Based Optimization In Cell Finishing of Battery Production

Achim Kampker[1], Heiner Hans Heimes[1], Benjamin Dorn[1], Sarah Wennemar[1]
[1]*Chair of Production Engineering for E-Mobility Components, Aachen, Germany*

Abstract

Due to the global warming, a significant reduction in the emission of greenhouse gases is necessary. One part of the solution is the electrification of today's transportation and traffic sector. An essential component of today's electric vehicles is the lithium-ion battery (LIB), which is largely responsible for their range, performance and cost. In order to increase the use of such climate-friendly technologies, it is therefore essential to reduce the production costs of LIBs. With a duration of up to three weeks, the process steps of formation and aging are particularly capital-intensive and have high demands on storage capacities. Formation and aging therefore account for up to 30% of the manufacturing costs for battery cells. During formation, the solid electrolyte interphase (SEI) is formed, which has a major influence on the quality and lifetime of the LIB, among other things. In order to reduce production costs and simultaneously increase battery cell quality, it is therefore necessary to optimize the formation and aging process. Because of the complexity and the interdependency of these processes towards previous process parameters the application of machine learning algorithm is predestined to optimize these process steps. For this purpose, a general approach for the application of a machine learning algorithm in the formation and aging are first analysed and relevant parameters from the literature as well as reasonable assumptions about the structure are derived. Based on these requirements and boundary conditions a machine learning algorithm structure will be developed to optimize the cell finishing process in the battery cell production.

Keywords

Battery Cell Production; Data-based Optimization; Cell Finishing; Electromobility; Industry 4.0;

1. Introduction and motivation

The conversion of the energy supply to renewable energies and the increasing demand for electric vehicles are leading to a rapidly growing need for high-performance storage technologies. In this context, the lithium-ion battery (LIB) has established itself as a key technology in recent years. So far, the higher manufacturing costs, lower energy and power density, and safety concerns compared to the internal combustion engine limit the widespread use of this technology. The battery accounts for the largest share of the total costs of an electric vehicle, which in turn is partially related to the battery cell production [1]. Optimizing the battery cell production process plays a key role in reducing costs since it is related to almost 20 % of the total production costs [2,3]. Manufacturers are currently attempting to reduce production costs through economies of scale, automation and digitization of production. One of the highest costs shares is created in the cell finishing with 25-30 % of the total production costs [4,5]. The process in the cell finishing are the wetting, formation, degassing and End-of-Line (EoL)-Test as shown in Figure 1.

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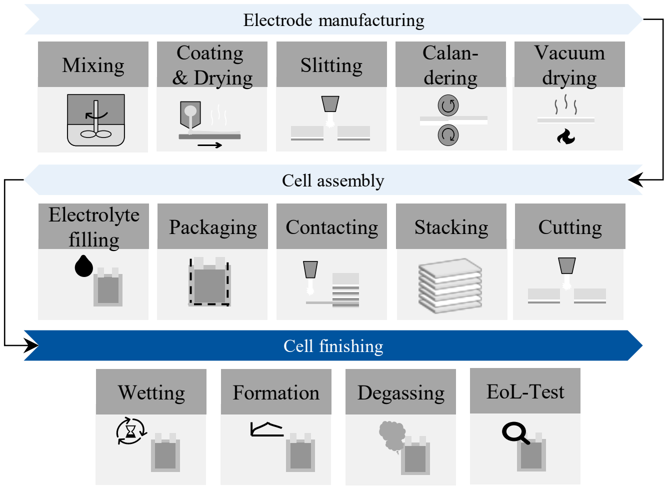

Figure 1: Battery cell production process for a pouch cell

The wetting process is a storage phase in which the optimal wetting degree with the infiltrated electrolyte should be achieved. This can take several hours. The formation process is defined as the first charging and discharging cycle(s). This process step is characterized by very long process times up to several hours due to the formation process of the solid electrolyte interface (SEI) layer on the anode surface during the first cycles [4,6,7]. To remove the gases that have been produced in the formation, cells are degassed. Followed by a long aging step (part of the EoL-Test) which takes for larger cells up to 3 weeks and is mainly there for the quality control of the production process and especially the formation process [6]. There the self-discharging of the cells is measured. Due to other internal balancing reactions (after formation) to attain an electrochemical equilibrium, the self-discharge can only be measured correctly after a few weeks.

The SEI is an essential component of the LIB including the impact on its initial capacity loss, self-discharge characteristics, rate capability, and safety [8]. The initial SEI creation and its growth are dependent on multiple factors e.g. anode material, electrolyte, and previous process parameters [8]. Beside those factors there are also different factors in the formation process that influence the SEI layer, e.g. the formation protocol, temperature, pressure, wetting degree [9,6]. Therefore, process control and optimization are difficult to conduct due to the high complexity, strong dependency of previous production parameters and sensitivity to the process. There is no standardization regarding an optimal formation protocol. Every cell manufacturer is setting up a functional protocol and process order to fit their individual requirements. To reduce the time identifying a suitable cell finishing protocol or to be able to predict the quality earlier in the production process, research approaches are invested regarding the application of machine learning algorithm to solve those challenges. [10]

2. Technical background

A few machine learning applications and approaches do exist that deal with process optimization for a complex process system with interlinked product-quality relation in the battery cell production. These approaches mainly focus on other production processes than cell finishing. THIEDE ET AL. (2020) [11] have investigated the influence of process parameters on energy consumption of the coating plant in electrode production without considering the effect on the cell quality. CUNHA ET AL. (2020) [12] investigated the relationships between final electrode properties and production parameters of the slurry. In this study several trends between the electrode properties and the independent variables could be found. DUQUESNOY ET AL. (2020) [13] designed a hybrid model based on experiments and physics-based models together with Machine Learning (ML) approaches to determine the influence of production parameters on final electrode properties.

In regard of quality prediction, TURETSKYY ET AL. (2021) [14] developed a model for deriving necessary interim product features (IPFs) to achieve desired final product properties (FPPs). A total of 191 battery cells from the entire process chain except formation and aging were used as data for the predictive model. SCHNELL ET AL. (2019) [15] used and compared ML models to predict cell quality and identify quality parameters. STOCK ET AL. (2022) [16] analysed two algorithms regarding the ability to predict quality and cluster cells based on the results already in the cell production process.
As previously stated, the cell finishing, especially the formation and aging, have only been insufficiently researched in terms of their potential in machine learning based optimization. One challenge in the data-based optimization is the high dependency of the cell finishing on multiple factors and properties. To reduce the complexity of this, three main clusters have been identified and are introduced in the following.

2.1 Material and design properties

In SHIN ET AL. (2020) [17] differences between the SEI formation, compositions and challenges in a graphite vs. Silicon containing Si/graphite anode are analysed. It was shown that the SEI and the optimal formation parameters are highly dependent on the used anode material and their properties. In Li et al. (2017) [18] the impact of different electrolyte additives on the formation and the SEI quality have been studied. It was shown that the additives not only have an impact on the SEI layer composition but also should be considered for the development of the formation parameters. In GÜNTER ET AL. (2020) [19] the impact of the cell format on the electrolyte filling and wetting process have been analysed. The results are stressing out that the electrolyte filling and wetting process as a preparation for the formation process has to be designed based on the individual cell design and format. Since the structural design and later the electrochemical reactions are dependent on the used materials, format and design, the cell finishing parameters and the detection of the quality has to be adapted to every material combination in the cell.

2.2 Process parameters before cell finishing

In LIU ET AL. (2017) [20] the porosity and film thickness of both electrodes are related to the achievable specific energy density and the capacity loss in the formation. The results show that, in general, cells with increased porosity have also a higher capacity. Increasing the porosity can improve the conductivity and diffusivity of lithium ions through the electrode. However, an optimum porosity cannot be derived because the formation of the solid electrolyte interphase also varies with varying porosity within the electrode. GÜNTER ET AL. (2019) [21] investigate the relationship between the amount of electrolyte and the maximum current rate during formation. The results show that there is no change in the increase in current rate above a ratio of 1.2 between electrolyte quantity and pore volume. Overall, it can be said that previous process parameters, e.g. the electrode manufacturing steps and the electrolyte filling, have an impact on the optimal process parameters.

2.3 Process parameters in the cell finishing

In the approach of XU ET AL. (2019) [22], an optimal multistage charging protocol for lithium-ion batteries is developed for an LFP (Lithium iron phosphate) cell using an electrochemical and thermal model. In the model, the relationships of the capacity drop due to the increase in solid electrolyte interphase (SEI) are to be minimized, the SEI potential maximized to reduce lithium plating, and the temperature rise reduced to avoid thermal runaway. The model result shows that the optimized charging current profile varies with state of charge (SOC) and cycle number. In the approach of DREES ET AL. (2021) [23] an electrode equivalent circuit model is introduced to reduce the process time of the formation time. The model optimises the charging profile of the cell by predicting the electrode voltages. In HEIMES ET AL. (2022) [6] it was shown that pressure and temperature during the formation can decrease the formation time. Different approaches already exist to develop an optimal process parameter setting in the formation, which however are limited to the local optimization and cannot or only to limited extent integrate previous process parameters and properties in their optimization.

2.4 Research gap

There is a significant gap in terms of an universal approach for the identification of the ideal process parameter in the cell finishing or for the early quality prediction in the cell finishing due to various reaction taking place after the formation. In the next chapter, a framework is presented to describe an approach how to develop a data-based optimisation model in the cell finishing.

3. Approach and methodology

The standard process for the application of Machine Learning is the Cross Industry Standard Process for Data Mining (CRISP-DM). This approach contains six steps: Business understanding, data understanding, data preparation, modelling, evaluation and deployment. The approach was chosen because the step monitoring is not included in the CRISP-DM approach and also not considered in this paper instead e.g. the CRISP-ML or the approach of AMERSHI ET AL. (2019) [24]. [25],[26]

3.1 Business and data understanding

The first two steps, business understanding and data understanding, are closely linked and are therefore combined in the CRISP-DM process. Here, economic or research-oriented goals are derived and translated into machine learning-specific goals. In the cell finishing there are two main challenges in terms of production optimization:

- Standardized parameter definition for an optimal cell finishing process with minimum process times while maintaining or even increasing the cell quality.
- Quality prediction before or directly after the formation process for a reduction or even elimination of the EoL-Test, especially the aging process.

Both approaches could reduce the cell cost about 7 % for the optimal process parameters and 4 % for the quality prediction [4]. In Figure 2 the basic concept of the two mentioned use cases in the cell finishing are presented. In general there are roughly around 2,100 product process relation in the battery production [27].

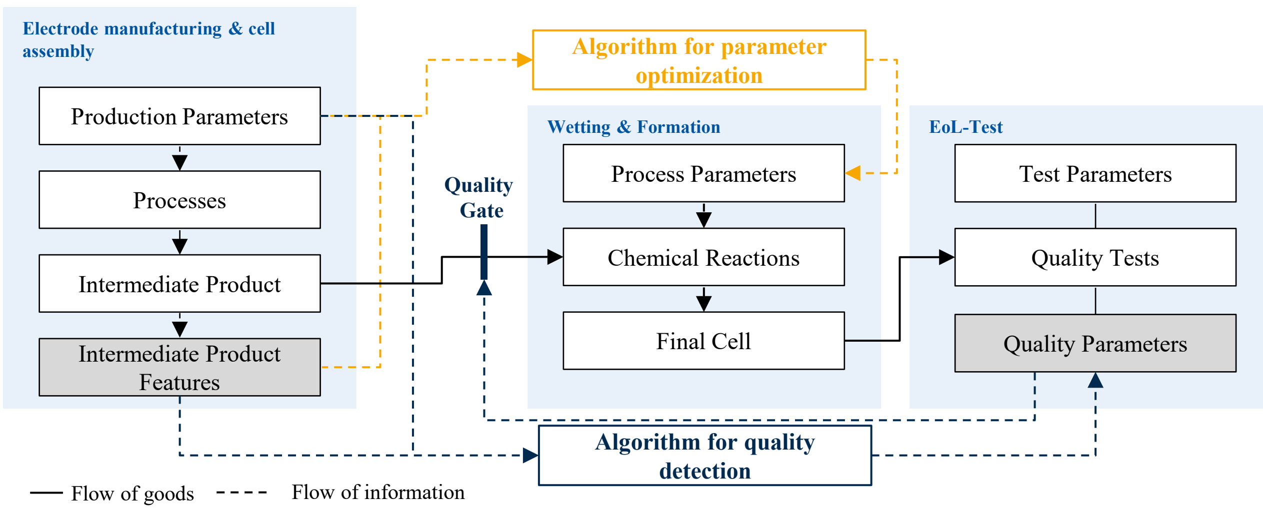

Figure 2: Overview of the main optimization use cases in the cell finishing

But the measurable process, material and intermediate product feature do not have the same impact on the cell finishing. The mixing, coating, drying and calendaring are the main steps to create the electrode structure and are therefore critical for the reaction mechanism in the battery cell, e.g. diffusion processes and de-/intercalation processes [8],[20]. The electrolyte filling has also a high impact on the wetting time and formation results [21],[19]. The vacuum drying, stacking and contacting process have a medium impact on the cell finishing. The slitting and cutting processes only have a limited effect on the cell finishing. Therefore, the data points for the use case has to be selected.

3.2 Data preparation

The business and data understanding are followed by data preparation. In this process, data is selected, cleaned and standardized. Data that does not meet the required quality are removed during this process. Also, only input variables that have an influence on the modelling are selected. In the cleaning process, missing values are determined by, for example, interpolation or the average, and distortions are removed. In the so-called feature engineering, new variables (features) can be derived from the already existing ones. Features are divided into predictors and output factors. While predictors provide the input for the machine learning algorithms, the output is predicted by the algorithm.

3.3 Modelling, evaluation and deployment

Most machine learning algorithms can process a high number of predictors. However, most algorithms are single output algorithm and can only predict one output. For both approaches in the cell finishing, the process optimization and the quality prediction, algorithm which predict multiple targets simultaneously are necessary. There are different approaches for multi target algorithm as shown in Figure 3. In general, the approaches can be clustered into two groups: Problem transformation and algorithm adaption. The approach of the problem transformation is to reduce the problem into single output problems and solve them individually. In the algorithm adaption, single output algorithms are adapted and modified to solve a multi output problem. Those kinds of algorithm are more difficult to develop but can also consider interdependencies between the output variables. [28]

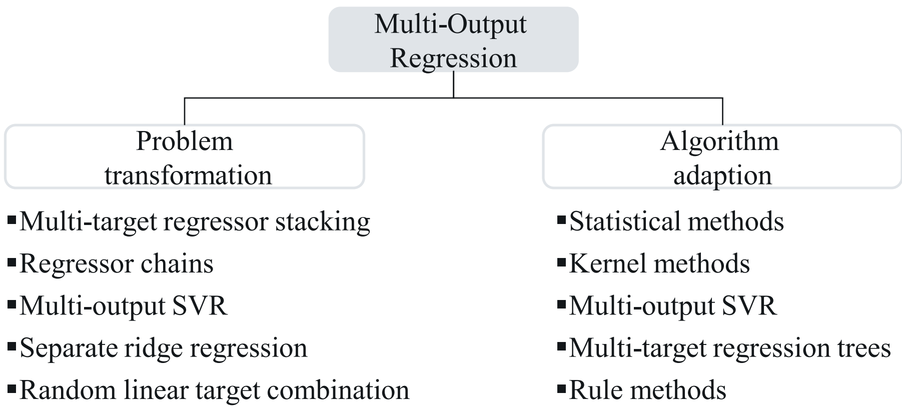

Figure 3: Overview of multi-output regression methods [28]

For the optimal process parameter development, there is a strong interdependency between the output parameter. Therefore, the algorithm adaption approach is favoured. For the quality prediction both approaches could be used. Based on the selected use case an algorithm has to be selected, modified and trained. The resulting model is assessed in the subsequent evaluation and compared with the defined success criteria. If the model does not meet the criteria, the previous steps are run through again. In machine learning, this usually involves going back as far as the modelling stage, and more rarely also the data preparation stage. If the algorithm covers the defined target, then it is transferred into practice.

4. Case study: Cell finishing

Business and data understanding: To address one of the two main challenges in the cell finishing EL-cells in a three-electrode setup were manufactured in the pilot line at the PEM. The cell configuration is listed in Table 1. The goal of the case study was to predict the cell quality based on variable process parameters. Due to the limited amount of data, the number of variables has been primarily reduced to four variables in the cell finishing. The electrode manufacturing and the selected variables for this test series have been the electrolyte amount, wetting time, formation temperature and C-rate during the charging of the cell. The formation protocol was a constant current-charging phase until 4.2 V and a constant charging-constant and voltage-discharging until 3.0 V. In total 57 data points have been generated with four variable production parameters. The range of the varied process parameters have been listed in Table 2.

Table 1: Cell configuration of the manufactured cells

	Positive electrode	Negative electrode
Active material	NMC 622	SMG-A5
Areal capacity	2.37 mAh/cm²	2.70 mAh/cm²
Loading density	14.4 mg/cm²	8.8 mg/cm²
Thickness	117 µm	133 µm
Current collector material	Aluminium	Copper
Separator	20 µm Celgard 2320	
Electrolyte	1.0M LiPF6 in EC:DMC (1:1)	

Table 2: Overview of the process parameter variation range

Process parameter	Electrolyte amount [µl]	Wetting temperature [°C]	Formation temperature [°C]	C-Rate during the charging in formation [C]
Range	50 – 100	20 – 40	20 – 50	1/20 – 1

For the quality parameter that should be predicted with the machine learning algorithm, the quality parameter of the SEI layer that develop during the first cycles are an important factor. The quality of the SEI layer can not be measured only by one quality parameter. It is related to numerous factors, e.g. initial capacity loss, self-discharge characteristics, cycle life [8]. To reduce the complexity for this study, the output variable of the algorithm is reduced to the capacity after the first full cycle.

Data preparation:

Outliers were identified and removed. For the data preparation, non-numerical attributes are converted to numerical attributes. Based on the assumption that the data are approximately Gaussian distributed, the dataset was converted into a standard normal distribution with mean value of 0 and standard deviation of 1. The quality target is transformed by Min-Max normalization to a range between 0-1. After the data preparation there were 18 observations with four features and one quality target.

Modelling, evaluation and deployment:

For the modelling the support vector regression (SVR) algorithm was selected since this algorithm also showed good results for small samples sizes compared to other algorithms [29]. The aim of SVR is the identification of a ε-intensive function. In this context, ε refers to a threshold, and the data points that fall within the ε band are considered to be accurately predicted, while those outside the ε band are not included in the fitting of the regression. The support vectors are data points with residuals greater than the threshold, and they determine the regression line. The function for the linear SVR model is given in equation 1. [30]

$$f(\boldsymbol{x}, w) = \sum_{j=1}^{m} w_j g_j(\boldsymbol{x}) + b \qquad (1)$$

x: multi-dimensional input data points

w: weights for each transformation

b: constant term

g_j (·): a set of non-linear transformation

The loss function $L(y, f(\mathbf{x}, w))$, which quantifies the error cost and is 0 for all points inside of the ε-intensive function band, is defined as seen in equation 2 [30]:

$$L(y, f(\boldsymbol{x}, w)) = \begin{cases} 0 & 0, \text{ if } |y - f(\boldsymbol{x}, w)| \leq \varepsilon, \\ |y - f(\boldsymbol{x}, w)| - \varepsilon & \text{otherwise} \end{cases} \qquad (2)$$

For the training of the model 13 data points are used and five data points are used for the evaluation. This data set is split into a training set (80 % of the data) and a test set (20 % of the data). After a first cross validation hyper-tuning of specific parameters are conducted with the grid search approach. For the SVR there are five parameters C, ε and three kernel parameters [27]. The values after the parameter tuning has been set to: C = 1.707 and ε = 0.001, kernel type = radial basis function, gamma = 1 / ($n_{features}$ * X_{var}). After the training the model was evaluated with five new data points. The results are shown in Figure 4.

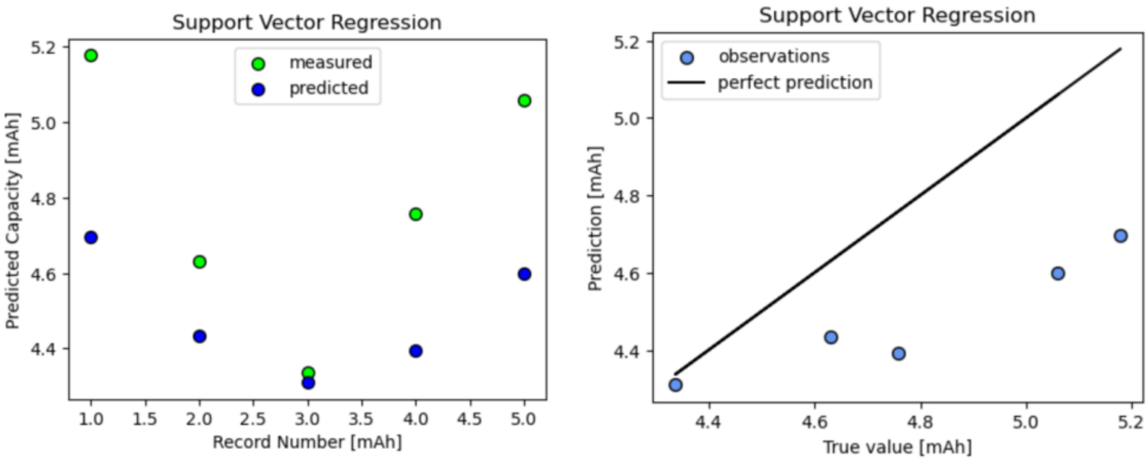

Figure 4: Prediction result of cell capacity after formation (mAh) with support vector regression

The results show that the prediction based on the SVR model is always predicting a lower capacity. The strong unilateral deviation can be a sign of overfitting of the model due to insufficient data base. This applies when all data points in the training set are used as support vectors. Therefore, the model actually overfits and has a poor prediction accuracy with new data sets. Afterwards a sensitivity analysis on the impact of the varied parameter on the cell quality is conducted. It was shown that the current rate in formation charging identified has the highest impact followed by the wetting temperature. The formation temperature has a much smaller impact than the other two factors.

5. Summary, discussion and outlook

In this paper two general use cases for the application of machine learning algorithm in the cell finishing has been introduced, the optimal process parameter selection and the quality prediction. The influencing parameter has been clustered into three groups: material and design parameters, process parameters before the cell finishing and process parameters within the cell finishing. For the modelling selection and development, the challenges within the cell finishing has been analysed and the multi-output regression algorithms has been introduced as a solution for both use cases.

On a data set of manufactured 3-electrode cells the quality prediction approach has been applied using a SVR model. The focus of the varied parameters was on the process parameters within the cell finishing. The following three process parameters have been varied: the electrolyte amount, the wetting temperature, the C-Rate and the formation temperature. As the output (quality prediction parameter) the capacity of the cells after three cycle have been selected. After data pre-processing and model development as well as training the results showed that the model prediction shows in four out of five data points a strong unilateral deviation. That is probably due to the small data base. The model tends towards overfitting. A sensitivity analysis showed that wetting temperature and C-rate during the formation have a higher impact on the quality than the formation temperature. Based on the results the next steps are (i) expand the data base to reduce prediction errors, (ii) modify the model to a multi-output regression model and (iii) compare and benchmarking the model towards other algorithm approaches, e.g. KNN, decisions trees.

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References

[1] König, A., Nicoletti, L., Schröder, D., Wolff, S., Waclaw, A., Lienkamp, M., 2021. An Overview of Parameter and Cost for Battery Electric Vehicles. WEVJ 12 (1), 21.

[2] Patry, G., Romagny, A., Martinet, S., Froelich, D., 2015. Cost modeling of lithium-ion battery cells for automotive applications. Energy Sci Eng 3 (1), 71–82.

[3] Sakti, A., Michalek, J.J., Fuchs, E.R., Whitacre, J.F., 2015. A techno-economic analysis and optimization of Li-ion batteries for light-duty passenger vehicle electrification. Journal of Power Sources 273, 966–980.

[4] Duffner, F., Mauler, L., Wentker, M., Leker, J., Winter, M., 2021. Large-scale automotive battery cell manufacturing: Analyzing strategic and operational effects on manufacturing costs. International Journal of Production Economics 232, 107982.

[5] Orangi, S., Strømman, A.H., 2022. A Techno-Economic Model for Benchmarking the Production Cost of Lithium-Ion Battery Cells. Batteries 8 (8), 83.

[6] Heimes, H.H., Offermanns, C., Mohsseni, A., Laufen, H., Westerhoff, U., Hoffmann, L., Niehoff, P., Kurrat, M., Winter, M., Kampker, A., 2020. The Effects of Mechanical and Thermal Loads during Lithium-Ion Pouch Cell Formation and Their Impacts on Process Time. Energy Technol. 8 (2), 1900118.

[7] Mao, C., An, S.J., Meyer, H.M., Li, J., Wood, M., Ruther, R.E., Wood, D.L., 2018. Balancing formation time and electrochemical performance of high energy lithium-ion batteries. Journal of Power Sources 402, 107–115.

[8] An, S.J., Li, J., Daniel, C., Mohanty, D., Nagpure, S., Wood, D.L., 2016. The state of understanding of the lithium-ion-battery graphite solid electrolyte interphase (SEI) and its relationship to formation cycling. Carbon 105, 52–76.

[9] Hagemeister, J., Stock, S., Linke, M., Fischer, M., Drees, R., Kurrat, M., Daub, R., 2022. Lean Cell Finalization in Lithium-Ion Battery Production: Determining the Required Electrolyte Wetting Degree to Begin the Formation. Energy Tech, 2200686.

[10] Wood, D.L., Li, J., An, S.J., 2019. Formation Challenges of Lithium-Ion Battery Manufacturing. Joule 3 (12), 2884–2888.

[11] Thiede, S., Turetskyy, A., Loellhoeffel, T., Kwade, A., Kara, S., Herrmann, C., 2020. Machine learning approach for systematic analysis of energy efficiency potentials in manufacturing processes: A case of battery production. CIRP Annals 69 (1), 21–24.

[12] Cunha, R.P., Lombardo, T., Primo, E.N., Franco, A.A., 2020. Artificial Intelligence Investigation of NMC Cathode Manufacturing Parameters Interdependencies. Batteries & Supercaps 3 (1), 60–67.

[13] Duquesnoy, M., Lombardo, T., Chouchane, M., Primo, E.N., Franco, A.A., 2020. Data-driven assessment of electrode calendering process by combining experimental results, in silico mesostructures generation and machine learning. Journal of Power Sources 480, 229103.

[14] Turetskyy, A., Wessel, J., Herrmann, C., Thiede, S., 2021. Battery production design using multi-output machine learning models. Energy Storage Materials 38, 93–112.

[15] Schnell, J., Nentwich, C., Endres, F., Kollenda, A., Distel, F., Knoche, T., Reinhart, G., 2019. Data mining in lithium-ion battery cell production. Journal of Power Sources 413, 360–366.

[16] Stock, S., Pohlmann, S., Günter, F.J., Hille, L., Hagemeister, J., Reinhart, G., 2022. Early Quality Classification and Prediction of Battery Cycle Life in Production Using Machine Learning. Journal of Energy Storage 50, 104144.

[17] Shin, J., Kim, T.-H., Lee, Y., Cho, E., 2020. Key functional groups defining the formation of Si anode solid-electrolyte interphase towards high energy density Li-ion batteries. Energy Storage Materials 25, 764–781.

[18] Li, J., Liu, H., Xia, J., Cameron, A.R., Nie, M., Botton, G.A., Dahn, J.R., 2017. The Impact of Electrolyte Additives and Upper Cut-off Voltage on the Formation of a Rocksalt Surface Layer in LiNi 0.8 Mn 0.1 Co 0.1 O 2 Electrodes. J. Electrochem. Soc. 164 (4), A655-A665.

[19] Günter, F.J., Rössler, S., Schulz, M., Braunwarth, W., Gilles, R., Reinhart, G., 2020. Influence of the Cell Format on the Electrolyte Filling Process of Lithium-Ion Cells. Energy Technol. 8 (2), 1801108.

[20] Liu, L., Guan, P., Liu, C., 2017. Experimental and Simulation Investigations of Porosity Graded Cathodes in Mitigating Battery Degradation of High Voltage Lithium-Ion Batteries. J. Electrochem. Soc. 164 (13), A3163-A3173.

[21] Günter, F.J., Burgstaller, C., Konwitschny, F., Reinhart, G., 2019. Influence of the Electrolyte Quantity on Lithium-Ion Cells. J. Electrochem. Soc. 166 (10), A1709-A1714.

[22] Xu, M., Wang, R., Zhao, P., Wang, X., 2019. Fast charging optimization for lithium-ion batteries based on dynamic programming algorithm and electrochemical-thermal-capacity fade coupled model. Journal of Power Sources 438, 227015.

[23] Drees, R., Lienesch, F., Kurrat, M., 2021. Fast charging lithium-ion battery formation based on simulations with an electrode equivalent circuit model. Journal of Energy Storage 36, 102345.

[24] Amershi, S., Begel, A., Bird, C., DeLine, R., Gall, H., Kamar, E., Nagappan, N., Nushi, B., Zimmermann, T., 2019. Software Engineering for Machine Learning: A Case Study, in: 2019 IEEE/ACM 41st International Conference on Software Engineering: Software Engineering in Practice (ICSE-SEIP). 2019 IEEE/ACM 41st International Conference on Software Engineering: Software Engineering in Practice (ICSE-SEIP), Montreal, QC, Canada. 25.05.2019 - 31.05.2019. IEEE, pp. 291–300.

[25] Schröer, C., Kruse, F., Gómez, J.M., 2021. A Systematic Literature Review on Applying CRISP-DM Process Model. Procedia Computer Science 181, 526–534.

[26] Studer, S., Bui, T.B., Drescher, C., Hanuschkin, A., Winkler, L., Peters, S., Müller, K.-R., 2021. Towards CRISP-ML(Q): A Machine Learning Process Model with Quality Assurance Methodology. MAKE 3 (2), 392–413.

[27] Kornas, T., Wittmann, D., Daub, R., Meyer, O., Weihs, C., Thiede, S., Herrmann, C., 2020. Multi-Criteria Optimization in the Production of Lithium-Ion Batteries. Procedia Manufacturing 43, 720–727.

[28] Dogan, A., Birant, D., Kut, A., 2019. Multi-Target Regression for Quality Prediction in a Mining Process, in: 2019 4th International Conference on Computer Science and Engineering (UBMK). 2019 4th International Conference on Computer Science and Engineering (UBMK), Samsun, Turkey. 11.09.2019 - 15.09.2019. IEEE, pp. 639–644.

[29] Tange, R.I., Rasmussen, M.A., Taira, E., Bro, R., 2017. Benchmarking support vector regression against partial least squares regression and artificial neural network: Effect of sample size on model performance. Journal of Near Infrared Spectroscopy 25 (6), 381–390.

[30] Gelfusa, M., Murari, A., Malizia, A., Lungaroni, M., Peluso, E., Parracino, S., Talebzadeh, S., Vega, J., Gaudio, P., 2015. Advanced signal processing based on support vector regression for lidar applications, in: Image and Signal Processing for Remote Sensing XXI. SPIE Remote Sensing, Toulouse, France. Monday 21 September 2015. SPIE, 96430E.

Biography

Achim Kampker (*1976) is head of the chair "Production Engineering of E-Mobility Components" (PEM) of RWTH Aachen University and known for his co-development of the "StreetScooter" electric vehicle. Kampker also acts as member of the executive board of the "Fraunhofer Research Institution for Battery Cell Production FFB" in Münster. He is involved in various expert groups of the federal and state governments.

Heiner Hans Heimes (*1983) studied mechanical engineering with a focus on production engineering at RWTH Aachen University. From 2015 to 2019, he was head of the Electromobility Laboratory (eLab) of RWTH Aachen University and chief engineer of the newly established chair "Production Engineering of E-Mobility Components" (PEM). Since 2019, Dr.-Ing. Heimes has held the role of executive engineer of the PEM facility.

Benjamin Dorn (*1990) studied industrial engineering with a focus on mechanical engineering at RWTH Aachen University. He worked as a research assistant from 2017 and as a group leader from 2020 at the PEM of RWTH Aachen in the Electric Drive Production group. Since 2021, he has been part of the institute's management as senior engineer of the Production Technologies and Organization division.

Sarah Wennemar (*1995) studied mechanical engineering and business administration with the focus on power engineering at RWTH Aachen University. Since 2020 she has been a research associate and since 2022 the group lead of the Battery Production Technology Group at the Institute for Production Engineering of E-Mobility Components at the RWTH Aachen University.

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Demands And Challenges For SME Regarding The Human-Centered Implementation Of Innovative Technologies And AI

Annika Franken, Christine Manthei, Roman Senderek, Volker Stich
Institute for Industrial Management at the RWTH Aachen University (FIR), Aachen, Germany

Abstract

Digitization is constantly affecting the working world and is of enormous interest in many fields of science. But to what extent are innovative technologies actually being applied in regional SMEs and what are the obstacles to their introduction? From a psychological point of view, it is essential to consider the employee's health and the effects of innovative technologies on their everyday work. The aim of using innovative technologies should not be to completely replace human labor or to dequalify employees, but to relieve the workforce and free up working time for more meaningful activities. One concept that should be included in the human-centered design of human-machine interaction in artificial intelligence is the HAI-MMI concept [1], which offers starting points for high-quality collaboration at various levels.

To reduce the gap between science and industry, this paper focuses on the actual demands of SME in the Aachen region in Germany referring to a requirements analysis within the research project AKzentE4.0 (N = 50 SME) and discusses how appropriate innovative technologies of the Industry 4.0 and AI can be implemented and deployed in a human-centered way. Moreover, the establishment of a Human Factors Competence Center for Employment in Industry 4.0 is outlined, which is meant to be used for the dissemination of research results and should narrow the gap between science and industry in the long run.

Keywords

Digitization; Industry 4.0; AI; Human-centered work design; SME

1. Introduction

Significant structural changes are taking place in the Aachen region due to the energy transition. The region has a unique mix of high technology and production expertise, which is mainly supported by small and medium-sized enterprises (SMEs) and prestigious universities. Industry 4.0 technologies and concepts, especially AI-based applications, have been used by only a few companies in the region so far. When introducing as well as developing these innovative technologies, some companies face obstacles such as human-centered introduction and implementation. These obstacles are analysed and addressed in the project "AKzentE4.0" (German acronym: Arbeitswissenschaftliches Kompetenzzentrum für Erwerbsarbeit in der Industrie 4.0), which is funded by the German Federal Ministry of Education and Research (BMBF). Together, multi-professional teams of the consortium develop and test precisely fitting solutions for the project-internal SMEs in consortium projects. Other companies across industries should benefit from these solutions because the AI-based potential in Germany remains mostly unutilized [2]. Particularly in SMEs, the consistent use of Industry 4.0 technologies and concepts is not widespread. For example, in a survey of 880 specialists and managers, only 7% of the respondents from SMEs and 12.6% of the respondents from large companies stated that they used AI in individual cases [3]. In a comparable survey by the Fraunhofer Institute for Industrial Engineering [4], only 16% (n = 309) of the industrial and service companies surveyed

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used a specific AI application. The reasons for this are varied: they range from a lack of AI expertise and competence in the company to be able to assess advantages and disadvantages, or a high level of uncertainty among employees in dealing with AI, to concerns about job loss or incapacitation due to AI systems.

Therefore, within the framework of AKzentE4.0, an infrastructure in the form of a mixed reality model factory is being established, through which both the exchange of knowledge by means of an open knowledge repository for work design and training offers, as well as the exchange between affected companies is being promoted. In this way, 4.0 technologies can be experienced in real and virtual terms in a mixed reality model factory and the gap between science, technology and industry could be closed a little bit more. In order to be internationally competitive, the concepts require not only a high degree of flexibility, but also an orientation towards an integrated human-centered work design [5–8], because despite the advancing automation through AI use, humans will be a decisive factor in the factory of the future with their ability to think creatively and abstractly [9]. By agreeing on these goals, this research contributes to the human-oriented as well as participatory design of work designs of the digital transformation together with the employees, as demanded by employee representatives [10], and thus to a socially sustainable and at the same time economically beneficial design of the digital transformation. On this basis, an analysis was made of how innovative Industry 4.0 and AI technologies can be implemented and used in a human-centered way.

2. Theoretical Background

In order to approach the object of research, important terminology will be theoretically classified, which will subsequently be used for the further work.

2.1 Innovative technologies

This paper makes several references to innovative technologies and AI. AI is seen as a form of innovative technology. Innovative technology means "new or improved product[s] or process[es] whose technological characteristics are significantly different from before" [11]. It is important that the innovation brings advantages over the status quo in the company or market. The introduction of these technologies requires preparation of the employees as well as the hardware, for example the digitization. Since both the companies in the AkzentE4.0 project and the companies throughout Germany require many preparations for the introduction, these preliminary stages are also included in this paper in the term innovative technologies. One example for such a preliminary stage is the installation of sensors that generate data which an AI can use later in the first place.

2.2 Artificial intelligence (AI)

Artificial intelligence has emerged as a subfield of computer science and is, at its core, a system that can perform certain procedures more or less autonomously. The traditional definition of AI, which is considered to be a "simulation of intelligent human thought and action" [12], is not used here because it interprets human thinking as absolute intelligence and does not take into account that technology has already been able to solve some capabilities in a different way, even partially overtaking human intelligence as a result [12]. This research is based on the understanding of Mainzer's [12] working definition, "A system is called intelligent if it can solve problems independently and efficiently. The degree of intelligence depends on the degree of autonomy, the degree of complexity of the problem, and the degree of efficiency of the problem-solving procedure" [12]. There are two kinds of interpretations in the scientific discourse about which goal AI would pursue: the "strong AI" pursues the goal to imitate human cognition. The "weak AI" pursues the goal to provide a technical solution for application problems in society and economy, in which incomplete controllability or incomplete knowledge would be unavoidable [13]. Since AI systems do not control their environment, the systems must be able to react flexibly, for example, by evaluating sensor data. Learning procedures (machine learning) can be used to optimize the behavior of the AI [13].

2.3 Comparison of previous needs assessments with the present study objectives

There are numerous surveys that focus on the state of digitization in general or specifically on the use of AI in companies. The studies each focus on various aspects and perspectives, which means that there basically is an overview of the status in companies. For the most part, it was ascertained what is understood by Industry 4.0 and what advantages arise from the fourth industrial revolution, furthermore in which areas of the company AI has already been introduced or where it is planned and what opportunities and advantages have been achieved and are expected as a result. In some cases, the evaluation of the use of AI was considered at the organizational or individual level. Furthermore, factors were surveyed that would inhibit or prevent the introduction of AI [15–23]. When reviewing these studies, it became clear, that none of them can provide sufficient information about regional needs and capabilities. There are various platforms on which best-practice examples are presented, most of which were created in the direct environment of (model) projects, which makes the interaction between projects and companies apparent. It is difficult to apply the individual projects to other companies. As a result of AKzentE4.0, therefore, adaptable best practice examples for digitization in companies are to be developed and made available in the competence center, which can be easily used as role models by other companies. Therefore, innovative technologies will be implemented exemplarily at the project partners of AKzentE4.0. Through this universal applicability, a sustainable closing of the gap between science and industry is to be achieved and no further simple listing of best practice examples is to be generated. For a successful, i.e. both socially sustainable and economically beneficial, introduction of AI, the human being has to be put in the center [9]. Thus, the labor science perspective of digitization is a dominant factor of the human-centered implementation of digital structures. However, this is strongly neglected in most surveys. Instead, the focus is placed primarily on the strategic benefits, such as cost reduction and increasing process quality and efficiency, opening up new market and customer segments, or agile and flexible management [24]. In the answers to the potentials of digitization or the introduction of AI, the relief of employees is considered, but the benefits for a humane work design are mentioned only marginally, if at all [18]. On the contrary, the use of AI is even perceived as a burden on work design [23]. This study takes up precisely this point and highlights the advantages of introducing AI and digitization, which, in addition to the above-mentioned benefits such as increased flexibility or process improvement, also pushes the improvement of human-centered work design using the Aachen region as an example.

2.4 HAI-MMI-Model

During the introduction of these innovative technologies, the human-oriented design of work is central. The working human being with his individual and social relations to the technical elements of the work systems is considered [25] in order to reduce stress and to positively increase job satisfaction and performance. For the future-oriented, user-centered design of collaboration and interaction between humans and AI-driven systems, criteria have been developed that address the protection of humans, the guarantee of trustworthiness of AI, and the creation of supportive working conditions [26].

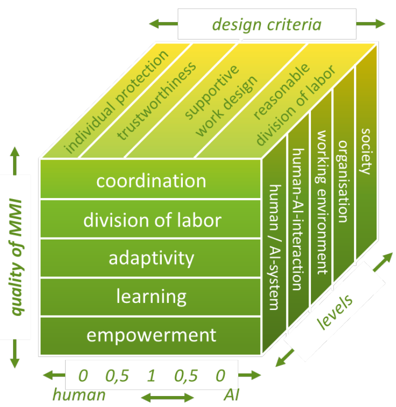

Figure 1: HAI-MMI model

A reflection and design tool for the complementarity between employees and AI is the HAI-MMI (Humanizing Men-Machine Interaction Model with AI) model developed by Huchler [1], shown in figure 1. This model can be used firs to evaluate concrete situations of collaboration between AI and humans regarding the quality of collaboration, and second to evaluate the design criteria of work as well as, in a third step, to estimate the consequences at various levels.

The Quality of MMI on the left side behaves on a scale, which can be seen below the graphic, between the two poles of sole dominance of human action and AI-supported full automation of work processes. In the middle there is the ideal, high-quality form of cooperation between AI and human. In the extreme poles, a lower quality of work occurs, as it can be read from the heading "0". No step-by-step full automation is aimed at as the highest form, but rather a complementary form of work that combines the advantages of humans with those of AI. On the vertical level, the various situations of "*interactive collaboration* with learning AI systems [emphasis in original]" [1] are presented. The extent to which there is coordination of labor, how the division of labor is designed, the extent to which a mutual learning process is present and possible, who adapts to whom in the work process, and whose interests are reinforced in the work process are still evaluated [1]. The different qualities of the work forms are outlined as examples for "Coordination" and "Learning" in table 1. The illustration is shortened so that the MMI of medium quality (at 0.5) was not shown due to space constraints. The complete description can be found in Huchler [1].

Table 1: Qualities of MMI

Human ← Human & AI → AI

	Low Quality	High Quality	Low Quality
Coordination	*One-sided Coordination* • System only works in background • No interaction	*Interactive Coordination* • Transparent and interactive distribution of control- /decisionpower • System proactively offers tasks that it can take on	*Compensating Coordination* • Human only involved in error correction/avoidance
Learning	*Separate Learning* • Human learns separately from technical system • Quality of machine learning is not improved by MMI	*Interdependent Learning* • System and human support each other in learning • High learning quality	*Prevented Learning* • System learns invisibly • Human becomes dequalified at the same time
...			

The design criteria therefore describe the conditions of human-machine interaction under which a human works in an organization. These can be seen in figure 1 above. The individual protection means the protection of human health and safety. In addition, it includes data protection and responsible performance recording, as well as sensitivity to diversity and thus freedom from discrimination. Trustworthiness means that the data is available in high quality and that it can always be explained transparently. This can create system trust and responsibility. A supportive work design means having scopes of action that enable learning and the experience of rich work. In addition, communication as well as cooperation and the promotion of social integration are prerequisites. Reasonable division of labor has the aim to create a work environment full of support, adequacy, and relief. In addition, it includes a setting in which mistakes are tolerated and tasks can be adapted as well as individualized. [1]. Based on these qualities, various levels can be considered, which can be seen on the lower right side of figure 1. With these, the focus is placed on the micro level on the impact assessments of the work both on the person and the technology itself as well as on outside persons or processes, on the meso level on the organization and on the macro level on the society [1].

In the implementation phase of the subprojects of the application companies, the HAI-MMI model provides a scientific basis for designing the introduction process of innovative technologies in a human-centered way. The following phases must be taken into account and awareness needs to be created in the companies in this regard: 1. goal setting and impact assessment, 2. planning and design, 3. preparation and implementation, 4. evaluation and adaptation. First, the objective and purpose of the AI system must be determined. For this purpose, the modes of operation must be uncovered. A potential analysis and operational impact assessment must be carried out in the company. Based on this, the participations are clarified and the contributors are mobilized on the basis of the corporate culture. In the second phase, the design of the human-machine interaction must be planned and the transparency of the data usage and the load profiles must be worked out. In the third phase, the experimentation phase, participants are qualified for new requirements at an early stage and the work organization and upcoming tasks are distributed. In this phase, processes are introduced across the board. In the final phase, the processes are reviewed, evaluated and adjusted. The empirical values are used for this and other innovation processes [27].

3. Method

To reach as many companies as possible an online survey was conducted in the middle of 2022. The survey had the aim to provide an overview of the digitization status of the companies as well as of initial information about the expectations and wishes the companies have regarding a regional competence center. Based on the preceding analysis, duplications of results were to be avoided, so that this survey explicitly considered the economic region of Aachen and especially included human-centered work design. In addition, the survey was intended to sensitize companies to the topic of innovative technologies and to arouse their curiosity.

3.1 Survey and data analysis

The link to the survey which was conducted via Unipark was distributed through the Chamber of Crafts, the VUV-Vereinigte Unternehmerverbände Aachen and especially addressed to the companies from the project consortium. The questionnaire consisted of three main parts which were, first, required general information about the company, second, questions about the status quo of the company (e.g. regarding the AI ability, data quality) and third, wishes and needs that should be addressed in the competence center. Afterwards, data were analyzed descriptively via the software SPSS.

3.2 Sample

A total of 50 representatives from manufacturing companies took part in the survey. Of these, 31 belonged to the craft, 9 to industry, and 10 categorized themselves as other but subsequently allowed themselves to be assigned to industry (therefore total n industry = 19). 44% of those companies (n = 22) had between 1 and 9 employees, 28% of the companies (n = 14) had 10-49 employees, 14% (n = 7) of the companies had 50-249 employees, 12% of the companies (n = 6) had between 250 and 499 employees, and one company (2%) had between 500 and 999 employees. In terms of AI enablement, on average, companies ranked themselves very midway between the poles of analogue (0) and autonomous (10) (M = 4.54, SD = 1.99, Range = 0 - 8). The range illustrates the need to focus not only on AI, but also to include innovative technologies in general.

4. Results

First, the needs of the participating companies were surveyed regarding existing hardware that should be used more intensively and digital hardware that should be purchased. Some kinds of innovative technologies are available in the companies, particularly in the very basic form of smartphones or tablets, and are to be used more intensively. This can be seen in the blue bars in Figure 3. Approximately 60% (n=30) of the companies surveyed use these technologies. Moreover, sensors on machines already exist in 18% (n =9) of the companies surveyed and are planned to be used in more detail. The green bars represent the planned acquisitions of technologies that are not available at all in the company at the moment. Especially the acquisition of data glasses (30%, n=15) as well as AR systems (26%, n=13) and VR systems (22%, n=11) is planned.

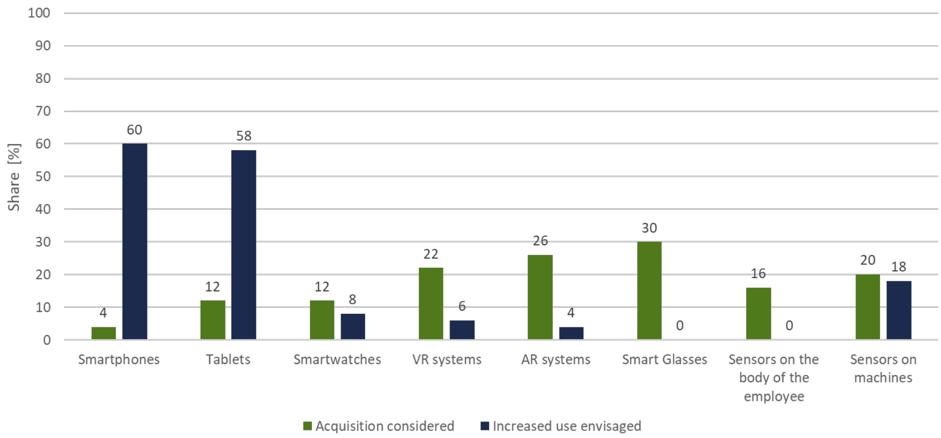

Figure 2: Usage of and need for innovative technologies

The introduction of innovative technologies is currently mainly carried out by the companies themselves. 70% (n = 35) of the respondents state that the introduction takes place in-house. Overall, employees would tend to co-operate with this introduction (M = 4.09; SD = 1.5; possible range = 1 - 6) and be actively involved (M = 4.18; SD = 1.42; possible range = 1 - 6). The average response to the question of whether further training would be offered in the company for the use of these technologies was "tend not to agree".

The survey asked which offerings companies would like to see for the digital transformation (see figure 3). These primarily include qualification offerings (72%, n=36) and networking offerings (62%, n=31)). 54% (n=27) each would like to receive an expert advice and a toolbox with various methods. Only 12% (n=6) would like to participate in conferences. The low interest in the mixed reality model factory can at least partially be explained by a lack of understanding of what is behind the term. This illustrates the importance of properly promoting the factory and creating awareness that encourages potential customers to engage with the issue. What seems to be most important are interactive exchange formats. What is noticeable about the results of the different responses is that the participants in the survey prefer different offerings depending on the branch of industry. This shows the need for a broad variety of offerings in the competence center.

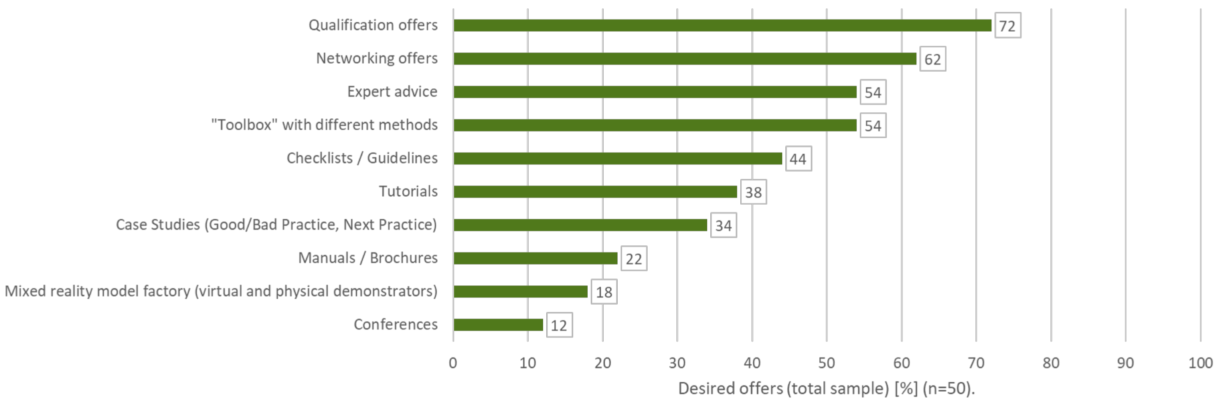

Figure 3: Desired offers

More detailed questions were asked about the desired networking offers. To this end, nine offerings were to be ranked in descending order of importance (1 = the most important, 9 = the least important). Overall, the offers through which companies with similar cases network with each other were prioritized. These include, for example, contact with other companies with the same/similar problems (M = 3.42; SD = 1.95) or networking with partner institutions (M = 3.90; SD = 2.61).

In addition to looking at the needs regarding the offers of the competence center, the focus was placed on the conditions of health as well as occupational safety and the human-centered introduction of the innovative technologies, since this has been neglected in previous studies. The question regarding the impact of innovative developments on the conditions shows that the respondents assume that especially competence and quality requirements of the employees as well as the transparency of work and performance behavior would increase with the introduction of innovative technologies (see figure 4). The individual dimensions from figure 4 are examined in more detail below, from bottom to top.

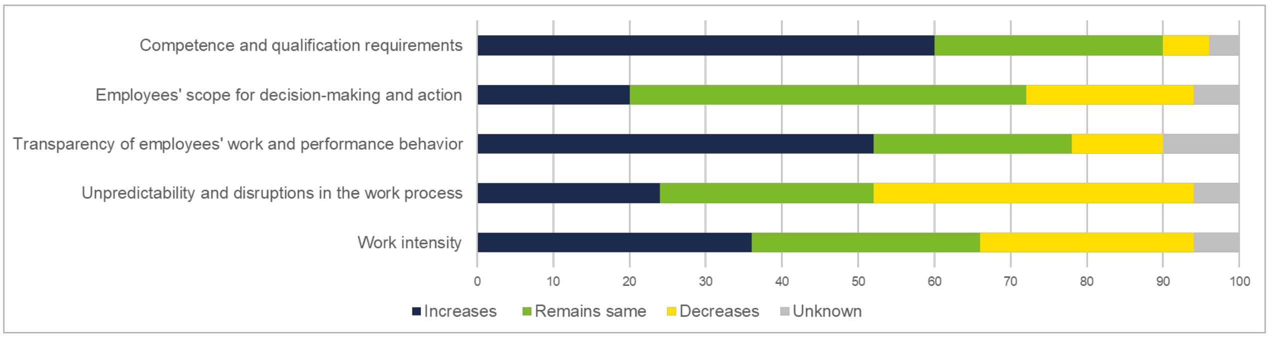

Figure 4: Impact of innovative developments

The effects on labor intensity were examined in more detail. Here, 36% (n = 18) of respondents assume that labor intensity will increase with the use of innovative technologies, while 28% (n = 14) expect it to decrease. This means that the increase in labor intensity is estimated to be lower than previous studies suggest, such as in the Innovation Barometer [23], in which 52% (n = 515) of respondents report an increase in labor intensity and only 8% (n = 42) a decrease. The comparison of respondents from the craft and industry shows that the effects in the craft were to be assessed as more severe from the respondents' point of view, but statistically significant differences could not be determined.

Regarding the increase or decrease in disruptions and imponderables, 42% (n = 21) of respondents assume that the use of innovative technologies will reduce disruptions and imponderables in the work process. This is predicted in particular by respondents from industry and other occupational groups (52.6% (n = 10)). In the craft, 35,5% (n = 11) expect this. Here, again, the results are contrary to previous findings, according to which 42% (n = 416) of the respondents see an increase in disruptions in work processes and only 11% (n = 109) speak of a reduction [23].

The transparency of work and performance behavior is assessed in line with the results of previous studies, which see a strong increase in the transparency of employees' work and performance behavior due to AI [23]. More than half of all respondents to this survey (52% (n = 26)) forecast an increase in the transparency of employees' work and performance behavior using innovative technologies, while only 12% (n = 6) forecast a decrease using innovative technologies.

In previous studies, 60% (n = 594) of the respondents expected the scope for decision-making and action to decrease. Only 31% (n = 307) would expect the scope for decision-making and action to remain unchanged. In the present study, more than half of the respondents (52% (n = 26)) stated that they did not expect any changes in employees' scope for decision-making and action as a result of the use of innovative technologies. Notable differences in this result emerged regarding occupational groups. While 63.2% (n = 12) of respondents from industry and other occupational fields forecast no changes, only 45.2% (n = 14) of respondents from the crafts occupational field did.

The results of this survey regarding expectations of competence and quality requirements are similar to the results of previous studies. 60% (n = 30) of the respondents expect competence and quality requirements to increase with the use of innovative technologies, and only 6% (n = 3) expect them to decrease. This distribution is evident across all subgroups surveyed.

The potentials, which could result from the introduction of innovative technologies, regarding the influence on healthy working, are estimated rather moderately. Thus, 56% (n = 28) rather or completely agree with the support of a better work-life balance through time- and location-flexible working, made possible by innovative technologies. Taking over cognitive activities, e.g., filtering information flows using innovative technologies, is rated best (M=3.81, SD=1.54). 60% (n = 30) of respondents somewhat or fully agree that cognitive relief will occur.

56% (n = 28) of respondents assume that no physical relief at all or rather no physical relief for employees will result from the use of AI. Only 46% (n = 23) assume that the safety of employees will be improved as a result of AI taking over dangerous activities. Overall, these findings show that respondents are aware of at least some of the potential opportunities and risks of using innovative technologies.

5. Discussion and outlook

The results of the literature analysis and survey show a clear need for a Human Factors Competence Center for Employment in Industry 4.0 in the Aachen region, which enables companies to introduce innovative technologies in an employee-centered way and contributes to the networking of local actors. Through contact with regional companies, specific needs became apparent, which will be incorporated into the development of the business model. However, the relatively small sample must be mentioned as a limitation of the study at this point. For this reason, additional needs assessments and more intensive discussions with potential customers of the competence center are planned for the further course of the project. It is also necessary that the HAI-MMI model is applied in practice and that this is evaluated in order to highlight the merits and practicality of the model.

In the form of value proposition canvas and business model canvas workshops, a start has already been made on setting the guard rails for the strategic orientation of the competence center. In this context, the structures of the competence center will be consistently aligned to be able to work on topics of labor research and work design relevant for industrial production systems in an agile manner, to build up competencies and to make them available for operational practice. The implementation strategy includes elements of infrastructure, networking and methods. The infrastructure consists of the mixed reality model factory with distributed virtual and real hub locations, whose main function is to draw attention to innovative technologies and arouse the enthusiasm of potential customers. This is intended to lower the inhibition threshold for the acquisition of innovative technologies as much as possible. In addition, the infrastructure is to include an open knowledge repository through which companies can access practically prepared research findings and training units on the topic of digitization for various target groups. Above all, networking with other companies with similar problems or best practice companies through a regional map with contact information, events in regulars' table format and working groups is a central task of the competence center. Methods include occupational science evaluation procedures and work design strategies, and companies are advised on how to implement them. The overriding goal is to develop the competence center into the central point of contact for the topic of work design in the region.

References

[1] Huchler, N., 2020. Die Mensch-Maschine-Interaktion bei Künstlicher Intelligenz im Sinne der Beschäftigten gestalten: Das HAI-MMI-Konzept und die Idee der Komplementarität. Digitale Welt - Das Wirtschaftsmagazin zur Digitalisierung (4), 30–33.

[2] Lerch, C., Jäger, A., Maloca, S., 2017. Wie digital ist Deutschlands Industrie wirklich?: Arbeit und Produktivität in der digitalen Produktion. Modernisierung der Produktion 71, Mitteilungen aus der ISI-Erhebung. https://www.isi.fraunhofer.de/content/dam/isi/dokumente/modernisierung-produktion/erhebung2015/pi71_readiness_i4-0.pdf.

[3] Bettenhausen, K.D., Botthof, A., Brandt, C., Dirzus, D., Froese, T., Gebhardt, J., Holzhauer, R., Kubach, U., Pickel, P., Rabe, M., Sauer, O., Senff, D., Sowa, T., Schumann, C.-A., Spiegelberg, G., Westerkamp, D., Weyrich, M., 2018. Künstliche Intelligenz: VDI-Statusreport Oktober 2018. https://www.vdi.de/ueber-uns/presse/publikationen/details/vdi-statusreport-kuenstliche-intelligenz.

[4] Dukino, C., Friedrich, M., Ganz, W., Hämmerle, M., Kötter, F., Meiren, T., Neuhüttler, J., Renner, T., Schuler, S., Zaiser, H., 2019. Künstliche Intelligenz in der Unternehmenspraxis: Studie zu Auswirkungen auf Dienstleistung und Produktion. Fraunhofer-Institut für Arbeitswirtschaft und Organisation IAO, Fraunhofer Verlag. https://publica-rest.fraunhofer.de/server/api/core/bitstreams/0dd40c4f-9c68-4fbe-ba56-e4743834805d/content.

[5] Dombrowski, U., Wullbrandt, J., 2018. Instandhaltungsmanagement in Ganzheitlichen Produktionssystemen, in: Reichel, J., Müller, G., Mandelartz, J. (Eds.), Betriebliche Instandhaltung, 2 ed. Springer, pp. 15–34.

[6] Jacobs, J.C., Kaermann, H., Spath, D. (Eds.), 2017. Arbeit in der digitalen Transformation: Agilität, lebenslanges Lernen und Betriebspartner im Wandel. Ein Beitrag des Human-Resources-Kreises von acatech und der Jacobs Foundation - Forum für Personalvorstände zur Zukunft der Arbeit. Herbert Utz.

[7] Mütze-Niewöhner, S., Nitsch, V., 2020. Arbeitswelt 4.0, in: Frenz, W. (Ed.), Handbuch Industrie 4.0. Recht, Technik, Gesellschaft. Springer, pp. 1187–1217.

[8] Wischmann, S., Hartmann, E.A. (Eds.), 2018. Zukunft der Arbeit: Eine praxisnahe Betrachtung. Springer, Berlin, Heidelberg.

[9] Korge, A., 2017. Konzepte, Methoden, Erfolgsfaktoren in der Produktion, in: Spath, D., Westkämper, E., Bullinger, H.-J., Warnecke, H.-J. (Eds.), Neue Entwicklungen in der Unternehmens-organisation. Springer, pp. 505–511.

[10] Deutscher Gewerkschaftsbund, 2020. Künstliche Intelligenz (KI) für Gute Arbeit: Ein Konzeptpapier des Deutschen Gewerkschaftsbundes zum Einsatz von Künstlicher Intelligenz (KI) in der Arbeitswlt. https://www.dgb.de/downloadCentre/++co++18197bd6-9f2d-11ea-80f0-525400e5a74a.

[11] Yedjou, C.G., Latinwo, L.M., Alo, R., Odewumi, C.O., Reaves, P.Y., 2022. Technology-Enhanced Student Learning, Improved Engagement, and Performance in an Anatomy and Physiology Course, in: Blankenship, R.J., Wiltsher, C.Y., Moton, B.M. (Eds.), Experiences and Research on Enhanced Professional Development Through Faculty Learning Communities. IGI Global, pp. 178–193.

[12] Mainzer, K., 2019. Künstliche Intelligenz - Wann übernehmen die Maschinen?, 2nd ed. Springer.

[13] Hertzberg, J., 2022. Was ist KI und welche ethischen Fragen stellt ihre Anwendung? Religion Unterrichten - Künstliche Intelligenz und Human Enhancement 3, 9–14.

[14] Pollert, A., Kirchner, B., Polzin, J.M., 2009. Duden, Wirtschaft von A bis Z: Grundlagenwissen für Schule und Studium, Beruf und Alltag.

[15] 2017. HR- und Gesundheits-management in der Arbeit 4.0: Bedarfe und Umsetzungshindernisse in KMU. Eine qualitative Interviewstudie im Rahmen des Projektes MEgA (Maßnahmen und Empfehlungen für die gesunde Arbeit von morgen), 65 pp. https://gesundearbeit-mega.de/sites/gesundearbeit-mega.de/files/u8/forschungsbericht_mega_kmu-experteninterviews_0.pdf. Accessed 17 November 2022.

[16] 2020. Der digitale Status quo des deutschen Mittelstands: Digitalisierungsindex Mittelstand 2020/2021, 18 pp. https://telekom-digitalx-content-develop.s3.eu-central-1.amazonaws.com/Telekom_Digitalisierungsindex_2020_GESAMTBERICHT_57e2241e33.pdf. Accessed 17 November 2022.

[17] Hill, J., 2017. Studie Industrie 4.0, 52 pp. https://www.lufthansa-industry-solutions.com/fileadmin/user_upload/dokumente/news/lhind-Studie-Industrie40.pdf. Accessed 17 November 2022.

[18] Lundborg, M., Gull, I., 2021. Künstliche Intelligenz im Mittelstand: So wird KI für kleine und mittlere Unternehmen zum Game Changer. Eine Erhebung der Mittelstand-Digital Begleitforschung im Auftrag des Bundesministeriums für Wirtschaft und Klimaschutz, 22 pp. https://www.mittelstand-

digital.de/MD/Redaktion/DE/Publikationen/ki-Studie-2021.pdf?__blob=publicationFile&v=5. Accessed 17 November 2022.

[19] Metternich, J., Biegel, T., Bretones Cassoli, B., Hoffmann, F., Jourdan, N., Rosemeyer, J., Stanula, P., Ziegenbein, A., 2021. Künstliche Intelligenz zur Umsetzung von Industrie 4.0 im Mittelstand: Expertise des Forschungsbeirats der Plattform Industrie 4.0, 69 pp.

[20] Nägele, A., Stangl, A., Ludmann, F., Wagner, S., Wolfnagel, S. Industrie 4.0 Barometer 2021. MHP Management- und IT-Beratung GmbH, Ludwig-Maximilian-Universität, 42 pp. https://www.mhp.com/fileadmin/www.mhp.com/downloads/whitepaper/MHP_Industrie_4_0_Barometer_2021_DE.pdf. Accessed 17 November 2022.

[21] Rammer, C., 2020. Einsatz von Künstlicher Intelligenz in der Deutschen Wirtschaft: Stand der KI-Nutzung im Jahr 2019, 43 pp. https://www.bmwk.de/Redaktion/DE/Publikationen/Wirtschaft/einsatz-von-ki-deutsche-wirtschaft.pdf?__blob=publicationFile&v=8. Accessed 17 November 2022.

[22] Slomski, S., 2019. Ausbildungscluster Thüringen Digitalisierung und Industrie 4.0: Ergebnisse der Bedarfsanalyse 2019, 20 pp. https://www.nucleus-jena.de/wp-content/uploads/2020/05/20191218_Ergebnisse-Bedarfsanalyse-Zusammenfassung_voll_vs3.pdf. Accessed 17 November 2022.

[23] Zanker, K., Roth, I., Hoppe, M., 2019. ver.di-Innovationsbarometer 2019: Künstliche Intelligenz. Studie im Auftrag der ver.di-Bundesverwaltung. Ressort 13, Bereich Innovation und Gute Arbeit, 29 pp. https://innovation-gute-arbeit.verdi.de/++file++5dd3f17cd62276747746838b/download/innobaro_KI_RZweb3.pdf. Accessed 17 November 2022.

[24] Mittelstand 4.0-Kompetenzzentrum Augsburg. Potenzialanalyse, Augsburg. https://digitalzentrum-augsburg.de/wp-content/uploads/2021/02/2021_Fragebogen_Potenzialanalyse.pdf.

[25] Gesellschaft für Arbeitswissenschaft (GfA), 1977. Denkschrift, Ausbau der Arbeitswissenschaft an den deutschen Hochschulen, Frankfurt.

[26] Huchler, N., Adolph, L., André, E., Bauer, W., Bender, N., Müller, N., Neuburger, R., Peissner, M., Steil, J., Stowasser, S., Suchy, O., 2020. Kriterien für die Mensch-Maschine-Interaktion bei KI: Ansätze für die menschengerechte Gestaltung in der Arbeitswelt, Plattform Lernende Systeme. https://www.plattform-lernende-systeme.de/files/Downloads/Publikationen/AG2_Whitepaper2_220620.pdf.

[27] 2022. Einführung von KI-Systemen in Unternehmen: Gestaltungsansätze für das Change-Management. Whitepaper aus der Plattform Lernende Systeme, München.

Biography

Annika Franken (*1999) is a psychologist and project manager in the department Smart Work at FIR e. V. at the RWTH Aachen University and is primarily involved in projects in the context of health-promoting work design and resilience. Previously, she worked on projects in the field of health psychology at RWTH Aachen University in the context of vocational rehabilitation and mental health of students.

Christine Manthei (*1997) is a childhood educator, social worker, and adventure pedagogue and is currently studying empirical educational research. Since 2021 she has been working in the department Smart Work at FIR e.V. at RWTH Aachen University as a junior project manager.

Roman Senderek worked as project manager in several German and Latin American companies before taking up his position as project manager at FIR e. V. at the RWTH Aachen University. In 2019 he founded the research group New Work, which eventually grew in 2021 into the department Smart Work at FIR, which focusses on the design of customized teaching and learning solutions as well as human-oriented design that promotes learning in the digitized world of work.

Prof. Dr.-Ing. Volker Stich is head of FIR e.V. at the RWTH Aachen University since 1997. Prof. Dr.-Ing. Volker Stich has been working at the St. Gobain-Automotive Group for 10 years and led the management of European plant logistics. His research focuses on operations management, logistics and business applications systems.

4th Conference on Production Systems and Logistics

A Linear Programming Model For Renewable Energy Aware Discrete Production Planning And Control

Vincent Adomat[1], Christian Kober[1], Maryam Ahanpanjeh[1], Jens P. Wulfsberg[1]

[1]*Institute of Production Engineering, Helmut-Schmidt-University, Hamburg, Germany*

Abstract

Industrial production in the EU, like other sectors of the economy, is obliged to stop producing greenhouse gas emissions by 2050. With its Green Deal, the European Union has already set the corresponding framework in 2019. To achieve Net Zero in the remaining time, while not endangering one's own competitiveness on a globalized market, a transformation of industrial value creation has to be started already today. In terms of energy supply, this means a comprehensive electrification of processes and a switch to fully renewable power generation. However, due to a growing share of renewable energy sources, increasing volatility can be observed in the European electricity market already. For companies, there are mainly two ways to deal with the accompanying increase in average electricity prices. The first is to reduce consumption by increasing efficiency, which naturally has its physical limits. Secondly, an increasing volatile electricity price makes it possible to take advantage of periods of relatively low prices. To do this, companies must identify their energy-intensive processes and design them in such a way as to enable these activities to be shifted in time. This article explains the necessary differentiation between labor-intensive and energy-intensive processes. A general mathematical model for the holistic optimization of discrete industrial production is presented. With the help of this MILP model, it is simulated that a flexibilization of energy-intensive processes with volatile energy prices can help to reduce costs and thus secure competitiveness while getting it in line with European climate goals. On the basis of real electricity market data, different production scenarios are compared, and it is investigated under which conditions the flexibilization of specific processes is worthwhile.

Keywords

Renewable energy; Production planning and control; Scheduling; Optimization; Simulation; Modelling; Mixed-integer linear programming

1. Introduction

In 2019 the European Union has declared its Green Deal as the framework for all member states to become climate neutral by 2050. While this already has great impact on everyday activities for European companies and individuals, likewise, especially the production and manufacturing sector is affected. [1] In terms of energy supply, lesser carbon certificates are leading to a higher share of renewables. Increasing energy prices are probably to be expected, but certainly the interconnected European energy markets are about to become more volatile [2]. Both, increasing energy prices and higher volatility, are traditionally said to interfere with economic growth. Companies and individuals similarly will reduce their economic activities once prices render them deficient. More energy intensive products will be discontinued first. For manufacturing companies, reducing production activity ultimately leads to individual economic decline. [3] Companies of

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the same sector often apply similar production techniques and processes, for which reason the decline likely affects the whole sector. Since the transition away from fossil fuels is not yet driven by shortages in fossil supply, companies from other countries, not bound to the European carbon certificate system, could be replacing local manufacturing capacity due to lower prices [4].

While these effects do not convey a bright look-out for the European manufacturing sector, there are chances of recovery even besides political measures. To remain competitive in a globalized market, manufacturing companies individually have to reduce the impact of increasing prices and greater volatility. Without doubt, the most important countermeasures for many industries are innovation and efficiency. No thoughts have to be made around energy, which is no longer needed for a certain output. [5] Besides innovation and efficiency, higher volatility also implies chances for those being able to freely distribute manufacturing operations in time. Today, energy tariffs often harness time independent pricing. Energy consumers pay suppliers an insurance like premium for time independency. Traditionally, industrial energy consumers do not incorporate variable energy prices in their planning of manufacturing activities. [6] The premium paid for time independence can be saved, once the ability to allocate energy intensive activities to periods of lower energy prices is achieved. In that way, utilizing periods of lower prices can contribute to keeping manufacturing cost low and to secure competitiveness in situations of global competition.

This article presents a holistic approach to modelling manufacturing revenue under variable energy prices. An overview of related literature and preceding work is given in chapter 2. Chapter 3 is dedicated to the differentiation of energy-intensive and labor-intensive manufacturing tasks and processes. The mixed-integer linear model depicting a generic manufacturing setting is presented in chapter 4. Experiments have been carried out to demonstrate the benefits of applying energy cost optimized production planning. The respective experiment design is described in chapter 5 and the corresponding results are given in chapter 6. Chapter 7 concludes with a discussion of the presented findings and their generalizability.

2. Related Works

Production planning and control in discrete manufacturing scenarios essentially results in a multiplicity of mathematical optimization problems. Discrete manufacturing, in contrast to process manufacturing, hereby creates products manufactured in such a way that they are turned into units. One of the common representatives of discrete manufacturing includes mechanical engineering. Particularly in the manufacturing industry, the manufacturing of products in discrete units is found, which arise from parts-related manufacturing and assembly processes. Discrete and process manufacturing both have their very own constraints and objectives, leading to two distinct areas of research. The mathematical modelling and optimization of both has yet attracted researchers´ attention for some decades. Already in 1979 [7] gave an extensive overview on the "rapidly expanding area of deterministic scheduling theory" and dating its origins back to the 1950th. For the theory of optimally distributing manufacturing jobs to machining equipment, [7] and [8] have categorized the discipline's problems according to their manufacturing context. Problems in which one single machine is required for every job are classified as "Single machine problems" and "Parallel machine problems", depending on the number of machines taken into account. In scenarios where one single job needs execution on multiple machines, scheduling problems are called "Open shop, flow shop, and job shop problems." For an open shop scheduling, the machine order is expected to be immaterial, whereas it is fixed in flow shop scenarios and of varying order in job shop problems. Ever since the foundation of this field of study, researchers are trying to improve existing algorithms and heuristics for known problems and to develop new ones for yet untreated problems.

In more recent years, concerns of manufacturing's environmental impact have received growing attention by scholars. Known problems in the sequencing and scheduling sphere have been adapted to incorporate perspectives of energy efficiency and sustainability. [9] For the most fundamental problems of single machine scheduling, [10] and [11] worked on the minimization of total energy consumption, tardiness, completion time and total energy usage. More complex optimization problems arise if two machines are put in line, which is the flow shop's simplest form. [12] and [13] discuss the minimization of total energy consumption and makespan for such manufacturing scenarios by means of mixed integer linear programming. [14] employed the same objectives to the parallel machine scheduling problem, considering identical machines running at the same speed. In the identical parallel machine context [15] proposed a model for the minimization of total weighted tardiness, total completion time and peak power consumption. For unrelated parallel machine setups with differing machine speeds [16] optimized for total tardiness and total energy consumption. [17] used mixed integer linear programming total energy consumption and makespan minimization. The same is applied by [18] for energy saving by scheduling machines on and off states. Many scholars focused on the practice-oriented flow shop problem modelling. For classical flow shop problems, [19] minimized peak power requirements together with inventory cost. [20] minimized total energy consumption under the perspective of product quality. [21] and [22] considered tardiness and delivery penalties together with total energy consumption. Scheduling of machine shutdowns in the flow shop scope is discussed by [23]. For the permutation flow shop with equal job orders among all machines [24]–[27] minimized total energy consumption together with the total makespan. [24] and [28] worked on the same objectives in the context of distributed non-idle permutation flow shops. [29] replaced the permutation flow shop makespan objective by total tardiness. [30] added complexity by also taking transportation and setup times into account. For flexible flow shop scheduling problem [31] considered peak power consumption. [32] minimized completion time and total energy consumption in the same context. [33] included labor cost and worker flexibility in their optimization. Peak power, makespan and tardiness are considered by [34], whereas [35] changed peak power for total power consumption and tardiness for overall production cost objectives. [36] and [37] cover optimization in the light of just makespan and total energy consumption, and [38] and [39] replace the makespan objective by total weighted tardiness.

For classical job shop scheduling problems, [40] took varying power requirements for manufacturing's initial and processing phase into account, under the objective of makespan optimization. [41], [42] and [43] optimized both makespan and total energy consumption in the job shop sphere, while [44] aimed for total energy consumed only. [45] proposed a two-stage approach, minimizing makespan first and optimizing total energy consumption be altering cutting speeds afterwards. [46] chose a two-stage approach as well, minimizing tardiness and makespan, while incorporating total energy consumed via a constraint. [47] minimized weighted tardiness and total energy consumption through variable machining speeds. [48] minimized total energy consumption by dismantling energy consumption to its direct and indirect portions. Distributed multi-factory job shops have been dealt with by [49], optimizing makespan and total energy consumption as well. For the flexible job shop problem with grouped identical parallel machines [50] minimized overall production cost through a mixed integer programming model. [51] used a linear approach to minimize total energy consumption in flexible job shop settings. [52] optimized for total energy consumption and [53] added a makespan objective. [54] focused on transportation induced flexible job shop energy consumption. [55] applied scheduling of machine on/off cycles under the goal of total energy consumption and makespan minimization. In contrast to flow shop and job shop problems, open shop optimization under the perspective of energy efficiency has not yet received considerable attention by scholars. Besides typical machine scheduling problems, some have worked on cellular and reconfigurable manufacturing systems. [56] minimized flow time, energy consumption and makespan for cellular manufacturing systems. In the context of reconfigurable manufacturing systems, [57] maximized throughput while minimizing energy consumption. While most contributions are aiming for the optimization of peak or total energy consumption, makespan and tardiness in their respective fields, some authors also include more extensive sustainability criteria. [58] optimized for waste reduction and greenhouse gas emissions in cellular manufacturing systems. [59] considered material waste in the scope of flexible flow shop systems.

While energy consumption and efficiency often are at the core of sustainability efforts, energy is mostly referred to as electrical power usage. As shown by the collection of publications mentioned above, many authors target peak power reduction or total power consumption, often combined with further objectives. Eventually, all energy related dimensions of optimization are aspects of a broader economical perspective of business, quantified in units of money. Since energy prices are largely dependent on the time of energy consumption in liberalized energy markets [60], researchers have already identified the potential of machine scheduling optimization under time of use energy tariffs.

Even though sustainability issues have already received some attention in the context of scheduling manufacturing activities, only few scholars have yet incorporated time of use tariffs in their scheduling modelling. For single machine scheduling, [61] and [62] incorporate variable energy prices in their optimization. [63] and [64] adapt the approach to scheduling of two machines in line. For identical parallel machine scheduling, [65] have optimized for variable energy tariffs, [66] did this for hybrid parallel machine scheduling and [67]–[69] for unrelated parallel machines. [70] presented classical flow shop optimization under variable energy prices, while [71] and [72] optimized the flexible flow shop problem. More scholars have focused on energy prices in various machine scheduling problems, without considering variable market prices [9].

This contribution aims at integrating the aforementioned perspectives of optimization under the goal of highest attainable revenue. The analysis of the existing literature on the integration of variable energy prices into operational planning and control shows that there is still a lack of realistic problem formulations. The above-mentioned works predominantly present general. The corresponding extension to be able to use energy price optimized production planning in specific manufacturing contexts is still pending. In addition to the usual restrictions of established operational planning, such as capacities, deadlines and personnel availability, additional constraints must be taken into account in the context of energy price-optimized planning. These include, in particular, electricity prices and, due to the growing share of renewable energy sources, also weather data. Here it is tried to integrate all planning aspects of production in workshop settings and for manufacturing of customized industrial goods. The perspectives of demand, availability and cost are acknowledged for the planning dimensions of employees, machinery/equipment and energy. Peak energy demand is incorporated, while not minimized, but rather limited via a constraint. In terms of business and overall cost, the total energy consumption of production activities is of comparatively lower interest in contrast to the associated cost.

3. Labor-intensive vs. energy-intensive processes

When trying to optimize industrial production along demand, supply, and cost with the goal of maximizing overall manufacturing revenue, cost of energy must not be neglected. Time variable energy tariffs offer an additional perspective of optimization, since energy intensive operations can be planned for execution in periods of comparatively lower prices. In practice, to obtain the possibility of such optimization, all activities planned to be executed have to be assessed for their energy demand. Commonly, planners know much about which machinery and equipment and how many personnel of which qualification is required for every operation's successful completion. Knowledge on how much energy is consumed over the course of operational execution, however, is typically more scarce.

A first step to remedy this circumstance is a detailed assessment of the equipment being used for every recurring operation. By measuring the true energy consumption and its course over time per machine, the most vital part for differencing energy-intensive processes from labor-intensive ones is completed. Additionally, dismantling the already existent data used for production planning is required to calculate the operation related demand of employees. Depending on the operational complexity, the assessment of workforce required has a quantitative and qualitative perspective. It is essential to denote the number of employees needed for every operation, but also the necessary qualifications employees need to hold available. Once assessing energy and workforce demand is accomplished, all operations or tasks, jobs or processes can be classified in terms of flexibilization requirements. Flexibilization hereby means the ability to shift operations in time with limited impacted on cost and tardiness risk. Not all operations are required to be highly flexible in time. Those of low energy demand can be scheduled with preference for other cost factors than energy prices. At the same time, operations of high energy demand and low workforce involvement are of high importance for time-dependent flexibilization. A trade-off has to be made for high energy operations with high workforce dependencies. While higher flexibility is generally preferable, changes to those operations to increase flexibility have to be made under the consideration of a possible associated increase in labor cost.

4. Optimization model

To tackle the challenges of an integrative and energy cost aware discrete production planning, the following mathematical model has been developed to represent all cost factors typically being relevant to scheduling in industrial manufacturing. This mixed-integer linear model is set up to optimize scheduling of a set of unlinked manufacturing operations $o \in O$. All operations require the availability of certain machinery $m \in M$ for their completion. Besides the essential machinery, also workforce demand is considered. Vital competencies $c \in C$ are defined for every operation. Employee availability is realistically modelled in dependence to the course of time, which in turn is sampled in periods $t \in T$. Table 1 depicts all sets used for modelling manufacturing scenarios. Table 2 lists all the parameters and a short respective description. Table 3 contains the decision variable formulation, and table 4 shows the actual model. The model is optimized by a single maximizing objective function and contains a total of six constraints, including the decision variable binary constraint. For the experiments carried out and presented in chapter 5, the model has been implemented using the PuLP linear programming API for Python [73]. Calculations have are done using the COIN-OR open source branch-and-cut solver Cbc [74].

Table 1: Model sets

Set	Notation	Description
Machines	$m \in M$	Every individual machine m is element of the set of machines M.
Operations	$o \in O$	Every individual operation o is element of the set of all operations O.
Periods	$t \in T$	Every individual period t is element of the set of all periods T.
Competencies	$c \in C$	Every individual competence c is element of the set of all competencies C.

Table 2: Model parameters

Parameter	Notation	Description
Energy demand	b_{om}	Average number of energy units needed per period by machine type m for operation o
Energy cost	k_t	Cost per energy unit in period t
Energy capacity	h_t	Maximum number of energy units available per period t
Employee demand	d_{oc}	Number of employees of competence c needed for operation o
Employee cost	w_c	Cost per employee of competence c per period
Employee capacity	f_{ct}	Available number of employees of competence c in period t
Machine cost	p_m	Cost per machine of type m per period
Machine capacity	g_m	Available number of machines of type m
Revenue	e_o	Revenue of operation o, if accepted

Table 3: Model decision variable

Decision variable	Notation	Description
Acceptance of Job	$X_{omt} \in \{0; 1\}$	Binary decision variable; One if operation o is executed on machine m and running in period t, zero otherwise

Table 4: Model formulation

Objective function		
1.	$\max \sum_{o \in O} \sum_{m \in M} \sum_{t \in T} \sum_{c \in C} (e_o - b_{om} * k_t - d_{oc} * w_c - p_m) * X_{omt}$	
Constraints		
2.	$\sum_{m \in M} \sum_{t \in T} X_{omt} \leq 1$	$\forall\, o \in O$
3.	$\sum_{o \in O} X_{omt} \leq 1$	$\forall\, m \in M \wedge t \in T$
4.	$\sum_{o \in O} X_{omt} \leq g_m$	$\forall\, m \in M \wedge t \in T$
5.	$\sum_{o \in O} \sum_{m \in M} X_{omt} * d_{oc} \leq f_{ct}$	$\forall\, t \in T \wedge c \in C$
6.	$\sum_{o \in O} \sum_{m \in M} X_{omt} * b_{om} \leq h_t$	$\forall\, t \in T$
7.	$X_{omt} = \{0; 1\}$	$\forall\, o \in O \wedge m \in M \wedge t \in T$

The energy demand is represented by parameter b_{om} and dependent on operation o and machine m. Energy cost denotes as k_t and peak energy consumption is limited by the parameter h_t, both are subject to period t. Employee demand, cost and availability are modelled alike by the parameters d_{oc}, w_c and f_{ct}. All are dependent on competence c, demand additionally dependents on operation o and availability on period t. For machines, cost and capacity formalize as parameters p_m and g_m and are naturally dependent on the machine m, but independent of their time of use. Since the model aims at maximizing overall revenue from production activities, besides all relevant cost factors, revenue obtained from operations has to be taken into account. Revenue is depicted as a parameter e_o, with dependence on operation o.

To determine the highest obtainable revenue, the optimization must decide on which operations are to be chosen for manufacturing and during which period every single chosen operation must take place. This is done via a single binary decision variable X_{omt}. If an operation o is scheduled for manufacturing on machine m in period t, the decision variable X_{omt} becomes one, while being zero otherwise.

The model's objective function (formula 1) sums up all cost relevant parameters and deducts them from the respective revenue obtainable. Energy cost is multiplied by energy demand and employee demand is multiplied by the respective cost. Together with the machine cost parameter, everything is deducted from the revenue. This sum is then multiplied by the decision variable X_{omt}, which decides on revenue and cost realization. The objective function is sensing for maximization of the sum of all revenues and cost. Formula 2 represents the model's first constraint, which ensures every operation is being planned for execution not more than once by setting the sum over all X_{omt} for each operation to be less or equal to one. The second constraint (formula 3) ensures no machine is scheduled more than in each period. For that, the sum over all X_{omt} for each machine and period is set to be smaller or equal to one. Constraint three (formula 4) keeps the machine allocation below the capacity available by setting the sum over all X_{omt} for each machine and period to be smaller or equal to the machine capacity g_m. The exceedance of the limits set for employee and energy capacity are guaranteed by the constraints four and five (formulas 5 and 6). Constraint four sums up the product of the decision variable X_{omt} times the employee demand for every period and competence. The sum is set not to be greater than the employee capacity per period and competence. Constraint 5 multiplies the decision variable X_{omt} by the energy demand and sums up all products for every period. This is set to be smaller or equal to the energy capacity per period. The last constraint 6 (formula 7) is a binary constraint, realistically limiting the solution space by setting the decision variable X_{omt} to either zero or one.

5. Experiment design

Following the optimization model's contrivance, its viability is tested by executing numeric experiments using the aforementioned Python implementation. Multiple data sets of varying sizes are used to answer two questions: Is a mixed-integer linear programming model of this vein solvable for scenarios of realistic sizes, and therefore relevant to industry applications? If the model turns out to have executions times low enough for business adoption, the second question is whether manufacturing companies can actually benefit from including time varying energy prices in their production planning? Eventually, the possibility of calculating price optimality does not convince decision makers of its adoption, but the proof of revenue increase might do.

A total of six data sets are optimized. For each, the objective function value or maximized revenue is calculated, and a production schedule is created. Since no consistent real manufacturing data has been available during the experiments, all manufacturing related numbers are randomized and drawn from ranges of estimates, in which the authors confide to be common industry values. However, data on energy prices is taken from the German Bundesnetzagentur's electricity market information platform 'SMARD' [75] and depict the actual course for the first week of 2022. All in all, the experiments optimize randomized average production scenarios under real market conditions. The data sets do contain three manufacturing scenarios (small, medium, large) of which each is optimized under varying and average energy prices. The course of energy prices and their average are shown in figure 1.

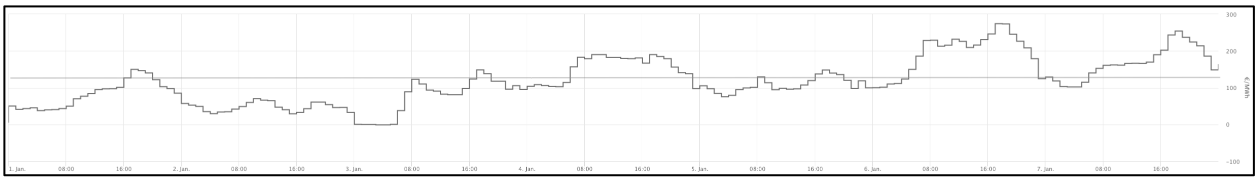

Figure 1: German wholesale electricity prices from [75], first week of January 2022, sampled hourly, in €/MWh

Since problem complexity rises disproportionately with larger data sets, variations in data mainly concern the number of machines, employees and operations taken into account. All calculations are reproducible using the code published under the associated GitHub repository[1]. Besides all Python code, the data set description and pre-generated data set files are available in structured JSON format. Solutions and scheduling tables are provided as well. All code and data are published under the CC BY 4.0 license.

6. Results

First and foremost, the experiments described above are showing, that optimizing scheduling in industrial manufacturing using freely available open source solver software [74] is possible not only for laboratory sized problems, but also for those keeping industrial practitioners busy today. While for mixed-integer linear optimization solution times grow exponentially with additional parameters or increased set sizes, readily

[1] Repository URL: https://github.com/vincentadomat/CPSL23

available hardware[2] is capable of deterministically computing optimal results for common problem sizes in a matter of seconds or minutes. For the smallest data sets, optimality has been found after only 0.14 seconds for average prices and 0.11 seconds variable prices. The largest data sets took 164.41 and 291.6 seconds to compute. Therefore, it can assuredly be said that executions times are low enough for business adoption.

From a business perspective, though, it is more important if optimization actually leads to improved revenue from manufacturing activities. Every optimization forecasts the total revenue from the operations scheduled. An example scheduling table depicting which operation is to be executed on which machine during which period is given by figure 2.

period	57	58	59	60	61	62	63	64	65
date	03.01.2022	03.01.2022	03.01.2022	03.01.2022	03.01.2022	03.01.2022	03.01.2022	03.01.2022	03.01.2022
time	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00
energy cost	122.93	110.17	93.38	90.73	82.37	80.9	80.99	98.05	123.51
machine 1			operation 35	operation 77				operation 81	
machine 2			operation 96					operation 5	
machine 3			operation 16			operation 67	operation 66		
machine 4						operation 4		operation 97	
machine 5		operation 37	operation 27				operation 71		
machine 6			operation 93		operation 62		operation 43	operation 65	
machine 7		operation 47							
machine 8		operation 8	operation 100					operation 2	
machine 9		operation 89		operation 98	operation 14			operation 12	
machine 10					operation 83			operation 61	
machine 11					operation 69	operation 21		operation 31	
machine 12						operation 78		operation 86	
machine 13			operation 91					operation 82	
machine 14					operation 18				
machine 15	operation 32		operation 39		operation 28	operation 17	operation 87	operation 40	
machine 16						operation 45			
machine 17			operation 36			operation 80	operation 72	operation 84	
machine 18									
machine 19		operation 51			operation 90				
machine 20					operation 11	operation 33	operation 13		
machine 21		operation 42					operation 30	operation 24	
machine 22			operation 25		operation 94				
machine 23						operation 63	operation 76	operation 74	
machine 24	operation 68					operation 53			
machine 25			operation 3		operation 41			operation 44	
machine 26			operation 19	operation 99	operation 34			operation 22	
machine 27								operation 1	
machine 28								operation 88	
machine 29							operation 7	operation 20	
machine 30				operation 23					

Figure 2: Example scheduling table as output by the Python model implementation, giving the optimal acceptance and scheduling of 100 operations over 30 machines for variable prices on 3rd January 2022 from 8 am till 4 pm.

Only if all operations are performed as scheduled, the revenue forecasted can be realized. Optimizing the experiment data sets based on average and varying prices with otherwise identical values has shown only little difference in overall revenue obtained. For the medium-sized data set total revenue under average prices is forecasted with €177,892.16 and with €178,724.86 for varying prices. Even though the increase of only 4.66‰ might not lead any decision maker to comprehensively reorganize manufacturing scheduling. At the same time, comparing not only total revenue but the scheduling tables also reveals great difference in which operations are chosen for manufacturing and for which periods their execution is planned. It can be seen, that under varying prices operations involving energy-intensive processes are scheduled towards periods of lower prices, while operations with labor-intensive processes are to be executed in periods of higher prices and higher workforce availability. Stronger evidence for revenue improvement from energy optimized scheduling is expected to be obtained under the use of less uniform and homogeneously distributed values in the manufacturing data sets.

7. Discussion

Performing industrial-sized manufacturing scheduling by mixed-integer linear programming optimization is shown to be viable and can increase overall revenue obtain from such activities. The experiments carried out to furnish proof to the initial assumptions have undoubtedly displayed the model's applicability, even though from a retrospective viewpoint the data on which the experiments are founded is believed to be unfit for generating persuasive results. On the other hand, the calculations presented for non-varying average prices

[2] 2020 M1 Apple MacBook Air with 16 GB RAM

are based on the arithmetic means and do not include common surpluses charged by energy suppliers. Nevertheless, the experiments demonstrate the model's ability to perform manufacturing scheduling under varying electricity prices. In terms of improving industrial manufacturing for adaption to renewable energy sources and increasing price volatility, the model presented in chapter 4 is giving an important prospect of how scheduling can be adapted. Besides an increase in revenue, the ability to shift manufacturing operations opens the opportunity to foster the switch to renewable energy sources even before required by European legislation. Flexibilization thereby is the key to enabling more variable schedule configurations. At first, the assessment of existing manufacturing processes for their energy-intensity and labor-intensity must be fulfilled. The prioritization of highest impact processes when increasing flexibility by removing scheduling constraints must follow.

To put the model presented to beneficial use in real manufacturing scenarios, some essentials are still missing. Currently, no technique for forecasting energy prices is discussed or integrated. Hence, an optimization can currently only be done retrospectively. According to [76] scholars already have identified the need for renewable energy forecasting, but this growing field of research is purposefully excluded from the work at hand. In the future, the model will be extended to especially incorporate operational dependencies. For many real manufacturing settings, the scheduling of unrelated operations among unrelated machines does not describe reality comprehensively and sufficiently. To solve this issue, additional constraints and an additional decision variable will be needed, which will render the model to be non-linear and thereby more difficult to solve optimally.

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References

[1] H. Lee-Makiyama, "The EU Green Deal and Its Industrial and Political Significance", European Centre for International Political Economy (ECIPE), 2021.

[2] M. Mulder and B. Scholtens, "The impact of renewable energy on electricity prices in the Netherlands," Renewable Energy, vol. 57, pp. 94–100, 2013.

[3] I. Berk and H. Yetkiner, "Energy prices and economic growth in the long run: Theory and evidence," Renewable and Sustainable Energy Reviews, vol. 36, pp. 228–235, 2014.

[4] H. N. Larsen, C. Solli, and J. Pettersena, "Supply Chain Management – How can We Reduce our Energy/Climate Footprint?," Energy Procedia, vol. 20, pp. 354–363, 2012.

[5] W. Cai et al., "Promoting sustainability of manufacturing industry through the lean energy-saving and emission-reduction strategy," Science of The Total Environment, vol. 665, pp. 23–32, 2019

[6] P. J. Burke and A. Abayasekara, "The Price Elasticity of Electricity Demand in the United States: A Three-Dimensional Analysis," EJ, vol. 39, no. 2, 2018.

[7] R. L. Graham, E. L. Lawler, J. K. Lenstra, and A. H. G. R. Kan, "Optimization and Approximation in Deterministic Sequencing and Scheduling: a Survey," in Annals of Discrete Mathematics, vol. 5, Elsevier, 1979, pp. 287–326.

[8] E. L. Lawler, J. K. Lenstra, A. H. G. Rinnooy Kan, and D. B. Shmoys, "Chapter 9 Sequencing and scheduling: Algorithms and complexity," in Handbooks in Operations Research and Management Science, vol. 4, Elsevier, 1993, pp. 445–522.

[9] P. Renna and S. Materi, “A Literature Review of Energy Efficiency and Sustainability in Manufacturing Systems,” Applied Sciences, vol. 11, no. 16, p. 7366, 2021.

[10] G. Mouzon and M. B. Yildirim, “A framework to minimise total energy consumption and total tardiness on a single machine,” International Journal of Sustainable Engineering, vol. 1, no. 2, pp. 105–116, 2008.

[11] M. B. Yildirim and G. Mouzon, “Single-Machine Sustainable Production Planning to Minimize Total Energy Consumption and Total Completion Time Using a Multiple Objective Genetic Algorithm,” IEEE Transactions on Engineering Management, vol. 59, no. 4, pp. 585–597, 2012.

[12] S. A. Mansouri, E. Aktas, and U. Besikci, “Green scheduling of a two-machine flowshop: Trade-off between makespan and energy consumption,” European Journal of Operational Research, vol. 248, no. 3, pp. 772–788, 2016.

[13] S. Assia, I. El Abbassi, A. El Barkany, M. Darcherif, and A. El Biyaali, “Green Scheduling of Jobs and Flexible Periods of Maintenance in a Two-Machine Flowshop to Minimize Makespan, a Measure of Service Level and Total Energy Consumption,” Advances in Operations Research, vol. 2020, p. e9732563, 2020.

[14] S. Wang, X. Wang, J. Yu, S. Ma, and M. Liu, “Bi-objective identical parallel machine scheduling to minimize total energy consumption and makespan,” Journal of Cleaner Production, vol. 193, pp. 424–440, 2018.

[15] C.-H. Liu, R. Nanthapodej, and S.-Y. Hsu, “Scheduling two interfering job sets on parallel machines under peak power constraint,” Prod. Eng. Res. Devel., vol. 12, no. 5, pp. 611–619, 2018.

[16] Z. Pan, D. Lei, and Q. Zhang, “A New Imperialist Competitive Algorithm for Multiobjective Low Carbon Parallel Machines Scheduling,” Mathematical Problems in Engineering, vol. 2018, 2018.

[17] L. P. Cota, V. N. Coelho, F. G. Guimarães, and M. J. F. Souza, “Bi-criteria formulation for green scheduling with unrelated parallel machines with sequence-dependent setup times,” International Transactions in Operational Research, vol. 28, no. 2, pp. 996–1017, 2021.

[18] L. Meng, C. Zhang, X. Shao, Y. Ren, and C. Ren, “Mathematical modelling and optimisation of energy-conscious hybrid flow shop scheduling problem with unrelated parallel machines,” International Journal of Production Research, vol. 57, no. 4, pp. 1119–1145, 2019.

[19] K. Nagasawa, Y. Ikeda, and T. Irohara, “Robust flow shop scheduling with random processing times for reduction of peak power consumption,” Simulation Modelling Practice and Theory, vol. 59, pp. 102–113, 2015.

[20] G.-S. Liu, H.-D. Yang, and M.-B. Cheng, “A three-stage decomposition approach for energy-aware scheduling with processing-time-dependent product quality,” International Journal of Production Research, vol. 55, no. 11, pp. 3073–3091, 2017.

[21] G.-S. Liu, Y. Zhou, and H.-D. Yang, “Minimizing energy consumption and tardiness penalty for fuzzy flow shop scheduling with state-dependent setup time,” Journal of Cleaner Production, vol. 147, pp. 470–484, 2017.

[22] B. Zhou and W. Liu, “Energy-efficient multi-objective scheduling algorithm for hybrid flow shop with fuzzy processing time,” Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering, vol. 233, no. 10, pp. 1282–1297, 2019.

[23] G. Chen, L. Zhang, J. Arinez, and S. Biller, “Energy-Efficient Production Systems Through Schedule-Based Operations,” IEEE Transactions on Automation Science and Engineering, vol. 10, no. 1, pp. 27–37, 2013.

[24] K. Fang, N. A. Uhan, F. Zhao, and J. W. Sutherland, “Flow shop scheduling with peak power consumption constraints,” Ann Oper Res, vol. 206, no. 1, pp. 115–145, 2013.

[25] E. Jiang and L. Wang, “An improved multi-objective evolutionary algorithm based on decomposition for energy-efficient permutation flow shop scheduling problem with sequence-dependent setup time,” International Journal of Production Research, vol. 57, no. 6, pp. 1756–1771, 2019.

[26] H. Öztop, M. F. Tasgetiren, D. T. Eliiyi, Q.-K. Pan, and L. Kandiller, “An energy-efficient permutation flowshop scheduling problem,” Expert Systems with Applications, vol. 150, p. 113279, 2020.

[27] X. Wu and A. Che, "Energy-efficient no-wait permutation flow shop scheduling by adaptive multi-objective variable neighborhood search," Omega, vol. 94, p. 102117, 2020.

[28] J.-J. Wang and L. Wang, "A Knowledge-Based Cooperative Algorithm for Energy-Efficient Scheduling of Distributed Flow-Shop," IEEE Transactions on Systems, Man, and Cybernetics: Systems, vol. 50, no. 5, pp. 1805–1819, 2020.

[29] D. Yüksel, M. F. Taşgetiren, L. Kandiller, and L. Gao, "An energy-efficient bi-objective no-wait permutation flowshop scheduling problem to minimize total tardiness and total energy consumption," Computers & Industrial Engineering, vol. 145, p. 106431, 2020.

[30] C. Lu, L. Gao, X. Li, Q. Pan, and Q. Wang, "Energy-efficient permutation flow shop scheduling problem using a hybrid multi-objective backtracking search algorithm," Journal of Cleaner Production, vol. 144, pp. 228–238, 2017.

[31] A. A. G. Bruzzone, D. Anghinolfi, M. Paolucci, and F. Tonelli, "Energy-aware scheduling for improving manufacturing process sustainability: A mathematical model for flexible flow shops," CIRP Annals, vol. 61, no. 1, pp. 459–462, 2012.

[32] M. Dai, D. Tang, A. Giret, M. A. Salido, and W. D. Li, "Energy-efficient scheduling for a flexible flow shop using an improved genetic-simulated annealing algorithm," Robotics and Computer-Integrated Manufacturing, vol. 29, no. 5, pp. 418–429, 2013.

[33] G. Gong et al., "Energy-efficient flexible flow shop scheduling with worker flexibility," Expert Systems with Applications, vol. 141, p. 112902, 2020.

[34] J. Luo, S. Fujimura, D. El Baz, and B. Plazolles, "GPU based parallel genetic algorithm for solving an energy efficient dynamic flexible flow shop scheduling problem," Journal of Parallel and Distributed Computing, vol. 133, pp. 244–257, 2019.

[35] A. Hasani and S. M. H. Hosseini, "A bi-objective flexible flow shop scheduling problem with machine-dependent processing stages: Trade-off between production costs and energy consumption," Applied Mathematics and Computation, vol. 386, p. 125533, 2020.

[36] D. Tang, M. Dai, M. A. Salido, and A. Giret, "Energy-efficient dynamic scheduling for a flexible flow shop using an improved particle swarm optimization," Computers in Industry, vol. 81, pp. 82–95, 2016.

[37] J. Li, H. Sang, Y. Han, C. Wang, and K. Gao, "Efficient multi-objective optimization algorithm for hybrid flow shop scheduling problems with setup energy consumptions," Journal of Cleaner Production, vol. 181, pp. 584–598, 2018.

[38] M. M. Nasiri, M. Abdollahi, A. Rahbari, N. Salmanzadeh, and S. Salesi, "Minimizing the energy consumption and the total weighted tardiness for the flexible flowshop using NSGA-II and NRGA," Journal of Industrial and Systems Engineering, vol. 11, no. Special issue: 14th International Industrial Engineering Conference, pp. 150–162, 2018.

[39] S.-L. Jiang and L. Zhang, "Energy-Oriented Scheduling for Hybrid Flow Shop With Limited Buffers Through Efficient Multi-Objective Optimization," IEEE Access, vol. 7, pp. 34477–34487, 2019.

[40] S. Kemmoe, D. Lamy, and N. Tchernev, "Job-shop like manufacturing system with variable power threshold and operations with power requirements," International Journal of Production Research, vol. 55, no. 20, pp. 6011–6032, 2017.

[41] J. Escamilla, M. A. Salido, A. Giret, and F. Barber, "A metaheuristic technique for energy-efficiency in job-shop scheduling," The Knowledge Engineering Review, vol. 31, no. 5, pp. 475–485, 2016.

[42] M. A. Salido, J. Escamilla, A. Giret, and F. Barber, "A genetic algorithm for energy-efficiency in job-shop scheduling," Int J Adv Manuf Technol, vol. 85, no. 5, pp. 1303–1314, 2016.

[43] G. May, B. Stahl, M. Taisch, and V. Prabhu, "Multi-objective genetic algorithm for energy-efficient job shop scheduling," International Journal of Production Research, vol. 53, no. 23, pp. 7071–7089, 2015.

[44] R. Zhang and R. Chiong, “Solving the energy-efficient job shop scheduling problem: a multi-objective genetic algorithm with enhanced local search for minimizing the total weighted tardiness and total energy consumption,” Journal of Cleaner Production, vol. 112, pp. 3361–3375, 2016.

[45] D. Tang and M. Dai, “Energy-efficient approach to minimizing the energy consumption in an extended job-shop scheduling problem,” Chin. J. Mech. Eng., vol. 28, no. 5, pp. 1048–1055, 2015.

[46] D. Lei, M. Li, and L. Wang, “A Two-Phase Meta-Heuristic for Multiobjective Flexible Job Shop Scheduling Problem With Total Energy Consumption Threshold,” IEEE Transactions on Cybernetics, vol. 49, no. 3, pp. 1097–1109, 2019.

[47] M. Abedi, R. Chiong, N. Noman, and R. Zhang, “A multi-population, multi-objective memetic algorithm for energy-efficient job-shop scheduling with deteriorating machines,” Expert Systems with Applications, vol. 157, p. 113348, 2020.

[48] L. Zhang, Z. Li, G. Królczyk, D. Wu, and Q. Tang, “Mathematical modeling and multi-attribute rule mining for energy efficient job-shop scheduling,” Journal of Cleaner Production, vol. 241, p. 118289, 2019.

[49] E. Jiang, L. Wang, and Z. Peng, “Solving energy-efficient distributed job shop scheduling via multi-objective evolutionary algorithm with decomposition,” Swarm and Evolutionary Computation, vol. 58, p. 100745, 2020.

[50] J.-Y. Moon and J. Park, “Smart production scheduling with time-dependent and machine-dependent electricity cost by considering distributed energy resources and energy storage,” International Journal of Production Research, vol. 52, no. 13, pp. 3922–3939, 2014.

[51] L. Meng, C. Zhang, X. Shao, and Y. Ren, “MILP models for energy-aware flexible job shop scheduling problem,” Journal of Cleaner Production, vol. 210, pp. 710–723, 2019.

[52] D. Lei, Y. Zheng, and X. Guo, “A shuffled frog-leaping algorithm for flexible job shop scheduling with the consideration of energy consumption,” International Journal of Production Research, vol. 55, no. 11, pp. 3126–3140, 2017.

[53] S. Luo, L. Zhang, and Y. Fan, “Energy-efficient scheduling for multi-objective flexible job shops with variable processing speeds by grey wolf optimization,” Journal of Cleaner Production, vol. 234, pp. 1365–1384, 2019.

[54] M. Dai, D. Tang, A. Giret, and M. A. Salido, “Multi-objective optimization for energy-efficient flexible job shop scheduling problem with transportation constraints,” Robotics and Computer-Integrated Manufacturing, vol. 59, pp. 143–157, 2019.

[55] X. Wu and Y. Sun, “A green scheduling algorithm for flexible job shop with energy-saving measures,” Journal of Cleaner Production, vol. 172, pp. 3249–3264, 2018.

[56] V. Saddikuti and V. Pesaru, “NSGA Based Algorithm for Energy Efficient Scheduling in Cellular Manufacturing,” Procedia Manufacturing, vol. 39, pp. 1002–1009, 2019.

[57] Y.-C. Choi and P. Xirouchakis, “A holistic production planning approach in a reconfigurable manufacturing system with energy consumption and environmental effects,” International Journal of Computer Integrated Manufacturing, vol. 28, no. 4, pp. 379–394, 2015.

[58] F. Niakan, A. Baboli, T. Moyaux, and V. Botta-Genoulaz, “A bi-objective model in sustainable dynamic cell formation problem with skill-based worker assignment,” Journal of Manufacturing Systems, vol. 38, pp. 46–62, 2016.

[59] Z. Zeng, M. Hong, Y. Man, J. Li, Y. Zhang, and H. Liu, “Multi-object optimization of flexible flow shop scheduling with batch process — Consideration total electricity consumption and material wastage,” Journal of Cleaner Production, vol. 183, pp. 925–939, 2018.

[60] The European Commission, “Electricity market design”, 2022. https://energy.ec.europa.eu/topics/markets-and-consumers/market-legislation/electricity-market-design_en (accessed Sep. 09, 2022).

[61] F. Shrouf, J. Ordieres-Meré, A. García-Sánchez, and M. Ortega-Mier, “Optimizing the production scheduling of a single machine to minimize total energy consumption costs,” Journal of Cleaner Production, vol. 67, pp. 197–207, 2014.

[62] S. Wang, M. Liu, F. Chu, and C. Chu, “Bi-objective optimization of a single machine batch scheduling problem with energy cost consideration,” Journal of Cleaner Production, vol. 137, pp. 1205–1215, 2016.

[63] S. Wang, Z. Zhu, K. Fang, F. Chu, and C. Chu, “Scheduling on a two-machine permutation flow shop under time-of-use electricity tariffs,” International Journal of Production Research, vol. 56, no. 9, pp. 3173–3187, 2018.

[64] M. H. Ho, F. Hnaien, and F. Dugardin, “Electricity cost minimisation for optimal makespan solution in flow shop scheduling under time-of-use tariffs,” International Journal of Production Research, vol. 59, no. 4, pp. 1041–1067, 2021.

[65] J. Rocholl, L. Mönch, and J. Fowler, “Bi-criteria parallel batch machine scheduling to minimize total weighted tardiness and electricity cost,” J Bus Econ, vol. 90, no. 9, pp. 1345–1381, 2020.

[66] H. Zhang, Y. Wu, R. Pan, and G. Xu, “Two-stage parallel speed-scaling machine scheduling under time-of-use tariffs,” J Intell Manuf, vol. 32, no. 1, pp. 91–112, 2021.

[67] B. Kurniawan, A. A. Gozali, W. Weng, and S. Fujimura, “A genetic algorithm for unrelated parallel machine scheduling minimizing makespan cost and electricity cost under time-of-use (TOU) tariffs with job delay mechanism,” in 2017 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), 2017, pp. 583–587.

[68] J.-Y. Moon, K. Shin, and J. Park, “Optimization of production scheduling with time-dependent and machine-dependent electricity cost for industrial energy efficiency,” Int J Adv Manuf Technol, vol. 68, no. 1, pp. 523–535, 2013.

[69] H. Saberi-Aliabad, M. Reisi-Nafchi, and G. Moslehi, “Energy-efficient scheduling in an unrelated parallel-machine environment under time-of-use electricity tariffs,” Journal of Cleaner Production, vol. 249, p. 119393, 2020.

[70] H. Zhang, F. Zhao, K. Fang, and J. W. Sutherland, “Energy-conscious flow shop scheduling under time-of-use electricity tariffs,” CIRP Annals, vol. 63, no. 1, pp. 37–40, 2014.

[71] H. Luo, B. Du, G. Q. Huang, H. Chen, and X. Li, “Hybrid flow shop scheduling considering machine electricity consumption cost,” International Journal of Production Economics, vol. 146, no. 2, pp. 423–439, 2013.

[72] M. Zhang, J. Yan, Y. Zhang, and S. Yan, “Optimization for energy-efficient flexible flow shop scheduling under time of use electricity tariffs,” Procedia CIRP, vol. 80, pp. 251–256, 2019.

[73] S. Mitchell et al., “coin-or/pulp: 2.6.0.” Zenodo, Dec. 04, 2021, doi: 10.5281/ZENODO.5759078.

[74] J. Forrest et al., “coin-or/Cbc: Release releases/2.10.8.” Zenodo, May 05, 2022, doi: 10.5281/ZENODO.6522795.

[75] Bundesnetzagentur, “SMARD | Marktdaten,” SMARD - Strommarktdaten für Deutschland, 2022. https://www.smard.de/home/downloadcenter/download-marktdaten (accessed Nov. 01, 2022).

[76] C. Croonenbroeck and G. Stadtmann, “Renewable generation forecast studies – Review and good practice guidance,” Renewable and Sustainable Energy Reviews, vol. 108, pp. 312–322, 2019.

Biography

Vincent Adomat, M.Sc. (*1994) studied Industrial Engineering and Business Economics at Leuphana University Lüneburg and International Management and Engineering at Hamburg University of Technology and the National University of Singapore. For pursuing his PhD in Engineering, he joined the Institute of Production Engineering at Helmut Schmidt University in 2020.

Christian Kober, M.Sc. (*1995) studied Industrial Engineering at the University of Applied Sciences Wedel. He joined the Helmut Schmidt University Hamburg in 2021 as research associate and doctoral candidate. His research focuses on economic aspects of Digital Twins in manufacturing. He previously gained experience in the aerospace and automotive industry.

Maryam Ahanpanjeh, M.Sc. (*1989) has been a research associate and doctoral candidate at the Helmut Schmidt University since 2021. She received the Master degree in Mechanical Engineering from the Tarbiat Modares University in Tehran. Her main research interests are digitalization of lightweight production and robotics.

Univ.-Prof. Dr.-Ing. Jens Wulfsberg (*1959) is head of themchair of Production Engineering in the Department of Mechanical Engineering at Helmut Schmidt University in Hamburg since 2001. After having been dean of the Faculty of Mechanical Engineering, he has been the president of the German Scientific Society for Production Engineering (WGP) since 2022.

4th Conference on Production Systems and Logistics

Data Science To Measure The Efficiency Of Delivery Of The Last Mile Processes In Logistics

Verónica Saavedra Gastélum[1], Carlos Alberto González Almaguer[1], Beatriz Murrieta Cortés[1], Eréndira Gabriela Avilés Rabanales[1]
[1] *Tecnologico de Monterrey/ Queretaro, Mexico*

Abstract

One of the most critical parameters of logistics processes is to measure the efficiency of delivery of the final product to the customer, or last mile processes. Historically, the customer does not care about the processes that are carried out before delivering the product, the end customer is interested in the product reaching their hands on the promised date. The measurement of the efficiency of the logistics processes transit time is necessary to analyse it partially by the different processes and the entities that intervene, from suppliers, manufacturing centres, distribution centres, and carriers. The design of the layout to collect the information allows statistical analysis to evaluate the performance in each part of the process and the generation of algorithms to predict different compartments that can be potentially negative for the fulfilment of the product delivery promise times. The current investigation shows the application of statistical models for predicting delivery errors and delays in delivery in the last mile process in logistics.

Keywords

Higher Education; Educational Innovation; Logistics KPI; Last mile; Data Sciences

1. Introduction

The last mile process has become one of the most attractive processes for continuous improvement in logistics processes. It is thus called the last part of delivering an order to the final customer. Escudero, et al said the “one of the biggest challenges faced by e-commerce is to reduce the number of incidents that occur in the delivery of goods to the homes of customers” [1]. The journey of the package from the last delivery base to the final recipient is considered one of the most expensive parts of the supply chain and it is the most difficult to plan [2]

In 2021 Chen et al. presented an approach to last mile performance evaluation at the parcel level by measuring desirable destinations reasonably reachable through accessible transit stations, they analysed some areas within Chicago and found out that areas with low last-mile accessibility performance are more likely to cluster in communities that have greater economic disadvantages, lower density, and less mixed land use, implying spatial inequality and disparity in overall accessibility. This can cause problems in the last mile process, hence they proposed an approach to implement interventions with the use of big data to improve transit connectivity and to reduce the disparity of transit connectivity and accessibility across neighbourhoods. [3]

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Therefore, it is important to try to minimise the time and the cost of the last mile part of the process of delivery. In 2021 Rosendorff, et al. proposed an Artificial intelligence for last-mile logistics to improve delivery forecasting. They used data mining techniques to illustrate the complexity and importance of preparation of the data as well as the analysis of the information in a theoretical way. [4]

The last mile process is always affected by the whole process from the moment the client places an order until he receives the product at his home or warehouse. Each part of the process must be measured and compared to what it should be (duration), each delay will be called a deviation. Each deviation must be subject to analysis and study to reduce delivery time. Historically, the process analyst is tempted to focus on the last mile processes as the source of the problem when the delivery time in the last mile is compromised since the customer order is placed.

The objective of this analysis is to propose a methodology to measure the possible risks that can affect the delivery of the parcels in the last mile process by the simulation of possible scenarios that can be reached and adapted by the delivery companies in order to minimise the possible problems that can emerge in the last mile process.

2. **Background**

The state of Querétaro currently has 45 industrial parks, most of them located in the Colón area, while in the metropolitan area of the city of Queretaro there are approximately 21, the predominant being those installed in the municipalities of El Marqués, Colón, and Santa Rosa.

Querétaro has a great tradition within the industrial sector, especially as a manufacturer of household goods, auto parts, the chemical industry, and the food sector. New industry sectors, such as aerospace, logistics, contact centres, and information technology, have been developed in recent years. The industrial sector of Querétaro contributes 34.5% of the jobs, and the industry offers a total of 153 thousand 337 jobs.

Querétaro has doubled its population in the last 25 years; this, coupled with its growing real estate and industrial activity, has placed Querétaro as a virtual logistics node for the dynamic national economy. [5]

This is the reason why the analysis of the last mile process and all the risks that affect this part of the process was addressed. The growth of the state of Queretaro has generated the need to use data science in logistics to minimise costs, minimise delivery times, and analyse the factors that precisely affect the last mile based on probabilistic analysis.

Figure 1 shows a soft system analysis of the main elements of the delivery process for the last mile. In Queretaro the components of the final product could be received according to the design of the routes by plane, by truck, by train, or by boat. Once that the components are in the manufacturing complex/facility an assignment plan must be faced. Together with the city rules and norms, concurrent thinking and prospective thinking must be addressed. The final product now should be ready to deliver on time and it is in this part of the process where this paper is intended to simulate all the possible problems that can occur. These problems can be road accidents, routes closed for road repairs, traffic at peak hours, and even theft. After the problem identification, it's possible to optimise the last mile processes through the application of data science models.

When the final customer receives the product on time, both the client and the company are going to be happy and satisfied. On the contrary, if the customer receives the product with delay, there will be a loss of money and the credibility of the company will be compromised.

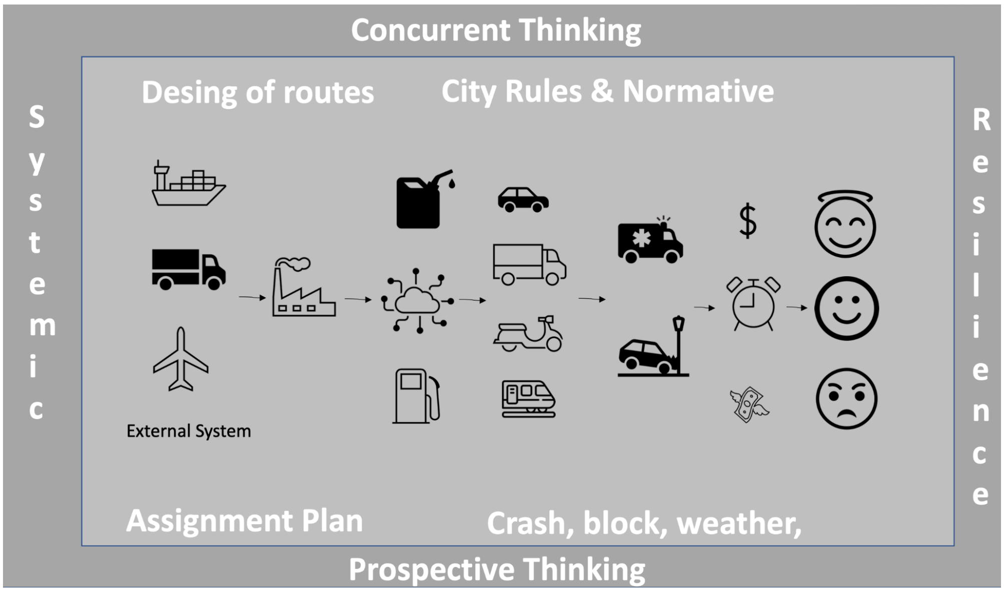

Figure 1. Soft systems for last mile

The data science model design is proposed to incorporate system thinking, concurrent and prospective thinking, for taking into account regulatory compliance, risks and to select routes, make alterations, and gain resilience through modelling iterations.

For the subsequent development of this research, it is proposed the data analysis of information provided by the state of Querétaro and the consideration of furthering mobile distribution Hubs, which would facilitate the deliveries of small-sized envelopes and boxes through light transport -bicycles and motorcycles- to avoid city traffic.

3. **Statistical Model Proposal**

3.1 First approximation

The first approximation to minimise the problems that can occur in the last part of the delivery process is going to be modelled by the use of some probability distributions. The delay caused by traffic jams can be solved using GPS as Feng [6] proposed, hence that problem is not going to be analysed in this paper. The Statistical model will include only the problems caused by accidents and theft.

As a first approximation the Pert distribution is proposed since there is no information of the delivery times. The opinion of the expert is requested to be able to define the minimum time, the maximum time, and the most likely time of the deliveries in the last mile process.

At this point, Statistics helps us model these processes by adding probabilities of occurrence to the problems that may arise during the last mile process. According to Traxion [7], For Cargo Mobility and last mile, the data are road accidents and thefts in Mexico reported to insurance companies (claims) as follows in Table 1. Theft data includes theft of motor units and merchandise.

Table 1: Cargo Mobility and Last Mile - Road Accidents and theft in 2021

	Incidents	Travels	Percentage
Cargo Mobility and Last Mile - Road Accidents	2,481	340,132	0.7294%
Cargo Mobility and Last Mile - Theft	48		0.0141%

The probability of road accidents and theft can be integrated through a Binomial distribution.

$$P(x) = \frac{n!}{(n-x)!n!} p^x (1-p)^{n-x} \qquad Mean = n * p \tag{1}$$

Where n is 1 and p is the probability given in Table 1 for each case.

For this case, a Pert distribution can be used for modelling the expected time of delivery, where the minimum could be 2 hours, maximum 72 hours, and the most likely value 8 hours.

It is important to notice that when a theft occurs, the delivery time will be affected, since it could be that the theft causes a delay of double of the time for delivery. On the other hand, in cases where an accident occurs, the delivery time will be affected by a Pert distribution and the values of minimum, maximum and most likely time must be given.

All these values can be adjusted by an expert in the area and for the particular company in order to have better results according to their needs.

3.2 Simulation

A simulation was run with the following conditions in order to show the impact of the accidents and theft in the delivery times.

A Pert distribution was used for modelling the expected time of delivery, where the minimum was 2 hours, maximum was 72 hours, and the most likely value was 8 hours. For modelling the accidents, the minimum was 10 hours, maximum was 72 hours, and the most likely value was 20 hours. (The parameters were given by an expert)

For the parameter of the Binomial distribution, the probability of accident was 5% and the probability of theft 0.014%. Figure 2 shows the comparison of the two cases, case 1 is the normal delivery time and case 2 delivery with delays.

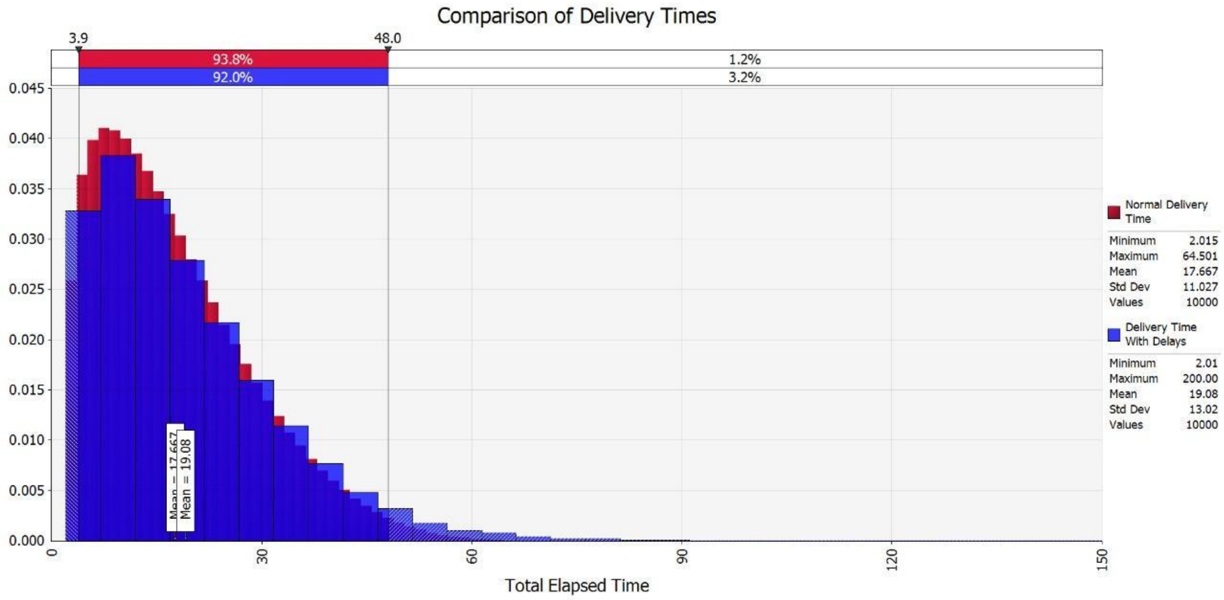

Figure 2. Comparison of delivery times

Although there is not much difference between the two means, it is important to notice that the maximum values are pretty different. Furthermore, the probability of delivering in more than 48 hours in the normal delivery case is 1.2% while in the delay case is 3.2%.

As it was said, this is a scenario that can help the reader to understand the model, but with the information of the expert for a specific company applied to the model can provide more accurate information to the company.

4. Conclusions

A simulation of the delivery times with the use of the information of an expert as well as the data of road accidents and thefts in Mexico reported to insurance companies (claims) was done in order to measure the impact in the delivery times that a theft or a car accident can have. It was found that the probability of delivering in more than 48 hours in the normal delivery case was 1.2% while in the delay case was 3.2%.

By incorporating statistical analysis in the logistics system, it is possible to anticipate and take the appropriate actions to minimise the problems associated with the last mile. The probability of problems will always exist; however, awareness will reduce their impact and minimise the main potential risks in last-mile delivery.

Another critical factor is knowing the delivery area derived from statistical analysis to find possible alternate routes, parking places, or simply putting distribution places closer to the end customer.

Data science then takes on a significant value because it helps us precisely find the necessary values to minimise the probability of delivery delays and find the best access routes that minimise the cost of deliveries to the end customer.

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References

[1] Escudero-Santana, A.; Muñuzuri, J.; Lorenzo-Espejo, A.; Muñoz-Díaz, M.-L. 2022. Improving E-Commerce Distribution through Last-Mile Logistics with Multiple Possibilities of Deliveries Based on Time and Location. J. Theor. Appl. Electron. Commer. Res. 17, pp 507–521. https://doi.org/10.3390/ jtaer17020027

[2] Hsiao, Y. H., Chen, M. C., Lu, K. Y., & Chin, C. L., 2018. Last-mile distribution planning for fruit-and-vegetable cold chains. The International Journal of Logistics Management, 29(3), pp 862:886.

[3] Chen, S; Yan, X.; Pan, H.; Deal, B., 2021. Using big data for last mile performance evaluation: An accessibility-based approach. Elsevier, Travel Behaviour and Society 25, pp 153:163 https://doi.org/10.1016/j.tbs.2021.06.003

[4] Rosendorff, A.; Hodes, A.; Fabian, B., 2021. Artificial intelligence for last-mile logistics – Procedures and architecture. A Publication of the International Institute for Applied Knowledge Management. Online Journal of Applied Knowledge Management. Volume 9, Issue 1, pp 46:61.

[5] Luna Vázquez, J.A., 2018. Dispersión urbana de las zonas metropolitanas de México, estudio de la zona metropolitana de la Ciudad de Querétaro. (Trabajo Fin de Máster Inédito). Universidad de Sevilla, Sevilla.

[6] Feng, T., & Timmermans, H. J., 2015. Detecting activity type from GPS traces using spatial and temporal information. European Journal of Transport and Infrastructure Research, 15(4).

[7] Traxion Global, 2021. Informe Integrado 2021. https://traxion.global/assets/assets/II21_ESP.pdf

[8] Morris, E., 2002. How Data Analytics Can Help Improve Last Mile Logistics. https://datafloq.com/read/how-data-analytics-can-help-improve-last-mile-logistics/

[9] Giuffrida, N.; Fajardo-Calderin, J.; Masegosa, A.D.; Werner, F.; Steudter, M.; Pilla, F., 2022. Optimization and Machine Learning Applied to Last-Mile Logistics: A Review; Sustainability, 14 (9):5329.

[10] Praet, S., Martens, D., 2019. Efficient Parcel Delivery by Predicting Customers' Locations; Decision Sciences; vol 51, issue 5, pp 1202-1231.

[11] Gabrindo, A.L., 2020. Modelado de un sistema Camión-Remolque para la asignación de bahías de carga y descarga a vehículos de reparto en áreas urbanas: Un caso de estudio del Centro Histórico de la Ciudad de Querétaro.

[12] J.J. Méndez Palacios y E. Álvarez Alfaro, 2018. Caracterización de empresas logísticas en la metrópolis de Querétaro; Revista NTHE, n 21, pp 28-38.

[13] Regalao-Noriega, C. J.; Prieto-Pulido, R. A.; Saucedo-Martínez, J. A., 2020. Evaluation of the feasibility of implementing 4.0 industry technologies in the Last Mile processes case: Logistic Operators of the Department of Atlántico. 15th Iberian Conference on Information Systems and Technologies (CISTI) Seville, Spain, pp 24:27.

[14] Sułkowski, Ł.; Kolasinska-Morawska, K.; Brzozowska, M.; Morawski, P.; Schroeder, T, 2022. Last Mile Logistics Innovations in the Courier-Express-Parcel Sector Due to the COVID-19 Pandemic. Sustainability, 14, 8207. https://doi.org/10.3390/su14138207

[15] Muñoz-Villamizar, A.; Solano-Charris, E.L.; Reyes-Rubiano, L.; Faulin, J., 2021. Measuring Disruptions in Last-Mile Delivery Operations. Logistics 2021, 5, 17. https://doi.org/10.3390/logistics5010017

Biography

Verónica Saavedra Gastélum (*1974) has a bachelor's degree in actuarial sciences, a Master of Science in Statistics, and a Ph D in Engineering. Verónica Saavedra has been a professor at Tecnologico de Monterrey since 2001. She is a member of the Research and educational innovation team (REIT) at Tecnologico de Monterrey.

Carlos Alberto Gonzalez (*1970) has been professor of the Industrial Engineering Department (IIS) at the Tecnologico de Monterrey since 2003. Prof. Dr.-Ing. Carlos Alberto Gonzalez, actually is the leader of the Research and Educational Innovation Team R&EIT (2015-2022) and has been a member of the E&PDE International Scientific Review Board since 2015.

Beatriz Murrieta Cortés (*1972) has been head of Industrial Engineering Department (IIS) at the Tecnologico de Monterrey Campus Queretaro since 2008. Prof. Dr.-Ing. Beatriz Murrieta is also a member of many academies of technical sciences and other scientific societies.

Lourdes Jazmin Muciño Garcia (*1999) is a student of bachelor's degree in Development and Innovation Engineering at Tecnologico de Monterrey to graduate in June 2023. She has been a member of the Research and educational innovation team (REIT) for a year.

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Application-Oriented Method For Determining The Adhesion between Insulated Flat Copper Wire And Impregnation Resin

Achim Kampker[1], Heiner Hans Heimes[1], Benjamin Norbert Dorn[1], Florian Brans[1], Henrik Christoph Born[1]

[1]*Chair of Production Engineering of E-Mobility Components, RWTH Aachen University, Aachen, Germany*

Abstract

In the field of hairpin stator technology, increasing demands are currently being made on the semi-finished product of insulated flat copper wire. In particular, the focus is on the electrical requirements against the background of increasing voltage levels to 800 V and more. The test procedures described in the standards IEC 60317 & 60851 for verifying the properties of insulated flat copper wires only partially map the requirements from the point of automotive industry. An example for insufficiently considered properties lays in the correlation between wire and insulation resin. In addition to electrical and thermal benefits, impregnation helps to mechanically stabilize the winding and protect it from ambient factors. Adhesion between the winding and the impregnating resin is a key parameter here but is not considered in material pre-selection today. The adhesion of the impregnation resin to the insulated wire is essential to ensure the lifetime of electric motors. This paper describes a method for determining the adhesion of the impregnating resin to the insulation of the wire. It could be shown that there is a correlation between the material of the wire insulation and the impregnating resin in terms of adhesion. Further on the described method can be used for an application-oriented specification of insulated copper flat wires to ensure a consistent composition of the insulation material.

Keywords

Hairpin stator technology; Electric motor production; Secondary insulation; Flat copper wire; Impregnation; 800V; Test procedure; PAI; PEEK

1. Introduction

While hairpin stator technology is still in the ramp-up phase, the next wave of product-side optimization is already emerging with 800 V technology and the use of SiC-based semiconductors in power electronics. The significantly higher voltages - coupled with higher switching frequencies - are accompanied by higher requirements for insulation systems along the entire electrical drivetrain. [1,2] These also affect the insulation material on insulated copper flat wires in hairpin applications. To meet the increased requirements, the hairpin sector is working towards thicker layers, but also more and more towards alternative insulation materials. While polyamide-imide (PAI) is the most common material in automotive traction drives, other insulation materials such as polyetheretherketone (PEEK) or perfluoroalkoxy polymers (PFA) are also used.

In the context of the electric motor, wire insulation is also referred to as primary insulation. Secondary insulation involves, besides the insulation paper, impregnation of the stator winding. In one of the later process steps within the stator production process the wound stator is impregnated by a trickling or dipping

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process. The impregnation process contains a sub-process in which the stator winding is cast with a liquid resin, which hardens under the influence of heat in the second sub-process. [3] The impregnation serves to mechanically fix the winding and optimize the insulation and thermal conductivity properties of the insulation system by casting the wire gaps. In the process, capillary action causes the liquid resin to penetrate and fill the wire gaps in the stator slots. [4]

By optimizing the properties of the electrical insulation and the thermal conductivity of the stator insulation system, impregnation leads to an increase in the service life of the entire stator. A decisive quality feature in this context is the filling factor, especially at the bottom of the slot and between the windings. A faulty process causes cavities, which can lead to premature stator failure due to the increasing probability of partial discharges or electrical breakdowns (cf. Figure 1) [5].

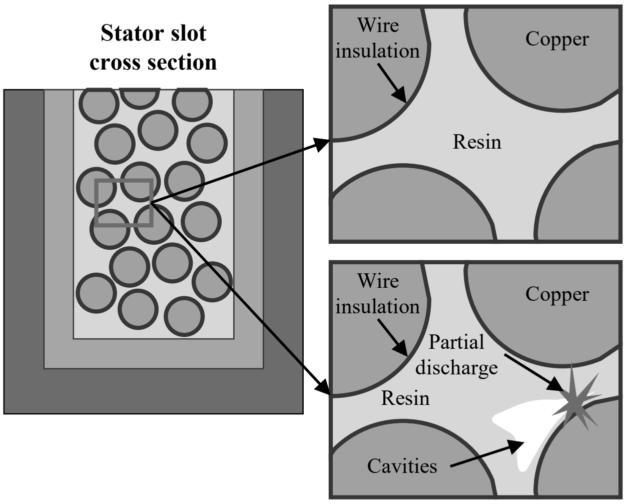

Figure 1: Quality features of impregnated stator windings

The impregnation resin as the secondary insulation interacts directly with the insulation material on the copper flat wire as the primary insulation. To ensure a sufficient fill factor in the spaces between the windings, the adhesion between the wire insulation and the resin is also decisive. For long-lasting operation of the electric motor, it is also crucial that the resin does not detach from the insulation material due to vibrations during operation, as damage in this insulation system can also lead to failure of the drive unit.

Against this background, the interaction in the form of adhesion between insulated flat copper wire and the impregnation resin must be investigated for different material combinations. Up to now, there has been no standardized test method for quantifying the adhesion in a reproducible manner. The common standards IEC 60317 and 60851 for winding wires do not consider this property [6,7]. The test procedure described below represents an approach to measuring adhesion between the two insulation materials. In this way, material combinations are to be investigated with regard to adhesion, so that the best material combination for wire insulation and impregnation resin can be selected. In perspective, the transfer of this method e.g., into a material specification as well as for quality control is suitable to ensure application-oriented properties of flat copper wires and impregnation resins.

2. Methodology

2.1 Experimental setup

The overall objective is to determine the adhesion between the impregnating resin and the insulation of the copper wire. The force with which a cylinder of resin can be pulled off a wire sample represents the central measured variable. With this measurand, differences in the adhesion of the impregnating resin to the insulation layer are to be identified and made measurable.

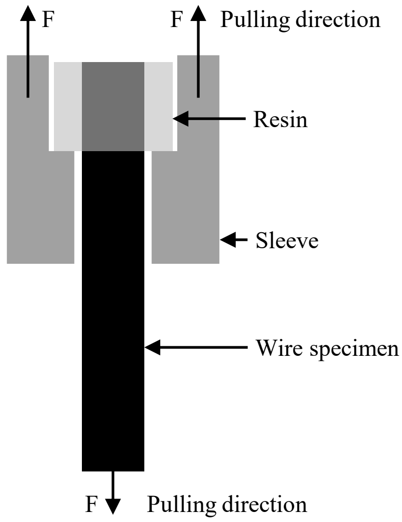

Figure 2: Schematic illustration of the test procedure

The experimental setup of the test is shown in Figure 2. The wire specimen is coated with impregnation resin at one end. In order to clamp the specimen in a tensile testing machine, a sleeve is placed directly against the hardened resin. This allows a tensile force to be applied to the resin in a subsequent tensile test. The sleeve is made of steel and is clamped in the tensile testing machine. As a result, the cured impregnation resin is not affected by shear forces. Since the cured resin is very brittle, there would otherwise be a risk that the shear forces would damage it.

2.2 Preparation of specimen

The process for producing the specimens is divided into four main steps, which are shown schematically in Figure 3. In the first step, a mold is 3D printed which contains the positive shape of the specimen to be cast later. For the later demoldability of the parts to be cast, demolding chamfers are provided on the flanks. In the second step, this mold is filled with a silicone. Curing of the silicone creates a negative mold, in which the actual specimens for the test are cast in the next step. An addition-curing silicone (Wacker Elastosil® RT 620 A/B [8]) was used to make the silicone molds. The advantage of this material is that it vulcanizes quickly and without shrinkage at room temperature. Meanwhile, vulcanization can be significantly accelerated by applying heat. In the context of the production of the silicone molds, vulcanization took place at 60 °C in the oven. In order to prevent the 3D printed molds from melting at this temperature, they were manufactured using stereolithography, since the material used loses its mechanical properties at significantly higher temperatures. It would also be conceivable to manufacture the 3D printed molds using fused filament fabrication (FFF), but the silicone can then only vulcanize at room temperature, which is time-consuming.

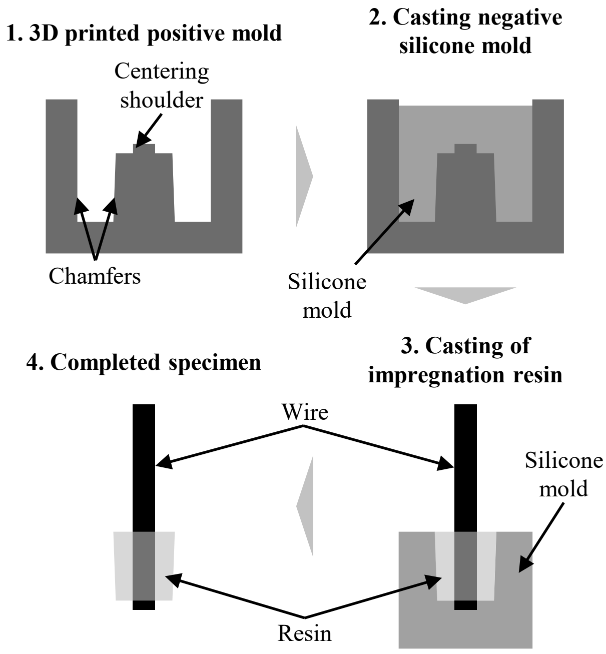

Figure 3: Schematic procedure for the preparation of the specimen

The 3D printed molds are provided with a small shoulder on the middle cylinder, which exactly corresponds to the wire cross-section. This shoulder results in a recess in the silicone mold, which serves to center the wire used exactly in the silicone mold during the production of the wire specimen. As a result, new molds must be made for each wire cross section used. However, due to the low material costs of the molds, the advantages resulting from the possibility of exact centering outweigh dis disadvantage.

In order to produce several wire specimens simultaneously, a jig was designed and manufactured, which is shown in Figure 4. The lower, laser-cut sheet contains cutouts in which the silicone molds can be placed and clearly define their position. The upper sheet also has cutouts that correspond exactly to the wire cross-section. The cutouts in the upper sheet serve both to fix the wires and to center the wire sample in the silicone mold. The cutouts in the sheet are exactly above the previously mentioned shoulder in the silicone molds, so that the wire is positioned exactly centered and straight in the silicone mold.

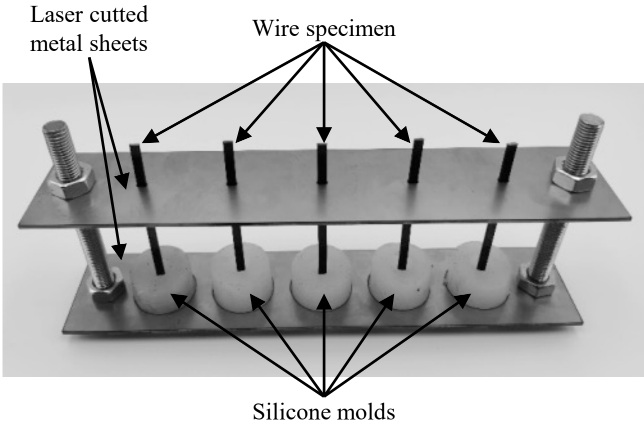

Figure 4: Setup for the production of multiple wire samples

After positioning the wires in the build-up, the silicone molds are filled with impregnation resin. The entire assembly is then placed in an oven, for curing of the impregnation resin. The temperature of the oven as well as the time for curing depends on the resin used.

After the resin has cured in the oven, the specimens are demolded. This is where the advantage of silicone becomes apparent. Due to the soft properties of the silicone, it can be separated from the resin with little force, so that neither the specimen nor the mold is damaged. The finished specimen is shown in Figure 5.

Figure 5: Finished wire sample with cured resin

2.3 Execution of tests

The specimens are clamped on a tensile testing machine as shown in Figure 6. In the starting position, the distance between the clamping jaws is 25 mm. The turned sleeve is clamped over its complete length with the clamping jaws. For a total specimen length of 90 mm, the length of the clamping of the wire is 40 mm.

The specimen is pulled at a test speed of 100 mm/min. The test ends as soon as the test force drops, as it can be assumed that the impregnating agent detaches from the wire at this point. The maximum measured force is noted as the force at which the impregnating agent detaches from the wire and is thus the relevant measurand for determining the adhesion between resin and insulated flat copper wire.

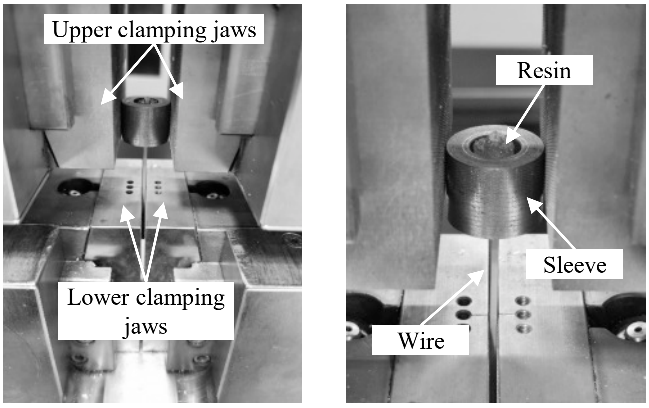

Figure 6: Test setup on tensile testing machine

3. Results and Discussion

In the following the results of the tests are presented and discussed. The tests were performed with three different flat wires. The properties of the flat wires are shown in Table 1. For the impregnation resin, a material from the company Elantas© (ELAN-protect® UP142 [9]) was used. This resin is widely used in the production of electric motors and hairpin stators.

Table 1: Characteristics of the flat wires used for the tests

Name	Dimensions [mm x mm]	Insulation thickness [µm]	Insulation material
PAI 1	4,00 x 1,50	80	PAI
PAI 2	3,64 x 2,59	100	PAI
PEEK	3,90 x 1,80	100	PEEK

First, the measurement results of the maximum force according to the wire used are shown in a box plot. Based on this, the functionality and informative value of the developed test procedure is assessed. Subsequently, three force-elongation curves per wire used are compared with each other as examples in order to analyze and interpret the measurement results for the individual wire insulation materials.

For each of the three wires, 15 samples were prepared and examined. The resin of sample 11 of the PAI 1 wire cracked during the testing process, so the overall test series of this wire contains measurement data of 14 samples. Figure 7 shows the measured values for each of the three wires tested in a boxplot diagram. For the PAI 1 wire, the lowest measured force was 914 N and the highest measured force was 1143 N. The range from the lower quartile to the upper quartile spans the range of 983 N to 1088 N. The mean and median are very close to each other with 1043 N for the mean and 1037 N for the median. For wire PAI 2, the lowest measured force was 630 N, whereas the highest measured value was 1243 N. The lower quartile could be measured at 805 N and the upper quartile at 1040 N. The range of the box is thus significantly higher than the values of the box of the PAI 1 wire. The mean value with a value of 919 N as well as the median with a value of 923 N are also significantly below the values for the PAI 1 wire. The lowest and highest measured force for the PEEK wire is 116 N and 277 N, respectively. The lower quartile has a value of 194 N, whereas the upper quartile has a measured value of 244 N. The mean and median values are very close to each other at 210 N and 203 N. It is striking that the mean value of the PEEK wire is about a factor of 5 smaller than the mean values of the two PAI wires.

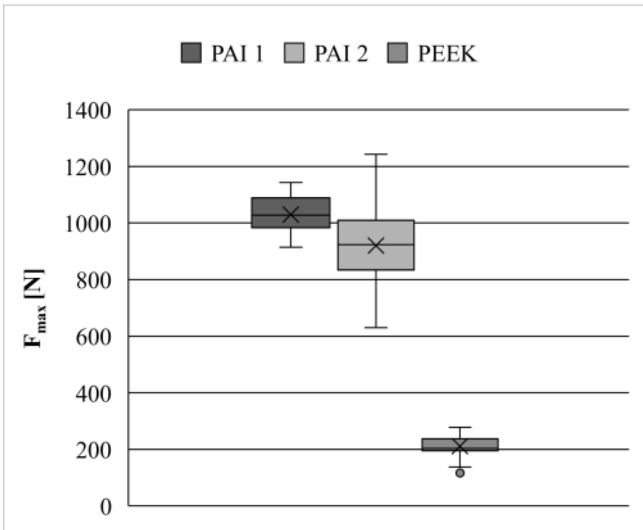

Figure 7: Display of the measured values in a boxplot diagram

The measurement results show that there is a significant difference in adhesion between an impregnation resin and wire insulations that differ in material. In particular, the adhesion of the PEEK-coated flat wire is significantly lower than that of PAI.

It is also noticeable that the measured values of the PAI 2 wire show a significantly greater scatter compared to the PAI 1 wire. This fact suggests that within one wire there may be high differences in the surface properties resulting in varying adhesion of the impregnating agent. One potential explanation lies in the production process of the enameled flat wire. One possible cause, for example, is that the solvent is not uniformly evaporated in the coating process, thus affecting the adhesion properties.

With regard to the developed test procedure, the high reproducibility of the measurement results shows that a valid method for determining adhesion has thus been created. Standard deviations of 62 N (PAI 1), 159 N (PAI 2) and 43 N (PEEK) support this statement.

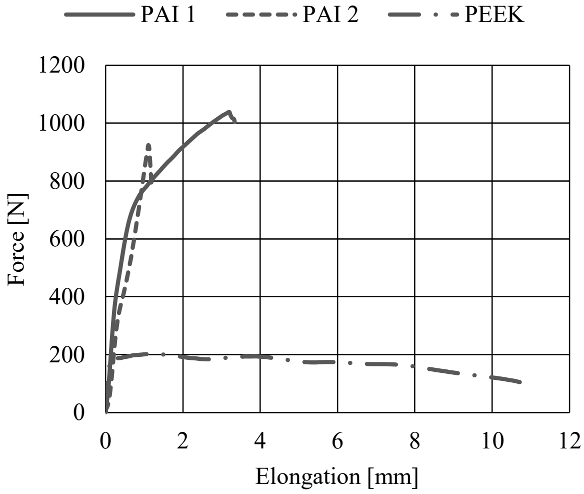

Figure 8: Exemplary force-elongation curves of three different wire samples

The force-elongation curve of one specimen from each of the three test series executed is shown in Figure 8. When looking at the PAI 1 curve, it is noticeable that the curve initially rises very steeply linearly, and the slope drops in the range between 700 N and 800 N. The maximum force at which the resin dissolves is 1037 N. The falling slope suggests that plastic deformation of the copper wire occurs here. The detachment of the resin therefore only occurs as soon as the specimen has left the elastic range. As a result of the plastic deformation, a significant reduction in the cross-section of the flat wire can be assumed during the test. Against the background outlined, it remains open what influence the reduction of the cross-section has on the adhesion of the resin and how this influences the test results. The curve of PAI 2 is also very steep. The detachment of the resin occurs here before the wire passes from the region of elastic to the region of plastic deformation. The fact that the PAI 1 wire already enters the plastic deformation range during the tensile test is also supported by the fact that the average length change at F_{max} is 3.56 mm, whereas this is only 1.09 mm for PAI 2. For the PEEK specimens, this value amounts to 0.88 mm. However, it should also be considered that the cross-section of the PAI 2 copper wire is about 57 % larger than that of the PAI 1 copper wire.

4. Conclusion

The choice of the right insulation system for electric motors, consisting of primary and secondary insulation, is one of the greatest challenges against the background of increasing voltage levels in electric drivetrains. The insulation on the flat copper wire for hairpin stators is the main focus here. To avoid aging effects at higher voltage levels, various insulation materials are used. The current trend is mainly towards PAI and PEEK as insulation materials. However, when choosing the insulation material, not only the electrical properties but also the interactions with the impregnating resin should be considered. In order for the resin to fulfill its requirements as secondary insulation, sufficient adhesion between wire insulation and resin is necessary. If the resin detaches from the wire insulation during operation due to vibration, cavities are created which favor partial discharge effects and thus lead to the failure of the drive unit in the long term.

Within the scope of this work, a method was developed to test and measure the adhesion between copper flat wires with different insulation materials and an impregnating agent. The tests carried out with three different insulated copper flat wires showed that the method is very well suited for reproducibly measuring the adhesion between resin and wire. It was also shown that there are significant differences in adhesion between the impregnating resin and different insulation materials. The adhesion on the insulation material PEEK is significantly lower than on PAI. It was also shown that differences in adhesion exist with the same insulation material, but from different manufacturers. The reasons for this observation cannot be clearly identified. However, it is reasonable to assume that the wire manufacturing process varies. The process parameters in wire production thus have a strong influence on the properties of the insulated flat copper wire, which can be observed, for example, in fluctuating adhesion between wire and resin. The extent to which these fluctuations influence the properties in operation must be investigated further.

For future investigations, the measured values obtained must be evaluated in the context of the automotive application. So far, there is a lack of investigations that have made the acting forces between insulation material and impregnation resin quantifiable. The adhesion requirements, particularly with regard to service life tests, must be defined so that different insulation materials and impregnating resins can be evaluated with regard to use for automotive electric motors.

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References

[1] Moghadam, D.E., Herold, C., Zbinden, R., 2020. Electrical Insulation at 800 V Electric Vehicles, in: 2020 International Symposium on Electrical Insulating Materials (ISEIM). IEEE, pp. 115–119.

[2] Moghadam, D.E., Lange, J., 2020. The future of e-cars - will high-voltage systems become a new standard? JEC Composites Magazine, 30–33.

[3] Kampker, A., Heimes, H.H., Kawollek, S., Treichel, P., Kraus, A., 2020. Production Process of a Hairpin Stator, 2nd ed., Frankfurt am Main.

[4] Hagedorn, J., Sell-Le Blanc, F., Fleischer, J., 2018. Handbook of coil winding: Technologies for efficient electrical wound products and their automated production. Springer, Berlin, 306 pp.

[5] Moghadam, D.E., Herold, C., Zbinden, R., 62020. Effects of Resins on Partial Discharge Activity and Lifetime of Insulation Systems Used in eDrive Motors and Automotive Industries, in: 2020 IEEE Electrical Insulation Conference (EIC). 2020 IEEE Electrical Insulation Conference (EIC), Knoxville, TN, USA. 22.06.2020 - 03.07.2020. IEEE, pp. 221–224.

[6] DIN German Institute for Standardization. Winding wires - Test methods. Beuth Verlag GmbH 29.060.10.

[7] DIN German Institute for Standardization, 2021. Specifications for particular types of winding wires: Part 0-2: General requirements - Enamelled rectangular copper wire. Beuth Verlag GmbH 29.060.10.

[8] Wacker Chemie AG. Elastosil® RT 620 A/B: Technical Data Sheet. https://www.wacker.com/h/en-hu/medias/ELASTOSIL-RT-620-AB-en-2020.07.01.pdf. Accessed 21 August 2022.

[9] Elantas GmbH. ELAN-protect® UP 142: Technical Data Sheet. https://products.elantas.com/beckinsulation/productReport/ELAN-protect%C2%AE%C2%A0_UP_142.pdf?language=en&country=&download=productReport&productid=000002de&brandid=66958. Accessed 21 August 2022.

Biography

Prof. Dr.-Ing. Achim Kampker (*1976) is head of the chair “Production Engineering of E-Mobility Components” (PEM) of RWTH Aachen University and known for his co-development of the “StreetScooter” electric vehicle. Kampker also acts as member of the executive board of the “Fraunhofer Research Institution for Battery Cell Production FFB” in Münster. He is involved in various expert groups of the federal and state governments.

Dr.-Ing. Dipl. Wirt.-Ing. Heiner Hans Heimes (*1983) studied mechanical engineering with a focus on production engineering at RWTH Aachen University. From 2015 to 2019, he was head of the Electromobility Laboratory (eLab) of RWTH Aachen University and chief engineer of the newly established chair "Production Engineering of E-Mobility Components" (PEM). Since 2019, Dr.-Ing. Heimes has held the role of executive engineer of the PEM facility.

Benjamin Norbert Dorn (*1991) is chief engineer of the chair "Production Engineering of E-Mobility Components (PEM) of RWTH Aachen University. From 2017 to 2021 he was research associate at the PEM facility of which he has been responsible for the research group Electric Drive Production for the last two years. Since 2021, he has been responsible for the department production technology and organization.

Florian Brans (*1992) studied mechanical engineering and business administration at RWTH Aachen University. From 2019 to 2021, he was a research associate at the chair of "Production Engineering of E-Mobility Components" (PEM) of RWTH Aachen University. Since 2021, he has been responsible as group leader for the research group Electric Drive Production at PEM.

Henrik Christoph Born (*1994) is research associate at the chair of "Production Engineering of E-Mobility Components" (PEM) at RWTH Aachen University. He studied mechanical engineering and business administration with a focus on production engineering as well as corporate development and strategy the same university.

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Computer Aided Inspection Planning For Automation Of On-Machine Inspection Of Customised Milling Parts

Jonas Krebs[1], Gregor Mueller[1], Lars Roedel[1]
[1]*Fraunhofer Institute for Manufacturing Engineering and Automation, Stuttgart, Germany*

Abstract

Customised products force manufacturing systems to operate efficient at batch size one. Automation in upstream processes and on shop floor increase productivity. Besides value-adding processes, quality management to sustain product quality must be considered regarding automation and consistency from 3D model to the execution on shop floor. Computer aided inspection planning addresses the automation of measurement operations. The inspection planning starts with a customised 3D model and realises a simple execution of the measurement task on shop floor level. A method for implementation of computer-aided inspection planning for tactile on-machine inspection will be presented to realise potentials like tool deviation and work piece correction based on measurement results. The developed method focuses on ensuring automation of computer aided inspection planning and sets up the basis for a self-controlling manufacturing system of customised milling parts. A validation was performed at a manufacturing company for customised drilling tools and enabled less downtime and rework time for milling machines.

Keywords

Computer aided inspection planning; on-machine inspection; automation; CAx

1. Introduction

Mass personalisation forces manufacturing companies to face the challenge of producing customised products economically of consistent or increased quality [1-3]. In addition to the value-adding process of production, quality management is also part of the production process, which must cater to the individuality of the products [4]. Production and quality management need to be automated for the sake of high quantities despite batch size one in order to ensure economic efficiency [5].

1.1 Initial situation

Quality assessment of products contains various steps of assessment. The production processes is the determining factor of product quality. Therefore, the focus will be on the quality of production processes. Based on the assumption that manufacturing steps for product manufacturing take place in a CNC machining centre. The contours realised by machining vary based on customer requirements [6]. The focus is set on milling operation due to the higher complexity of milled geometry compared to turning operation and its higher wear compared to 3D printing. Consequently, the objective is the quality assessment of personalised milled products down to batch size one. As quality assessment, the result of the performed milling operation are in need of evaluation.

Inspections of milled parts operate within the machine or in a separate measurement work station by the use of measurement equipment. At the current state measurement operation are performed in or around the machine manually [7]. The worker themselves decides whether the quality is good enough and what kind of

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steps to rework are necessary. In specific measurement workplaces, automation of measurement task is state of the art, but due to the spatial separation of production and measurement, decisions for rework are delayed and errors can occur [8].

1.2 Solution modules

Cost efficient mass personalisation is in need of automation to reduce cost extensive manual process steps. For products with high likelihood of quality issues on-machine Inspection (OMI) is suitable. OMI provides the possibility to rework parts in exactly the same clamping situation, because of the measurement equipment being connected to the machine control system. Therefore, time for setting up rework is eliminated. Due to batch size one of rare occurring repeating parts, automation solutions are still challenging. The challenge is to operate inspection for each customer-individualised part at the right location of the part and provide the suitable inspection strategy. The scope will be set on tactile OMI via tactile probing. Tactile measurement tends to be the most robust way in a milling environment influenced by coolants and lubricants.

Computer aided inspection planning (CAIP) plans measurement operations based on the CAD-model of products. An automation of CAIP is still lacking and done manually when used. CAIP solves worker biased quality assessment and reduces machine-programming times for measurement operations. Nevertheless, the highest potential exists in automating the planning and the measurement itself.

This paper focuses on the automation of OMI using CAIP for machining. With the help of OMI, the manufactured contours are measured by the tactile measuring probes in the machining centre and thus enable the quality assessment of the work piece and the direct conclusion on the production-determining variables. Subsequently, existing CAIP approaches will be examined and further developed with regard to OMI and fitness for automation.

2. State of the art

2.1 On-machine inspection

OMI is used when advantages result from the fact that the measuring operation takes place in the same clamping situation as manufactured. A significant advantage is the possible immediate subsequent correction of the work piece based on the measuring operation without the influence of a changed clamping situation. The tool correction is based on the result of the machining operation and the performed measurement operation afterwards [9]. Furthermore, handling times of the work piece are reduced compared to a measurement on a coordinate measuring machine (CMM). This is done at the expense of availability of machinery time for value-adding activities [10-11].

The accuracy and reproducibility of tactile OMI is within the range of the machine tolerances on the installed machine tool. Currently, the range of reproducibility for 5-axis turning and milling centres on the market is within few µm. Consequently, the reproducibility decreases with increasing machine wear due to machine crashes with necessary alignment of the axes. Especially for older machines, the necessary reproducibility should be checked before installing OMI [12].

In general, OMI is suitable for use with correction-intensive work pieces, as it takes place directly after the measuring operation in the same clamping. Tool correction is made by the production result and not only by the tool wear, which increases production quality.

2.2 Computer aided inspection planning

ElMaraghy et al. describe CAIP as the ability to automatically obtain an inspection plan [13]. The inspection plan enables feedback into the design and manufacturing process and provides the basis for handling a large number of product features. The focus is on tactile measurement with a coordinate measuring machine and is based on the computer aided design (CAD) model of the component to be measured. The process for CAIP ("Fig. 1") includes feature extraction or construction of elements to be measured. A feature is understood here as one or more geometry elements that have a reference to the component or among each other. These features are analysed with regard to their use on a CMM and the measurement sequence is subsequently planned. After selecting the inspection equipment, the inspection path is planned and simulated in order to derive the measurement programme [14].

Wong et al. define CAIP as a module that recognises geometry features to be measured, plans the measurement task, and integrates it into the inspection planning. This process is automated or semi-automated and can be tolerance- or geometry-driven [15].

Zhao et al. summarise the literature on CAIP approaches for coordinate measuring machines and OMI [10]. For this purpose, they define CAIP as a system that contains the following modules ("Figure 1"):

- Selection and sequencing of inspection features,
- Selection and optimisation of the measuring points,
- Measurement path planning and measurement programme generation,
- Execution of the measuring operation

Sources earlier than the year 2000 almost exclusively address measurement on CMMs. CAIP research for OMI therefore builds on these approaches and extends them in the areas of inspection feature extraction and measurement path optimisation. However, gaps exist for the interaction of CAIP and manufacturing in the context of OMI. The interaction is insufficiently considered. This also applies to the integration of the measuring operation into the measuring programme to be executed and the lack of uniform standards regarding numerical control (NC) code and CAD format [16].

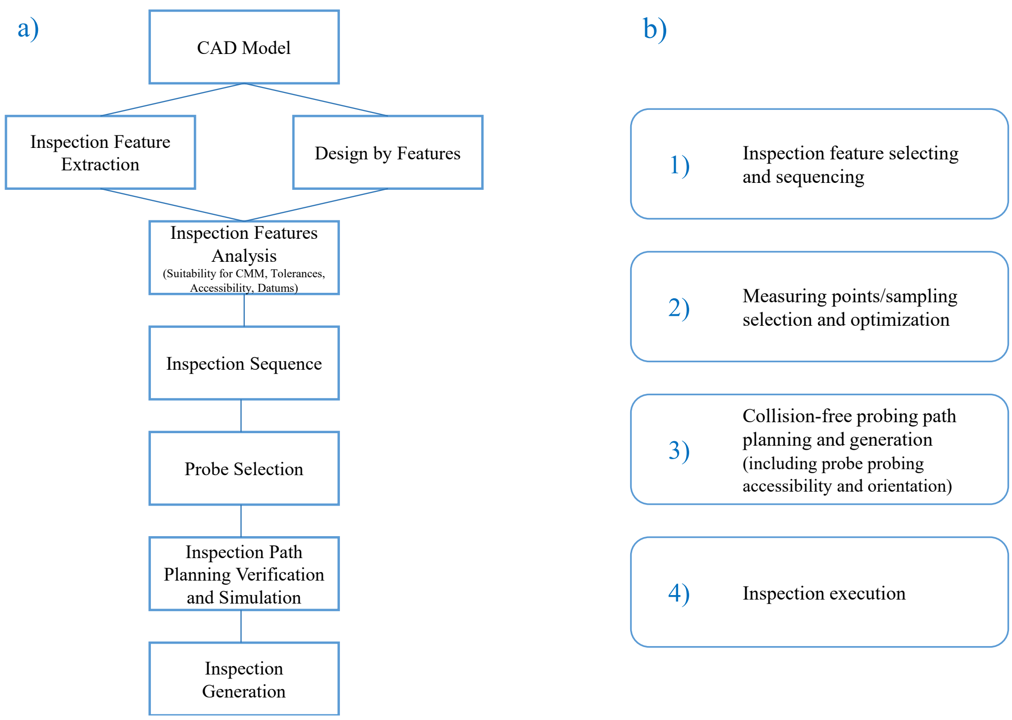

Figure 1: a) Process of CAIP by ElMaraghy et al. [13], b) Modules of CAIP by Zhao et al. [10]

3. Method for implementing computer aided inspection planning for on-machine inspection

The presented approaches for a CAIP are mostly based on the CMM target system and thus do not consider the necessary modules for the application of OMI. Based on the direct interaction of OMI and production on shop floor, the NC programming of the production task must also be taken into account. This includes the necessary interfaces to be implemented on the shop floor. The aim is to show a method for implementing a tactile OMI that can subsequently be automated (“Figure 2”).

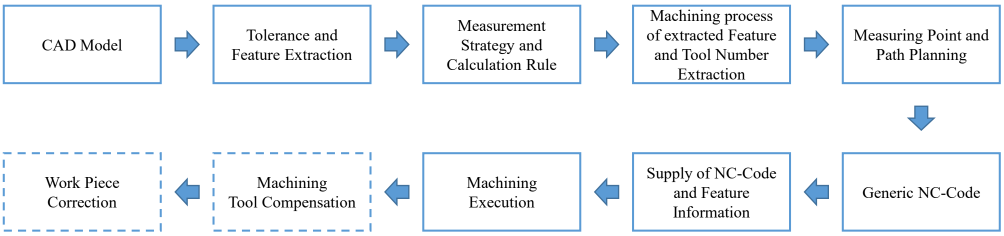

Figure 2: Method for OMI to connect CAIP and manufacturing

As prerequisite for the developed architecture a 3D-CAD-model need to be available. The geometry to be inspected is within a extracted feature. The feature is a geometric shape within the part, which can be described by an explicit parameter set, and contains tolerances due to quality requirements. The feature can be freely configured in its dimensions and position on the work piece. To reduce complexity it will be assumed that all tolerances regarding the size of the feature are given and are not subject to any changes.

The first step contains the analysis of the CAD-model to derive the feature, its position and size. This is important information to evaluate the results of the measurement and address the suitable inspection strategy based on the feature and its shape. Based on the feature shape the measurement strategy is defined beforehand. For each strategy a generic calculation scheme exists, which calculates the tolerance equivalent based on the inspection points to evaluate the quality. The strategy defines the number of inspection points, their location within the feature and the start point for each inspection path.

Besides the 3D-model, the operation planning of the process steps in manufacturing is a major information source. Within the CAM-setup and the NC-code the information about the tool, which performs the manufacturing operating, and the corresponding operation are stored. This information is needed in order to evaluate in which section of the NC-code the inspection operation has to take place and which tool need adjustment when failing the quality assessment. Based on the chosen inspection strategy the measurement points can be set in the 3D-model to calculate starting points and provide a file with all inspection points to be checked and their travels to each other.

A necessary condition to automate the whole inspection for customer individual parts is to provide a modular machine-readable inspection code. The modular structure of the generic NC-code allows using varying inspection strategy based on different calculation schemes, varying inspection points and operating with varying information about the quality assessment like tolerances and tools. The generic NC-code is written in G-code and can be easily scaled and updated regarding the information mentioned.

Before operating the CNC machining centre, the architecture needs to be set up to supply the machine with all created files during CAIP (for example: files containing inspection point). In this stage has to be taken care of the enabling inspection on all possible CNC machining centres on shop floor level without creating redundancy or differing file versions across machines.

The last step is the operation on the machine at shop floor level. It is important to provide a feedback of the quality assessment to the worker and the quality management department for further use. If the quality assessment evaluates a good part, the process is terminated at this point. If on the other hand the quality does not fit the expectations, the tool need to be adjusted. Using manual inspection the adjustment process has to be iterative. Because of the CAIP process beforehand and automation of the measurement task, the necessary adjustment can be calculated and executed by the measurement programme. The adjusted tool will fulfil the quality assessment next time being used. Based on the adjusted tool there is the possibility to rework parts directly in the same clamping right after the inspection operation with the adjusted tool. This work piece correction will not be objective of the paper and is meant for future research.

The novelty of this approach is based on the interaction of inspection and manufacturing. The combination of manufacturing planning and inspection planning due to its joint execution on shop floor is solved by the presented method. Based on this framework a self-controlled manufacturing system is enabled by computer aided inspection planning. The results will be presented for each step of the presented method. In the end, all results will be put in the overall perspective of automation of inspection planning.

4. Results

The method presented in the methodology is now exercised for an example part and the results when applying the architecture are presented. Each step of the described architecture in chapter 3 will be executed and ways of implementation and existing hurdles are pointed out. The starting point is the CAD model, which contains the geometries to be inspected. The sample component is shown in Figure 3, was produced with varying features and measured within a project at a tool manufacturing company for customer individual tools. At the current state, the customised tools are produced and manually checked in the clamping of the milling machine, because of a high likelihood of violating tolerances. Workers decide on their impression whether rework is necessary. This actual quality check prevents the manufacturing process to be automated. The introduced method enables automation via OMI and reduce preparation time for measuring operation.

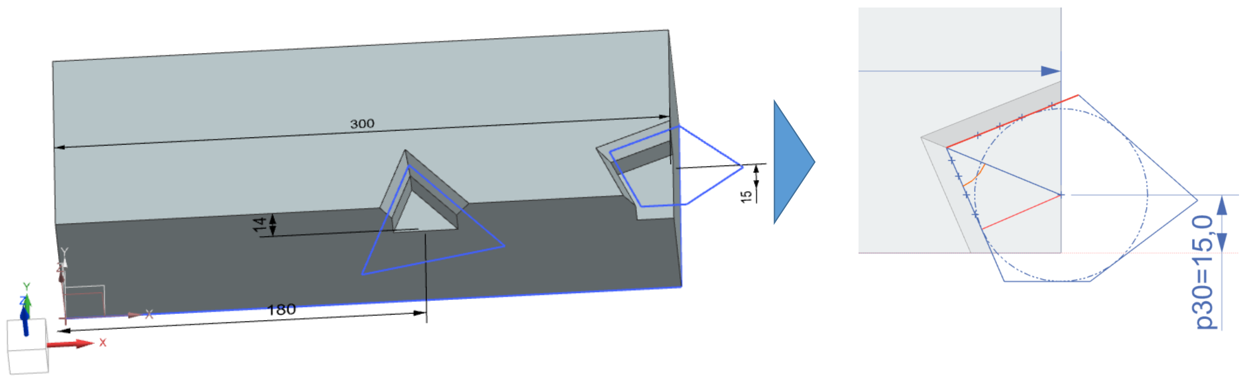

Figure 3: Sample part for execution CAIP for OMI at tool manufacturing company

The assumption is made that the base body is a cuboid into which subtracting features are placed. The feature is a polygon, which can be described by the size of a circle touching all sides of the polygon. The design, size and position within the basic body can vary. Thus, a customer-specific component is available.

Following the method, the first step is to examine the component with regard to the design suitable for production. This step is essential in the production environment, since deviations between the digital model and the real component will be measured. However, if there is a systematic error due to unequal centricity tolerances between tool and part, this will always falsify the measurement result, because of discrepancies of digital model and produced part.

The features are presented in the example part by the milled polygon structures, which can be configured. The configuration of the features is represented within the CAD model by parametric design. The parametric design enables the features to be adjusted within the parameters and placed anywhere on the part. The assumption is made that the size of the feature is the parameter to be inspected and the regarding tolerance is always the same for each configuration and known beforehand. Thus, the feature does not need to be extracted separately in the process, since the model of the feature is already created by customer specific input beforehand.

The measurement strategy is based on the fact that each feature size can be described by a circle touching the edges of the part surface (Figure 3, right side). Therefore a calculation logic is necessary, which calculates the circle radius on basis of inspection points. It is assumed that at least two edges are created by the feature. It is possible that more edges exists due to the polygon structure, but this will not interfere with the calculation logic. Based on the assumption, two edges can be measured by four inspection points each and the position of the edges can be determined by a regression function. Using the two regression lines, the angle and intersection between the two edges could be determined. By knowing the angle and the intersection point, the radius of the circle could be calculated. The visualisation of the geometry for calculation is shown in Figure 3 on the right side.

Computer Aided Manufacturing (CAM) must identify the process, which will manufacture the feature to enable an automated process of inspection and production. It is necessary to obtain the section of NC-code where the measurement operation must be inserted. The tool, which performs the machining, could be adjusted afterwards, must be known. In the present case of the example part, a machining operation with a fixed tool is already attached to the surfaces of the feature. For this reason, the tool is not to be identified forcibly in the process and can be taken over directly into the NC-code. The machining steps performed on the example part are exclusively to the milling of features, therefore the position in the NC-code for the measuring programme is also determined.

Since the parametric model for the feature is already available, it can be used directly for planning of the inspection points. Four points each are placed on two visible edges of the polygon at an equal distance. The position of the points results from the length of the visible edge subtracted with a safety distance to the next edge. The approach vectors are always orthogonal to the edge from the centre of the feature. Thus, the points automatically adjust with each configuration and can subsequently be derived as a spf. file. A spf. file can be read and processed directly by the machine control system.

The probe used is a TC52 from BLUM with application on a CTX Beta with Sinumerik control. The inspection programme was developed together with BLUM and has a modular structure. Within the inspection programme, the position of the feature is transferred and set as temporary zero point. Based on the new zero the inspection points and travels can be extracted from the generated inspection points file and are measured by the probe. The machine control processes the measured values and executes the calculation on basis of the measured values within the subprogram containing the calculation rules. The result of the calculation is returned to the inspection programme. In this case, the calculated circle radius is derived and compared with the default values from the corresponding subprogram. The tool number is transferred in case of tolerance or meshing limit violation and corrected by the deviation from the target value. Finally, the output is a protocol with measurement results and corrections made. The entire structure is shown in Figure 4 with an example of the measuring point file with 8 measuring points on 2 edges.

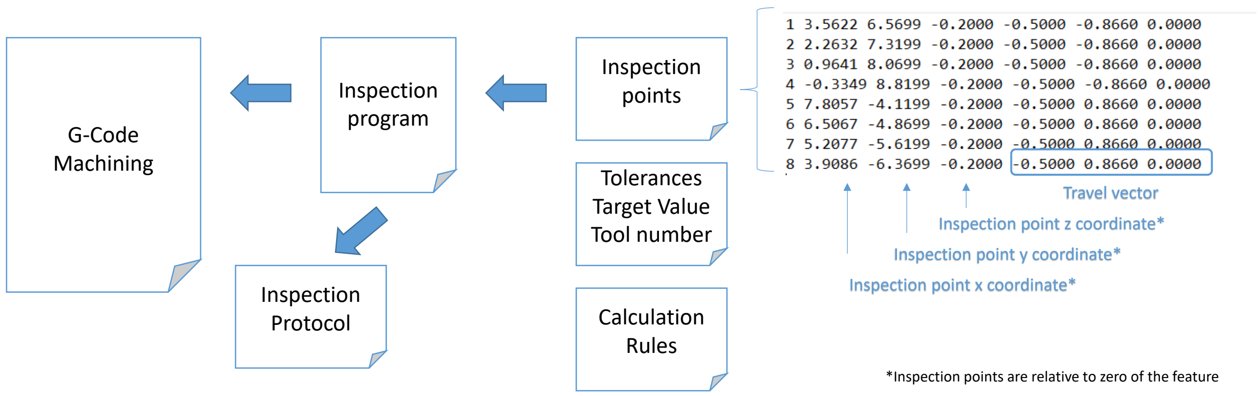

Figure 4: Modularity of inspection programme

The modular structure enables execution of other measuring tasks, since the measuring points, tolerances and calculation logic can be easily exchanged, since they are located in separate subprograms. Preventive correction is used for tool adjustment. Preventive correction sets intervention limits depending on the tolerances, consequently the tools are corrected in time and scrap material is avoided. These intervention limits are also variable and editable in the subprograms of the inspection programme. Based on this solution, no work piece correction is needed and provided for the example component.

Overall, the inspection programme was set up and enabled for the production of the example component. Four different components were produced on the CTX Beta, for each a call for the inspection programme was integrated in the machining programme. Two features on the components were deliberately manufactured too large and two too small. The inspection programme detected the derivation and the machine control automatically corrected the corresponding tool. This provides proof of the functionality of the mounted method.

5. Discussion

The established on-machine inspection at the tool manufacturer is not yet fully automated. Actually, there is a break in CAM programming and there is no feature recognition; instead, parametric models are used. These offer the advantage of simple and automatic adaptation with customer parameters when a basic similarity of the products is given. It also ensure the quality of the digital twin of the product. On the other hand, effort is required to create the models and to determine the dimensions to be parameterised in advance. Within the implementation of CAIP, the quality of the digital model, which describes the target shape, was a critical factor. If the digital model does not have the target shape, a deviating component will be created at shop floor level. Therefore, the path via the parametric models is the best choice if the features to be measured are available in a high number with a basic similarity that can be described via a manageable number of parameters.

One hurdle for the implementation was the various functional areas involved within the manufacturing company. The implementation links the areas of development (parametric modelling), design, CAM programming, production and quality. Based on existing implicit knowledge as well as missing interfaces and insufficient information flow, it is necessary to remove hurdles, create consistency and take a large number of stakeholders into account. On a technical level, skills from design, programming of software automation and programming on the machine tool are needed.

In summary, hurdles have to be overcome in the area of organisation and overarching competence in order to connect the areas that are not yet automated and sequentially integrated. Nevertheless, the potential of automating a previously performed manual subjective inspection was replaced by an automatically controlling inspection process on shop floor. This enabled a reduction in rework and gains in productive machine time. The method shows a way to avoid costly measurement preparation for customised tools, which can then be successively automated.

6. Conclusion

In summary, it can be stated that for tactile measurement with OMI, the CAIP approaches, which are primarily designed for the purpose of CMM, cannot solve the implementation satisfactorily. The weakness lies primarily in the unconsidered dependencies between CAIP and integration into manufacturing. An automatic tool correction based on the measurement results and the integration of OMI into an autonomous manufacturing can only be lifted after considering the interface between CAIP and manufacturing.

The method presented in this paper shows a possibility to design CAIP for tactile OMI for customised milling products. The methods requires a customer based CAD model, on which the inspection paths, calculation rules and underlying tolerances are planned. A modular structure of the NC-programme for a tactile probe realises the creation of a feature specific inspection programme. The inspection programme evaluates the inspection results and adjusts the tool for machining as necessary.

The method is largely validated based on a tool manufacturer. The validation shows hurdles for implementation in the area of interdisciplinary communication and interfaces. Current weaknesses regarding the integration of feature recognition and automation of the CAIP approaches also become apparent. These will be subject to future research to further develop automation of CAIP.

References

[1] R. Ogunsakin, C. A. Marin, and N. Mehandjiev, "Towards engineering manufacturing systems for mass personalization: a stigmergic approach," International Journal of Computer Integrated Manufacturing, vol. 34, no. 4, pp. 341–369, 2021.

[2] D. Mourtzis and M. Doukas, "Design and Planning of Manufacturing Networks for Mass Customisation and Personalization: Challenges and Outlook," Procedia CIRP, vol. 19, pp. 1–13, 2014.

[3] S. J. Hu, "Evolving Paradigms of Manufacturing: From Mass Production to Mass Customization and Personalization," Procedia CIRP, vol. 7, pp. 3–8, 2013.

[4] F. Z. Fang, Z. Li, A. Arokiam, and T. Gorman, "Closed Loop PMI Driven Dimensional Quality Lifecycle Management Approach for Smart Manufacturing System," Procedia CIRP, vol. 56, pp. 614–619, 2016.

[5] S.-L. Jämsä-Jounela, "FsUTURE TRENDS IN PROCESS AUTOMATION," IFAC Proceedings Volumes, vol. 40, no. 1, pp. 1–10, 2007.

[6] B. Stump, F. Badurdeen, "Integrating lean and other strategies for mass customization manufacturing: a case study", J Intell Manuf 23, p. 109–124, 2012

[7] S. Sahoo, C.-Y. Lo, "Smart manufacturing powered by recent technological advancements: A review", Journal of Manufacturing Systems, vol. 64, p. 236-250, 2022

[8] Y. Jin, H. Pierson, H. Liao, "Scale and Pose-Invariant Feature Quality Inspection for Freeform Geometries in Additive Manufacturing", J. Manuf. Sci. Eng., vol. 141, 121008, 2019

[9] S.-M. Wang, Y.-S. Chen, C.-Y. Lee, C.-C. Yeh, and C.-C. Wang, "Methods of In-Process On-Machine Auto-Inspection of Dimensional Error and Auto-Compensation of Tool Wear for Precision Turning," Applied Sciences, vol. 6, no. 4, p. 107, 2016.

[10] F. Zhao, X. Xu, and S. Q. Xie, "Computer-Aided Inspection Planning—The state of the art," Computers in Industry, vol. 60, no. 7, pp. 453–466, 2009.

[11] S. G. Wang, Y. J. Wang, and Y. L. Fu, "Study on On-Machine Inspection Technology of Machining Center Based," AMR, vol. 97-101, pp. 4282–4286, 2010.

[12] J. Mou and C. Richard Liu, "A method for enhancing the accuracy of CNC machine tools for on-machine inspection," Journal of Manufacturing Systems, vol. 11, no. 4, pp. 229–237, 1992.

[13] H. A. ElMaraghy and W. H. ElMaraghy, "Computer-Aided Inspection Planning (CAIP)," in Advances in feature based manufacturing (Manufacturing Research and Technology 20), J. J. Shah, M. Mäntylä, and D. S. Nau, Eds., Amsterdam, New York: Elsevier, 2010, pp. 363–396.

[14] H. A. ElMaraghy, P. H. Gu, and J. G. Bollinger, "Expert System for Inspection Planning," CIRP Annals, vol. 36, no. 1, pp. 85–89, 1987.

[15] F. S. Y. Wong *, K. B. Chuah, and P. K. Venuvinod, "Automated extraction of dimensional inspection features from part computer-aided design models," International Journal of Production Research, vol. 43, no. 12, pp. 2377–2396, 2005.

[16] P. Lei and L. Y. Zheng, "A STEP-NC Compatible on-Machine Measurement System with Automated Correlation of Inspection Data," AMM, vol. 397-400, pp. 1772–1777, 2013

Biography

Jonas Krebs (*1995) is a research associate at the Fraunhofer Institute for Manufacturing Engineering and Automation IPA. Jonas Krebs joined the Department Factory planning and production management in early 2021. He finished his Masters in production engineering at RWTH Aachen University with a background in mechanical engineering.

Gregor Müller (*1992) is a research associate at the Fraunhofer Institute for Manufacturing Engineering and Automation IPA which he joined in 2021. He was working in the mechanical construction department at Siempelkamp Maschinen- und Anlagenbau GmbH between 2018 and 2021. He studied production engineering at the RWTH Aachen University and is an Alumnus with focus on mechanical engineering and automation.

Lars Rödel (*1994) is a research associate at the Fraunhofer Institute for Manufacturing Engineering and Automation IPA which he joined in early 2022. He was a technical expert for publicly funded projects at TÜV Rheinland Consulting GmbH between 2020 and 2022. In addition, he is a RWTH Aachen University Alumnus with a background in industrial engineering.

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Development of a Comparative Assessment Method For Additive and Conventional Manufacturing With Regard to Global Warming Potential

Pletzer-Zelgert, Leonie Pauline[1]; Pereira de Souza, Bruna[2]; Kolter, Moritz[1]; Traverso, Marzia[2]; Schleifenbaum, Johannes Henrich[1]

[1]*Chair of Digital Additive Production, RWTH Aachen University, Aachen, Germany*
[2] *Institute of Sustainability In Civil Engineering, RWTH Aachen University, Aachen, Germany*

Abstract

Additive Manufacturing (AM) opens new possibilities for producing complex parts while achieving high material efficiency. Besides the technological advantages, AM is considered a key technology for sustainable production. A widely used approach to measure the sustainability of a product is the Life Cycle Assessment (LCA) by using the impact category of the Global Warming Potential (GWP). The setup of LCA is complex and requires a deep understanding of the process. LCAs carried out so far for AM mainly focused on energy consumption and the printing process itself. GWP caused by other up and downstream manufacturing steps, such as material preparation, has received little attention so far. This requires more comprehensive LCAs, increasing the complexity and effort. Therefore, the GWP is often not considered when deciding whether to use AM or Conventional Manufacturing (CM) for producing a part in the industry. This work presents a simplified method (GWP-method) for comparing AM and CM regarding the GWP by identifying so-called hotspots (the most significant production steps in terms of GWP). Based on the identified hotspots, the assessment scope was narrowed down, and an Assessment Equation (GWPAE) was developed. The GWPAE can then be used for the analysis of produced GWP for other product families and production scenarios for the defined process route. The method is demonstrated for an aerospace part as a case study. Finally, the deviation of the derived GWPAE is checked by directly comparing the results of the GWP of an LCA for another production scenario and lies at 5,9%.

Keywords

Life Cycle Assessment; Additive Manufacturing; Global Warming Potential; Hotspots; Sustainability

1. Introduction

In the past, the manufacturing industry focused mainly on economic mass production. Today, the major challenge is to create production systems and supply chains that are not only economically but also ecologically sustainable. This leads several industries to focus their efforts on reducing the Global Warming Potential (GWP) of production and their products. This already starts with the planning and selection of the process route. For the quantification of the GWP of the process route, a Life Cycle Assessment (LCA) is a common procedure used in science [1]. However, carrying out an LCA requires detailed information along the entire process route and demands high costs and expertise. Hence, it is often not applied in industry, leading to decisions regarding manufacturing technology without considering ecological impact [2].

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One decision being made in the planning process of production is the decision between Additive Manufacturing (AM) and Conventional Manufacturing (CM). Compared to subtractive or forming manufacturing of CM, AM builds up the parts by iterative addition of layers [3]. As a result, more complex geometries and reduced material use in production can be achieved. Therefore the advantage of AM regarding ecological sustainability often lies in material efficiency and its application in the production of lightweight parts [4,5]. One of the most widely used AM technologies is the Powder Bed Fusion of metals using a laser-based system (PBF-LB/M). In this process, metal powder is melted layer by layer using a controlled laser beam movement [6,7]. Since AM is still a young manufacturing method compared to CM (the first patents for AM were filed in 1984 [7]), the preparation of an LCA is a particularly complex task due to the lack of process knowledge and data [8,4,9]. The process route for PBF-LB/M requires several pre- and post-processing steps, such as powder production and separation of the part from the supporting metal plate (with the associated loss of material). Those steps and their impacts are often neglected in an assessment [10,4]. So, it is not certain for which parts the AM process route is an option with lower GWP compared to CM. This work aims to facilitate the selection of parts with less GWP in production through AM. A method is presented to derive an assessment equation that facilitates this selection for product families and different process scenarios of a defined process route.

2. State of the Art

The reduction of effort when carrying out an LCA is already a widely discussed topic (see reviews of [11,12]). For example, Beemsterboer et al. alone summarized 166 sources in their literature review. For that, they used the database of 'Scopus' and 'Web of Science' and conducted different ways of spelling 'LCA' with 'simplification', 'streamlining', 'scoping', and 'screening' for the search. Due to the high amounts of hits (2653 hits), they decided to exclude abstracts and keywords from the keyword search [11]. Based on these sources 5 simplifying logics for LCA were defined. However, these logics still present generic solutions for the LCA of products and processes, which apply to a wide range of contexts. The approaches for specific production decisions in industry are very broad and still represent a very complex and time-consuming method.

The evaluation of the GWP of AM and CM process routes have also been discussed in several papers, such as [13–16], and is done by establishing LCAs for both process routes. For PBF-LB/M in particular, the results of the comparative LCA analyses deviate strongly [14,17–19,10,20,21]. The reason can be found in the difference between the considered process steps, industry sector, and material of a part and defined LCA system. Table 1 gives an overview of all comparative LCA analyses for PBF-LB/M with information on their modeling and key results. The fact that the results change depending on the industry and the part illustrates the complexity of the issue. None of these studies have addressed the question of how to identify parts where AM leads to a reduced GWP using a less complex method besides LCA.

Table 1 Literature review for comparative LCA between CM and AM (using PBF-LB/M).

Reference	Compared process steps with process route of	Material	System boundary	Part/ industry sector	Key finding
[14]	casting, forging, assembly	system of aluminum, cast iron, low-alloy steel, stainless steel	cradle-to-gate	automotive part: whole engine	• in the future, AM printing will be favorable for GWP reduction. • electricity mix is significant whether AM is worthwhile
[17]	Electron Direct Melting (EDM)	aluminum alloy	cradle-to-gate	compressor wheel	• EDM needs less energy than PBF-LB/M • higher packed build jobs produce less GWP

[18]	milling, cutting, turning, casting	aluminum alloy	cradle-to-gate	aircraft: seat buckle, fork fitting	• AM parts may use as little as 1/3 to 1/2 of the energy needed to produce CM parts
[19]	forming, turning	aluminum alloy	cradle-to-grave	four tubes	• PBF-LB/M does not appear to be a green solution without weight reduction
[10]	turning, milling, hobbing, casting, rolling, annealing, sawing, melting	steel, aluminum alloy	cradle-to-gate	gear	• Material losses and energy consumption for PBF-LB/M are important parameters for making it more sustainable. Energy consumption outweighs the ecological impact caused by material losses.
[20]	casting, aging, milling, drilling	stainless steel	cradle-to-gate	hydraulic valve	• PBF-LB/M is more environmentally sustainable than CM • powder preparation stage has the largest ecological impact through the life cycles
[21]	casting	nickel alloys	cradle-to-gate	aircraft: engine turbine blade	• reduction of the GWP and ecological impact in the use of AM is approximately 4% in comparison to CM for the given part.

3. GWP-method

The method developed here is used to derive an assessment equation that comparatively quantifies the ecological impacts between AM and CM for fixed production routes. On the one hand, the method is intended to simplify the production decision between AM and CM regarding the ecological impacts, and on the other hand, the derived assessment equation can be used to analyze the process route for different production scenarios. Global Warming Potential (GWP) is chosen as the quantified impact category for the assessment, which is expressed in units of CO_2 equivalent (kg CO_2 eq.), so the method is referred to as the GWP-method in this paper. The method identifies the hotspots, and the scope is reasonably narrowed without significantly weakening the informative value for decision-making. Hotspots are in this work the most significant production steps in terms of GWP. To establish an assessment equation that relatively compares the GWP of the AM and CM process routes, the hotspots of GWP first be identified for both process routes. The assessment equation is called the Global warming Potential Assessment Equation (GWPAE) in this work. For the hotspot identification, a reduced approach of an LCA analysis is carried out which performs both a horizontal and vertical reduction of the inventory model according to the definition of [11]. Therefore, the LCA includes the modules of extraction and production and includes the process steps that differ between the production route of AM and CM. So, **step 1** is the analysis of the use case and determination of the production routes for AM and CM together with the needed input and output sources like electric energy, materials, wastes, etc. Afterward, **step 2** identifies the different process steps of both process routes. **Step 3** includes the creation of the LCA models for the different process steps for AM and CM. Based on the LCA results the GWP hotspots HS were identified in **step 4**. The last step (**step 5**) is the establishment of the GWPAE that follows the form as shown in equations (1) and (2).

$$\Delta\mathrm{GWP}(GWP_{AM}, GWP_{CM}) = GWP_{AM}(HS_{AM,i}) - GWP_{CM}(HS_{CM,i}) \quad (1)$$

$$GWP_{PR} = \sum_{PR,i=1}^{PR,N} EF_{PR,i} \times HS_{PR,i} \quad (2)$$

Parameter	Explanation
ΔGWP	difference of GWP between AM and CM [kg CO_2 eq.]
GWP_{PR}	Amount of GWP of the process route PR
PR	type of process route with $PR \epsilon [AM, CM]$
$HS_{PR,i}$	hotspot i of process route PR [unit]
$EF_{PR,i}$	emission factor of the hotspot i in the process route PR [kg CO_2 eq. per unit]
i	index
PR, N	amount of identified hotspots N in the process route PR

So ΔGWP can be interpreted accordingly:

- ΔGWP < 0: GWP of the CM is higher than of the AM process route
- ΔGWP > 0: GWP of the AM is higher than of the CM process route

Emission Factors EF indicates how much GWP is released when a defined quantity of an energy source or material is used and can be looked up in different sources like databases such as Ecoinvent [22] etc. The application of the GWP-method through the five described steps is also schematically shown in Figure 1.

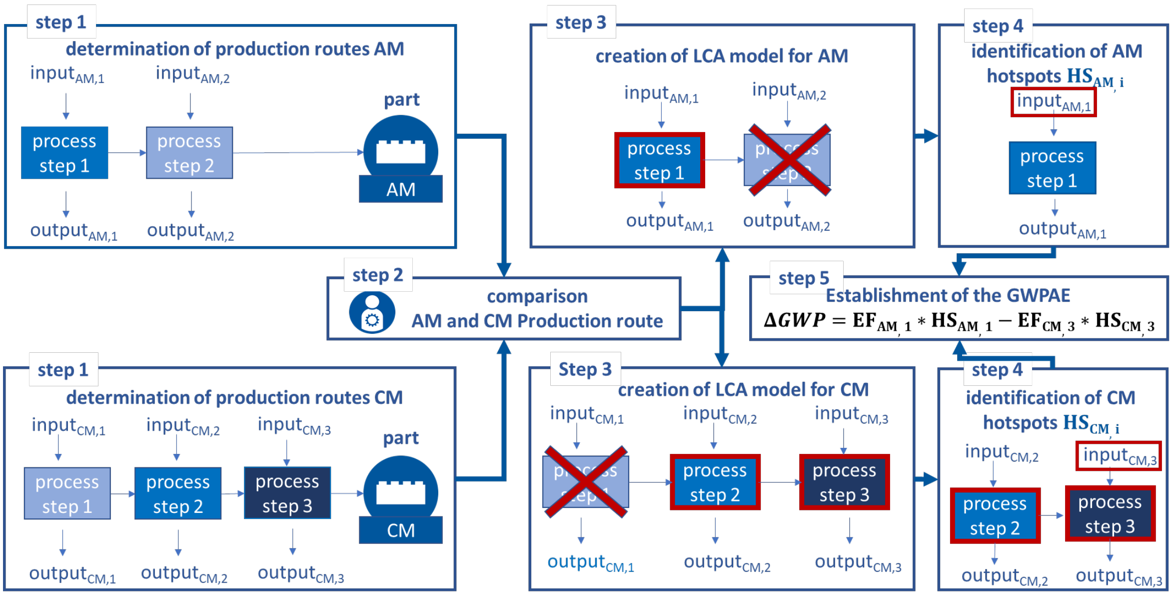


Figure 1: Schematic illustration of the GWP-method in the five steps.

4. Case study

In this work, the GWP-method is presented for an aircraft turbine bearing ring with cooling channels (material: M50NiL). The design of the bearing ring differs for the two process routes. The CM design is an assembly of two rings for the integration of the cooling system. The AM design can be printed directly as one part therefore the AM design allows placing the cooling system closer to the heat generation of the turbine. In addition, a weight reduction of 1 kg of the metal alloy can be achieved. More information about the use case can be found in [23].

Application of the GWP-method for the case study

Steps 1-3

First, the LCA is set up for the process route. Thus, the LCA aimed to quantify the GWP for the fabrication of one bearing ring by AM and CM [25]. Together with the bearing ring manufacturer, the different process steps between AM and CM are identified. This includes the process steps for CM forging, piercing, and ring milling. For AM the steps of PBF-LB/M, powder atomization, and Hot Isostatic Pressure (HIP) were included in the LCA (see Figure 2). Transport by lorry between the location of the bearing ring manufacturer and the company that used the bearing ring in the turbine was also considered due to the different part weights for AM and CM production. The distance between the companies is 189 km. [26]. Also, a green production (argon production with eco-electricity) of the argon is assumed. The bearing ring production took place in Germany, so the average energy mix of Germany is set as the energy source. The AM and CM process routes were detailed about input and output materials and a system was created for both process routes with primary and secondary data. The data used are presented in Table 2 for AM and Table 3 for CM.

The LCA follows ISO 14.044 recommendations with the exception that no external critical review of the results was carried out by third parties [24]. The impact assessment used the European CML-IA baseline from Ecoinvent v3 and the Global Warming Potential (GWP100) is set as the relevant impact category regarding the goal and scope of this study [24,22]. To perform the LCA, the data utilized for the AM processes were collected from the industrial partner of the manufacture of the bearing ring, and CM data was gathered from secondary sources from the literature. The simulations were done with SimaPro software, version classroom v.9.1.0.8, and the integrated database Ecoinvent v3 [22].

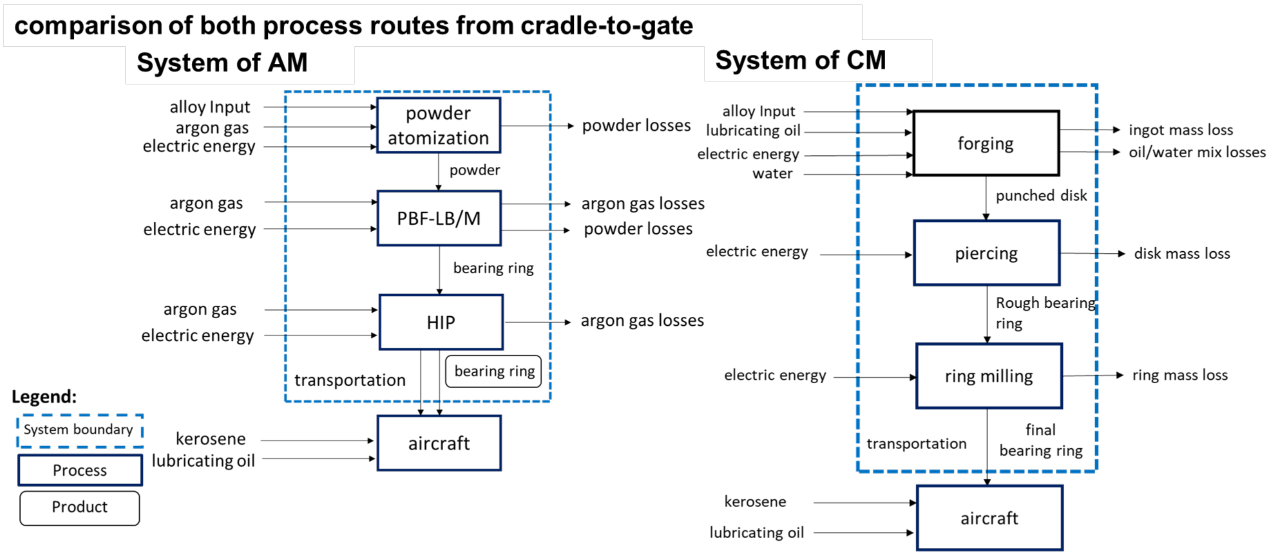


Figure 2: LCA model of the AM and CM process route from cradle-to-gate.

Table 2: Parameter for the AM process route.

Additive Manufacturing				
Unit process	**Parameters**	**Value**	**Unit**	**References**
powder atomization	alloy input	6,45	kg	primary source of manufacturer
	powder losses	1,45	kg	primary source of manufacturer
	electric energy	18,97	MJ	calculated based on [14]
	argon gas (green production)	9,70	kg	calculated based on [17]
PBF-LB/M	powder	5	kg	primary source of manufacturer
	powder losses	3	kg	primary source of manufacturer
	electric energy	195,84	MJ	calculated based on [27] and [28]
	argon gas (green production)	35	kg	calculated based on [29]
	argon gas losses	6,75	kg	measured in DAP labs
Hot Isostatic Pressing (HIP)	material input (bearing ring)	2	kg	primary source of manufacturer
	ring output (final bearing ring)	2	kg	primary source of manufacturer
	electric energy	3	MJ	calculated based on [30]
	argon	3,07	kg	calculated based on data from the manufacturer
	argon losses	0,15	kg	calculated based on data from the manufacturer

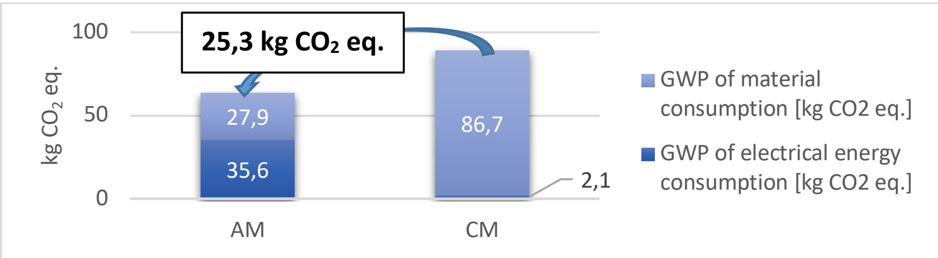
Table 3: Parameter for the CM process route.

Conventional Manufacturing				
Unit process	**Parameters**	**Value**	**Unit**	**References**
forging	alloy input	20	kg	primary source of manufacturer
	ingot mass loss	6	kg	calculated based on [31]
	electric energy	10	MJ	calculated based on [32] and [33]
	lubricating oil	0,338	kg	calculated based on [33]
	oil/water mix losses	1,64	kg	calculated based on [33]
piercing	punched disk input	14	kg	calculated based on [31]

	disk mass loss	0,7	kg	calculated based on [31]
	electric energy	0,18	MJ	calculated based on [32] and [34]
ring milling	rough bearing ring	13,3	kg	redundant
	final bearing ring	3	kg	primary source of manufacturer
	ring mass loss	10,3	kg	redundant
	electric energy	0,21	kJ	calculated based on [35] and [36]

Step 4

The results from the LCA show that 63,6 kg CO_2 eq. are emitted to produce the bearing ring by AM and 88,8 kg CO_2 eq. for the production process by CM. Therefore, the AM bearing ring from cradle-to-gate emits 25,3 kg CO_2 eq. (28,5%) less than the bearing ring produced by means of CM. In the CM route, the influence of the extraction of the metal alloy to produce the part is the largest share of the total GWP with 97,9%. GWP of AM is mainly caused by the extraction of the used metal alloy of the bearing ring (here M50NiL) and the energy consumed by the laser beam for the print process. Thereby, 49% of the GWP is caused by the electrical energy consumption for the printing process and 43,9% is prevenient from the material extraction of the metal alloy. 5% of the GWP originates from energy consumption during powder atomization. The results of the LCA calculation together with an overview of the percentage of GWP of the different process steps are shown in Figure 3.



Process route	Origin of GWP		Percentage of GWP for AM and CM [%]
CM	GWP of electrical energy consumption	forging	1,90
		other process steps	0,100
	GWP of material consumption	part metal alloy	97,9
		other materials	0,100
AM	GWP of electrical energy consumption	print process	49,0
		powder atomization	5,00
		other process steps	2,00
	GWP of material consumption	part metal alloy	43,9
		other materials	0,100

Figure 3: LCA results of the cradle-to-gate system of the bearing ring for AM and CM process route.

The hotspots of GWP for both process routes are in the extraction of the metal alloy w_{alloy}. For the AM process route, there is the additional hotspot of the electrical energy required for the print e_{print} and powder atomization e_{powder}.

Step 5

Based on the hotspots identified in Step 4 the following GWPAE can be established analog to equations (1) and (2):

$$\Delta\mathrm{GWP}(CF_{AM}, CF_{CM}) = GWP_{AM}(HS_{AM,w_{alloy}}, HS_{AM,e_{print}}, HS_{AM,e_{powder}}) - GWP_{CM}(HS_{CM,w_{alloy}}) \quad (3)$$

$$GWP_{AM} = EF_{AM,w_{alloy}} \times HS_{AM,w_{alloy}} + EF_{AM,e_{print}} \times HS_{AM,e_{print}} + EF_{AM,e_{powder}} \times HS_{AM,e_{powder}} \quad (4)$$

$$GWP_{CM} = EF_{CM,w_{alloy}} \times HS_{CM,w_{alloy}} \quad (5)$$

5. Results

Using the derived equation GWPAE (see equation (3)-(5)) the calculated difference of GWP between AM and CM amounts $\Delta\text{GWP}(CF_{AM}, CF_{CM}) = -24{,}5$ kg CO_2 eq. Table 4 shows the used values for the calculation of the GWPAE. Here is the EF of the metal alloy of AM and CM $EF_{AM,w_{alloy}} = EF_{CM,w_{alloy}}$ equal because both routes used the same material. Also, the energy mix that was used is equal for the powder atomization and print. Therefore $EF_{AM,e_{print}} = EF_{AM,e_{powder}}$ is also valid. The difference of GWP between AM and CM based on the results of the established LCA amounts $\Delta\text{GWP} = GWP_{AM} - GWP_{CM} = -25{,}3$ kg CO_2 eq. (see step 4 in subsection 4.1). So, the difference between the LCA and GWPAE results is less than 3,2%. Also, the GWPAE predicted that AM's process route causes a lower GWP compared to CM. It can thus be seen that the differences in GWP of AM and CM can already be mapped with little deviation over a few hotspots. In the next section, it is examined whether the derived GWPAE also provides valid results for other production scenarios.

Table 4: Values of the GWPAE for the origin process route of AM and CM.

Name of the parameter	Value	Source
$HS_{AM,w_{alloy}}$	6,45 kg	primary source of manufacturer
$HS_{CM,w_{alloy}}$	20 kg	primary source of manufacturer
$HS_{AM,e_{print}}$	195,84 MJ	calculated based on [27] and [28]
$HS_{AM,e_{powder}}$	18,97 MJ	calculated based on [14]
$EF_{AM,w_{alloy}} = EF_{CM,w_{alloy}}$	4,33 kg CO_2 eq./kg	EcoinventV3 (for the material M50NiL)
$EF_{AM,e_{print}} = EF_{AM,e_{powder}}$	0,159 kg CO_2 eq./MJ	EcoinventV3 (for the average energy mix of Germany)

6. GWPAE testing for another production scenario

For the study, the production scenario investigated whether AM or CM production led to a lower GWP if the powder in the build chamber of the PBF-LB/M machine is not reused for the next print. This is a real and common scenario in the aerospace industry for some part groups. It is checked if the GWPAE also predicted a valid estimation of the difference of GWP between AM and CM for another scenario. For checking the GWPAE the LCA for AM and CM of chapter 3 in Steps 1-3 were aligned for the new production scenario. So, the GWP of AM and CM are comparable. Therefore, the parameters in Table 2 "Alloy input" in the powder atomization process step are increased from 6,45 kg to 22,5 kg and the “electric energy” from 18,9 MJ to 66,15°MJ. Also, the "Powder losses" in the PBF-LB/M step are increased from 3 kg to 12,5 kg. The LCA was carried out again with the newly set values. Figure 4 shows the GWP [kg CO_2 eq.] calculated by the LCA.

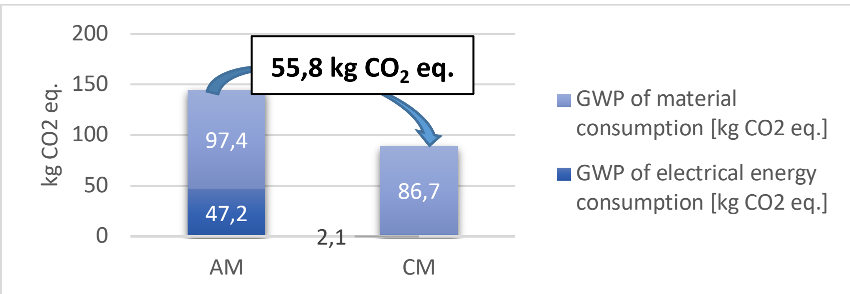


Figure 4: GWP of production scenario without powder recycling.

The difference of GWP through the LCA is 55,8 kg CO_2 eq. Using the derived GWPAE (see equation (3)-(5)) the calculated difference of GWP between AM and CM amounts $\Delta\text{GWP}(CF_{AM}, CF_{CM}) = 52{,}5$ kg CO_2 eq. and predicts that for the production scenario a lower GWP is caused by CM compared to AM. The used values for the calculation through GWPAE are shown in Table 5.

Table 5: Values of the GWPAE for the scenario without powder recycling.

Name of the parameter	Value	Source
$HS_{AM,w_{alloy}}$	22,5 kg	primary source of Manufacturer
$HS_{CM,w_{alloy}}$	20 kg	primary source of Manufacturer
$HS_{AM,e_{print}}$	195,84 MJ	calculated based on [27] and [28]
$HS_{AM,e_{powder}}$	66,15 MJ	calculated based on [14]
$EF_{AM,w_{alloy}} = EF_{CM,w_{alloy}}$	4,33 kg CO_2 eq./kg	EcoinventV3 (for the material M50NiL)
$EF_{AM,e_{print}} = EF_{AM,e_{powder}}$	0,159 kg CO_2 eq./MJ	EcoinventV3 (for the average energy mix of Germany)

So, the deviation between the results is 5,9%. This shows that the GWPAE can be used as a tool to estimate the GWP difference between AM and CM for different production scenarios if the same process route is used. The elaborated GWP-method facilitates the identification of the more favorable manufacturing process for a specific part in terms of emission reduction.

7. Summary and outlook

In this work, a GWP Assessment Equation was introduced via an established GWP-method. The GWP-method assumes that the GWP of a process route can already be reproduced validly enough by analyzing the most relevant steps (hotspots) to make production decisions for parts as of when production led to a lower GWP for AM or CM. The GWP-method was demonstrated with the setup of a part from the aerospace industry. The identified hotspots for CM were the material extraction of the metal alloy of the part. The identified hotspots for AM were the electrical energy consumption for the print and powder atomization and the extraction of the metal alloy. Based on the identified hotspots, the GWPAE was then established and compared with the LCA results. Also, the GWPAE was tested by setting up a different production scenario. It was found that the GWP differences of AM and CM between the LCA calculation results and the GWPAE were only between 3 and 6%. The GWPAE can thus be used to comparatively investigate different production scenarios in terms of GWP between AM and CM.

Since the hotspots can change with different process routes, the GWPAE can only be applied to product families and production scenarios that are manufactured with the same process route. With a different process route, the GWP-method for deriving the new GWPAE would have to be conducted again. In the future, further process routes are investigated using LCAs to obtain more knowledge about the variance of the hotspots with changes in the process route. Furthermore, it is checked if the hotspots for parts made of other materials would be different. The work thus gives a first indication of which GWP-methods can be used to make more sustainable production decisions in the future, but further studies are still needed. In the long run, the method described here could help industries to select manufacturing technologies for their process routes and to predict the inherent GWPs.

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References

[1] Klöpffer, W., 2003. Life-Cycle based methods for sustainable product development. Int J LCA 8 (3).

[2] Jacquemin, L., Pontalier, P.-Y., Sablayrolles, C., 2012. Life cycle assessment (LCA) applied to the process industry: a review. Int J LCA 17 (8), 1028–1041.

[3] DIN Deutsches Institut für Normung e. V. DIN EN ISO/ASTM 52900:2022-03, Additive Fertigung_- Grundlagen_- Terminologie (ISO/ASTM 52900:2021); Deutsche Fassung EN_ISO/ASTM 52900:2021. Beuth Verlag GmbH, Berlin. doi:10.31030/3290011.

[4] Kellens, K., Baumers, M., Gutowski, T.G., Flanagan, W., Lifset, R., Duflou, J.R., 2017. Environmental Dimensions of Additive Manufacturing: Mapping Application Domains and Their Environmental Implications. Journal of Industrial Ecology 21, S49-S68.

[5] Mehrpouya, M., Vosooghnia, A., Dehghanghadikolaei, A., Fotovvati, B., 2021. The benefits of additive manufacturing for sustainable design and production. Sustainable Manufacturing.

[6] DIN Deutsches Institut für Normung e. V. DIN EN ISO/ASTM 52911-1:2020-05, Additive Fertigung_- Konstruktion_- Teil_1: Laserbasierte Pulverbettfusion von Metallen (ISO/ASTM 52911-1:2019); Deutsche Fassung EN_ISO/ASTM 52911-1:2019. Beuth Verlag GmbH, Berlin. doi:10.31030/3060962.

[7] Gibson, I., Rosen, D., Stucker, B., Khorasani, M., 2021. Additive Manufacturing Technologies. Springer International Publishing, Cham.

[8] Huang, R., Riddle, M., Graziano, D., Warren, J., Das, S., Nimbalkar, S., Cresko, J., Masanet, E., 2016. Energy and emissions saving potential of additive manufacturing: the case of lightweight aircraft components. Journal of Cleaner Production 135, 1559–1570.

[9] Výtisk, J., Kočí, V., Honus, S., Vrtek, M., 2020. Current options in the life cycle assessment of additive manufacturing products. Open Engineering 9 (1), 674–682.

[10] Kamps, T., Lutter-Guenther, M., Seidel, C., Gutowski, T., Reinhart, G., 2018. Cost- and energy-efficient manufacture of gears by laser beam melting. CIRP Journal of Manufacturing Science and Technology 21, 47–60.

[11] Beemsterboer, S., Baumann, H., Wallbaum, H., 2020. Ways to get work done: a review and systematisation of simplification practices in the LCA literature. Int J LCA 25 (11), 2154–2168.

[12] Gradin, K.T., Björklund, A., 2021. The common understanding of simplification approaches in published LCA studies—a review and mapping. Int J LCA 26 (1), 50–63.

[13] Abu-Ennab, L., Dixit, M.K., Birgisson, B., Pradeep Kumar, P., 2022. Comparative life cycle assessment of large-scale 3D printing utilizing kaolinite-based calcium sulfoaluminate cement concrete and conventional construction. Cleaner Environmental Systems 5.

[14] Böckin, D., Tillman, A.-M., 2019. Environmental assessment of additive manufacturing in the automotive industry. Journal of Cleaner Production 226, 977–987.

[15] Kafara, M., Süchting, M., Kemnitzer, J., Westermann, H.-H., Steinhilper, R., 2017. Comparative Life Cycle Assessment of Conventional and Additive Manufacturing in Mold Core Making for CFRP Production. Procedia Manufacturing 8, 223–230.

[16] Lunetto, V., Priarone, P.C., Kara, S., Settineri, L., Sangwan K.S., H.C., 2021. A comparative LCA method for environmentally friendly manufacturing: Additive manufacturing versus Machining case. Procedia CIRP 98.

[17] Faludi, J., Baumers, M., Maskery, I., Hague, R., 2017. Environmental Impacts of Selective Laser Melting: Do Printer, Powder, Or Power Dominate? Journal of Industrial Ecology 21 (S1).

[18] Huang, R., Riddle, M., Graziano, D., Warren, J., Das, S., Nimbalkar, S., Cresko, J., Masanet, E., 2016. Energy and emissions saving potential of additive manufacturing: the case of lightweight aircraft components. Journal of Cleaner Production 135, 1559–1570.

[19] Ingarao, G., Priarone, P.C., Deng, Y., Paraskevas, D., 2018. Environmental modelling of aluminium based components manufacturing routes: Additive manufacturing versus machining versus forming. Journal of Cleaner Production 176, 261–275.

[20] Peng, T., Wang, Y., Zhu, Y., Yang, Y., Tang, R., 2020. Life cycle assessment of selective-laser-melting-produced hydraulic valve body with integrated design and manufacturing optimization: A cradle-to-gate study. Additive Manufacturing 36.

[21] Torres-Carrillo, S., Siller, H.R., Vila, C., López, C., Rodríguez, C.A., 2020. Environmental analysis of selective laser melting in the manufacturing of aeronautical turbine blades. Journal of Cleaner Production 246.

[22] 2014. Ecoinvent. ecoinvent.org, Zurich.

[23] O. Beer, C. Merklein, D. Gerhard, O. Hentschel, M. Rasch, M. Schmidt, 2018. Processing of the Heat Resistant Bearing Steel M50NiL by Selective Laser Melting: Verarbeitung des warmfesten Lagerstahls M50NiL mittels selektiven Laserstrahlschmelzens aus dem Pulverbett. HTM Journal of Heat Treatment and Materials 73 (1), 27–40.

[24] DIN EN ISO 14040:2021-02, Umweltmanagement_- Ökobilanz_- Grundsätze und Rahmenbedingungen (ISO_14040:2006_+ Amd_1:2020); Deutsche Fassung EN_ISO_14040:2006_+ A1:2020. Beuth Verlag GmbH, Berlin. doi:10.31030/3179655.

[25] Frischknecht, R., 2020. Lehrbuch der Ökobilanzierung. Springer Spektrum, Berlin, Heidelberg, 258 pp.

[26] Flouros, M., Hirschmann, M., Cottier, F., Gloeckner, P., Dullenkopf, K., 2013. Active Outer Ring Cooling of High-Loaded and High-Speed Ball Bearings. Journal of Engineering for Gas Turbines and Power 135 (8).

[27] Rupp, M., Klink, R., Merkel, M., Harisson, D.K., 2022. Additive Manufacturing in the Scope of Industry 4.0: A Review on Energy Consumption and Building Time Estimation for Laser Powder Bed-Fusion Processes. Industry 4.0 7 (4), 118–122.

[28] Ochs, D., Wehnert, K.K., Hartmann, J., Schiffler, A., Schmitt, J., 2021. Sustainable Aspects of a Metal Printing Process Chain with Laser Powder Bed Fusion (LPBF). Procedia CIRP 98, 613–618.

[29] EOS. EOS M 290 Pro Package: Der Industrie-Benchmark für die additive Fertigung hochwertiger Metallteile — jetzt mit einfacher und sicherer Materialhandhabung.

[30] Azevedo, J.M.C., Serrenho, A.C., Allwood, J.M., 2018. Energy and material efficiency of steel powder metallurgy. Powder Technology 328, 329–336.

[31] Arbak, M., Tekkaya, A.E., Özhan, F., 2005. Comparison of various preforms for hot forging of bearing rings. Journal of Materials Processing Technology 169 (1), 72–82.

[32] Schuler. The entire world of forging, 96 pp. https://www.schulergroup.com/major/download_center/broschueren_uebersichten/download_uebersichten/uebersicht_broschuere_produkte_massivumformung_e.pdf. Accessed 7 October 2022.

[33] Denkena, B., Park, H.-S., Behrens, B.-A., Henjes, J., Bertys, S., Dahal, P., Lüken, I., Klassen, A., 2013. Development of a concept to optimize the energy efficiency in forging process chains. Int. J. Precis. Eng. Manuf. 14 (7), 1229–1236.

[34] Mayank Dixit, D.D., 2019. Contact analysis of aircraft engine bearing.

[35] Shirani Bidabadi, B., Moslemi Naeini, H., Azizi Tafti, R., Tajik, Y., 2019. Optimization of required torque and energy consumption in the roll forming process. Int J Interact Des Manuf 13 (3), 1029–1048.

[36] Beer, O., Merklein, C., Gerhard, D., Hentschel, O., Rasch, M., Schmidt, M., 2018. Processing of the Heat Resistant Bearing Steel M50NiL by Selective Laser Melting. HTM Journal of Heat Treatment and Materials 73 (4), 187–201.

Biography

Pauline Pletzer-Zelgert has been a research associate of the chair for Digital Additive Production DAP at RWTH Aachen University since 2021. Before that, she completed a Master of Science degree in material science. Since 2020, she has been part of various research and development projects in academia focusing on Additive Manufacturing, Sustainability, and Digital Production.

Bruna Pereira de Souza is a master student in Sustainable Management – Water and Energy at the RWTH Aachen University.

Moritz Kolter is a group manager and research associate at the chair for Digital Additive Production DAP at RWTH Aachen University. He holds a Master of Science in Mechanical Engineering from Technical

University of Munich. Since 2017 he has been part of various research and development projects both in industry and academia focusing on Additive Manufacturing and Digital Production.

Marzia Traverso has been a Professor and Head of the Chair of Sustainability In Civil Engineering at RWTH Aachen University since 2017. She holds a PhD in environmental physics and is an environmental engineer in the field of life cycle assessment and sustainability performance of the construction and transport sector.

Johannes Henrich Schleifenbaum has been holding the Chair of Digital Additive Production DAP at RWTH Aachen University since 2016. Furthermore, he has been managing director at Aachen Center for Additive Manufacturing since 2018.

4th Conference on Production Systems and Logistics

Analysis Of Uncertainty Over The Factory Life Cycle

Lennart Hingst[1], Peter Nyhuis[1]

[1] Leibniz University Hannover, Institute of Production Systems and Logistics, An der Universität 2, 30823 Garbsen, Germany

Abstract

The cost and performance structure of a factory is determined in factory planning and activated in the operation phase with a time delay. Even though the majority of investments result from structural planning, the first conceptual and most important step in factory planning, the majority of costs occur during factory operation, the longest phase of a factory life cycle. Life cycle-oriented factory planning seeks to anticipate operation in order to increase the performance potential and reduce total costs over the entire factory life cycle. Experience shows that this can reduce total costs by about one-third, 80% of which are unplanned operating costs. Therefore, it is imperative to be aware of possible uncertainties in the course of a factory life cycle as a factory planner. Up to now, there has been an inconsistent understanding in this regard. By definition, the emphasis has been on long-term change drivers influenced by megatrends due to the strategic orientation of factory planning. The current crisis situation illustrates the relevance of an operational view on potential short-term uncertainties. The goal of the paper is to analyze the uncertainty over the factory life cycle in its entirety and to create a common understanding for factory planning so that life cycle-oriented planning and evaluation of factories can be aligned accordingly.

Keywords

Factory Planning; Factory Life Cycle; Uncertainty; Change Drivers; Risks

1. Introduction

The meta-goal "profitability of a factory" ensures the success of a company by producing products competitively in the long term [1]. Factory planning is responsible for the design of a factory according to corporate requirements [2]. It defines the cost structure of a factory and a large proportion of its costs, although they do not emerge until the factory is in operation [3]. Factory operation is the longest and hence most important life cycle phase of a factory, which can last several decades [4,5]. On the workstation level, capital expenditures are known to account for about 25 % of life cycle costs, while operating expenditures are associated with 75 %. Therefore, a life cycle-oriented system configuration can reduce total costs by about one-third over the lifetime of a machine. In particular, unplanned operating costs are reduced by 80 %. [6] If established on factory level, this involves the consideration of increasing uncertainties during factory operation. On the one hand, long-term megatrends such as digitization, mass customization or climate change are intensifying the effect of change drivers, which repeatedly create new requirements for the factory. On the other hand, there are short-term disturbances that can lead to disruptions in operations, which have a relevant impact on the profitability of a factory and are difficult to anticipate. [7,8] Instead of permanently and reactively adapting the factory to quasi-static conditions, life cycle-oriented factory planning aims for proactive planning of the factory life cycle. Operations is considered prospectively during planning, and a factory concept is developed from a life cycle-oriented perspective. [9] However, in contrast to capital

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expenditures, which can be determined at the end of the conceptual factory planning phases at the latest, operating expenditures can only be forecasted and are accompanied by the operational uncertainties described above. Therefore, the goal of this paper is to establish a clear understanding of uncertainty throughout the factory life cycle in order to create the basis for life cycle-oriented factory planning and clarification of factory design decisions for coping with uncertainties.

2. Background and state of research

2.1 Life Cycle Evaluation

A life cycle describes typical cyclical patterns of an observed system over time [10]. Based on these patterns, the life cycle of technical and socio-technical systems can be divided into several life cycle phases. Life cycle models consider either the chronological sequence of life cycle phases, e.g. from the raw material to the end-of-life of a product (flow orientation) or the time-dependent state development, e.g. of customer demand from the introduction to the phase-out of a product (state orientation) [10,11]. In technical systems such as a factory, value is created by combining the production factors equipment, material, energy, information and personnel [12]. Therefore, the production system is also called a flow system that converts the inputs material, energy and information into products and services [13]. The exchange of flows with the ecosphere consequently leads to environmental impacts that can be assessed and visualized with the help of life cycle assessment (LCA) [14]. The elementary flows determined in the life cycle inventory are analyzed in the impact assessment with regard to their environmental consequences [10]. Monetarily factored elementary flows are included in the cost structure of a factory, which can be evaluated holistically using the life cycle costing (LCC) method. Life cycle costs are defined as the sum of all expenses required for the intended use of a system from acquisition to disposal [15]. A holistic view of life cycle costs supports the acquisition of capital goods and long-lived products with high investment costs [16]. The life cycle-oriented perspective on the economic and environmental sustainability of a factory is summarized in figure 1:

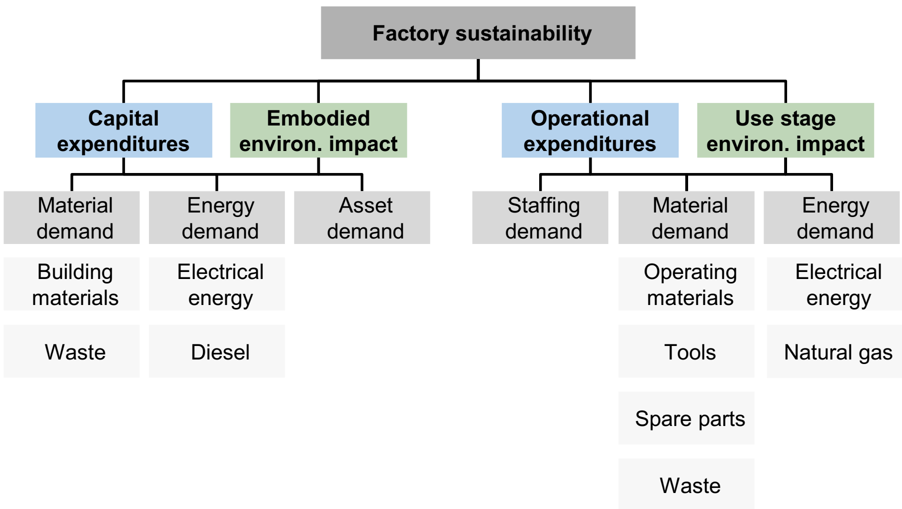

Figure 1: Performance measurement system for factory life cycle evaluation (following [17])

2.2 Factory Life Cycle

The life cycle approach was first applied to an entire factory system by SCHMENNER [18]. In recent publications, the approach has been adopted, and the term "factory as product" is used. Thus, a factory can be considered a very complex product with a long life cycle. As a result, the life cycle concept of a product can also be applied to a factory [19]. However, the factory consists of diverse factory elements that can be assigned to the design fields of technology, space or organization as well as to a hierarchical structure of the factory. The levels of the factory are plant, factory, section and workstation with decreasing level of detail [20]. The sustainability of a factory cannot be influenced directly. It is determined indirectly through the design of the factory elements within the framework of factory planning [21]. The process of factory planning has been described by various authors [22–24,20], which have been combined in VDI Guideline 5200 [25]. Throughout the planning process, developed planning variants are evaluated, and a preferred option is selected for subsequent planning steps or the eventual implementation. An overview of factory models and models for life cycle evaluation of factories was given by NIELSEN ET AL. [26] and updated by DÉR ET AL. [17]. Several detailed models are available for describing the life cycle of individual factory elements. These models address life cycle costs and environmental impacts quantitatively so that they can be used for decision-making. Qualitative description models are predominant for the entire factory. The qualitative approaches either represent phase models or address abstract qualitative key figures such as the utility value shown in Figure 2.

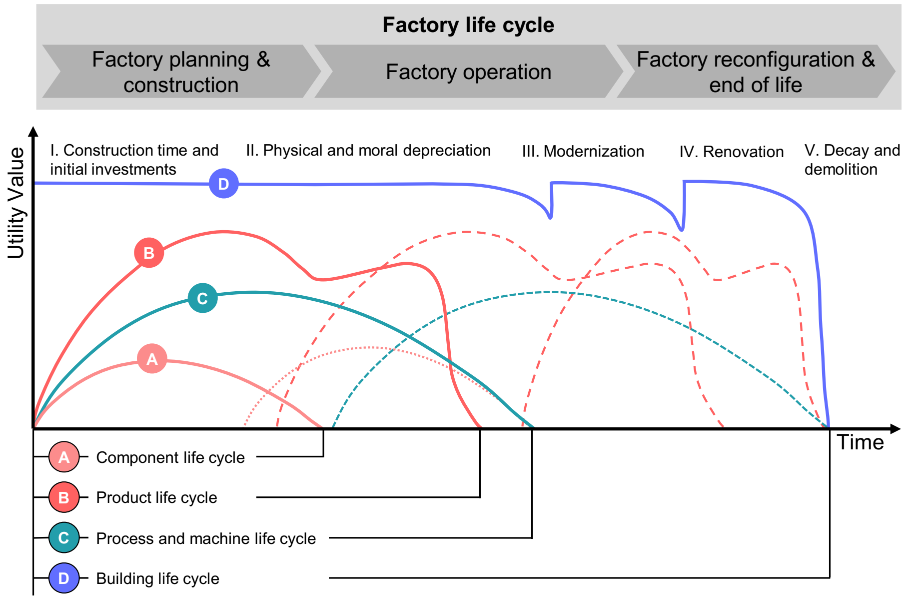

Figure 2: Qualitative model of the factory life cycle, based on [26,27]

The abstract concept of utility value describes whether the main function of a factory element meets the set requirements. Once the required performance cannot be fulfilled, the utility value drops, and the life cycle comes to an end. Therefore, it represents the individual life cycle behaviour of a factory element. The factory elements interact with each other so that requirements are also mutually placed [9]. Ultimately, however, the requirements come from the market, namely the products to be produced [28]. In the past, change and new requirements have always accompanied human, social and industrial developments [29]. In this context, three main stages of industrial development can be differentiated, which result in a static, dynamic and turbulent zone [30]: In the static zone of craftsmanship, it was not mandatory to adapt to economic changes. The beginning of the industrial revolution marked the dynamic zone, where strategic market developments were easy to predict given their low dynamism. The current globally interlinked information age is characterized as a turbulent zone due to the unpredictability of economic, technical and political events. The behaviour of the factory environment was first compared to the physical concept of turbulence in the early 1990s by H.-J. WARNECKE [31]. Here, turbulence describes instabilities of gases and fluids as well as cyclonic actions that are difficult to control [32]. In factory planning, the turbulence behaviour of the factory environment was derived from its dynamics and complexity. Environment dynamics describe erratic and unpredictable changes at an unprecedented speed. The significant increase in environmental complexity describes the numerous, strongly linked influencing factors whose interaction is constantly changing [33]. HERNÁNDEZ therefore summarizes that due to the given uncertainty, the traditional ability to forecast developments is practically non-existent. The risk of misjudgment and misinterpretation exceeds the tolerable level. [29] The term risk is closely related to uncertainty as a lack of knowledge or information that makes the occurrence of a future environmental condition or event not predictable with certainty [34]. If uncertainty can be described as a state of incomplete information and decision-makers can estimate subjective or objective probabilities of occurrence, different environmental states or characteristics of events are referred to as risks [35]. Recent crisis situations such as the Covid pandemic or the Ukraine war show that these uncertainties are no longer just about change but also about sudden disruptions so that the original turbulence characteristics of instability and uncontrollability apply more than ever today. At the same time, the efficiency gains sought in the past as well as the increasing complexity of production processes and the associated organization are contributing to the increasing vulnerability of factories [36,37]. 50% of all companies surveyed rank operational disruptions as the most serious business risk [38]. Earlier legalities are at least temporarily suspended, and stability of operations cannot be assumed. Due to the increased occurrence of unpredictable, disruptive events, the factory system sometimes rarely reaches a steady state. Therefore, life cycle-oriented factory planning must prepare the factory not only for medium- to long-term changes but also for short-term disruptions in the future.

2.3 Life cycle-oriented factory planning

The inherent uncertainties in both the factory and the factory environment mean that continuous reorganization of the factory is necessary [20]. Instead of permanently and reactively adapting the factory to quasi-static conditions, life cycle-oriented factory planning aims for proactive planning of the factory. Factory operation is anticipated and a factory configuration is developed and selected whose life cycle costs are minimal [9]. A final evaluation of the economic efficiency of the planned factory configuration can only be made by considering the factory life cycle. Any efforts to prepare the factory for turbulence will only pay off in the event of need. However, the occurrence of the event remains an uncertain variable. The higher the number and intensity of possible turbulences in the course of the factory life cycle, the faster the break-even point of additional expenditures is reached. Therefore, it is essential that life cycle-oriented factory planning takes into account both short-term as well as medium- to long-term uncertainties when planning and evaluating a factory configuration. Against this background, existing approaches are examined regarding their consideration of uncertainties over the factory life cycle.

Due to the historical development of the understanding of turbulence, there are many approaches in the field of factory planning that deal with uncertainties in the form of possible changes over the factory life cycle and the resulting new requirements for the factory. HERNÁNDEZ uses scenario management to determine the need for change [29]. KLEMKE aims to simplify existing approaches of transformability and examines change drivers in more detail [39]. Other approaches focus in particular on the product as a significant change driver in the form of quantity developments [40,41] or new product variants [42–44]. Short-term uncertainties with a disruptive effect on factory operations are anticipated by only a few approaches in factory planning. Usually, the focus is on demand fluctuations (as opposed to demand trends related to medium- to long-term uncertainties) and associated capacity requirements [45,46]. PEUKERT and KNÜPPEL are the only ones to consider disruptions holistically from a strategic perspective, with KNÜPPEL focusing on improving system understanding through system dynamics modelling of the cause-effect relationships of disturbance variables in complex factory systems [37] and PEUKERT considering the factory merely as a network element of a production network. Her approach is based on a catalogue of disruptions from the production and logistics point of view, whose effects are evaluated for strategic network design [47].

Currently, there is no approach in factory planning that considers the entire uncertainty spectrum over the factory life cycle. In particular, the effects of short-term disruptive events are only investigated to a limited extent. There is a lack of an adequate quantitative approach to evaluate the interactions of a factory with its turbulent effects. A dynamic consideration of randomness in terms of disturbances and change drivers is non-existent. Therefore, a literature review is conducted next in order to analyze uncertainty over the factory life cycle so that a basis for differentiation is established.

3. Literature Review

3.1 Overview

Accidents, probability and possibility are historically the first terms associated with uncertainty, dating back to Aristotle [8]. Uncertainty is omnipresent in a socio-technical system and variability is inevitable during the production of products, which is why MORSE ET AL. conducted an extensive literature review on uncertainty throughout the product life cycle [48]: According to THUNNISSEN, aleatory and epidemistic uncertainties form a basic distinction [49]. Aleatory uncertainty is the inherent variation or variability in a physical system and its environment that cannot be reduced. Epidemistic uncertainty means total unawareness about some constituent elements of the system or environment. ENGELHART ET AL. also refer to aleatory uncertainty as stochastic in terms of the probability and spread of an event and epidemistic uncertainty as unknown in terms of lack of knowledge about an event, effect, or behavior of a system. Estimated uncertainty involves both classifications because the effect is known, but the probability of the event is only partially quantifiable [50].

Economic decision theory [51] differentiates between a decision under certainty and a decision under uncertainty in terms of the completeness of the information. If probabilities for uncertainty are known, it is a decision under risk, otherwise it is a decision under incertitude. In many cases, risk is considered to be value-neutral, so both negative deviations in terms of loss possibilities (danger) and positive deviations of an expected outcome in terms of profit possibilities (opportunity) are included [52]. The subdivision of decisions under uncertainty can be traced back to KNIGHT, who attributes incertitude to one-time decisions that do not occur again [35]. In the field of order management for planning and controlling factory operations, uncertainties are also called turbulence drivers, which result in possible triggers for turbulence [53]. For planning, plan adjustments, fluctuations and variances are relevant because mean key figure values then become insignificant for values of individual orders. Unexpected deviations are relevant for controlling because they jeopardize the fulfilment of promised dates and thus the adherence to the planned schedule. Uncertainties can trigger certain events or environmental conditions [8]. In the literature on economics, they include the possibility of a deviation in target achievement and are called risk if it can be identified, analyzed, managed and controlled [8,54]. In this regard, WINCH AND MAYTORENA have elaborated four pairs of terms in a cognitive approach for project management [55]:

- **Known knowns:** Cognitive state of risk for which the source can be identified, and a probability distribution applied.
- **Unknown knowns:** Cognitive state of risk for which the source can be identified and a probability distribution applied, but the information is not accessible.
- **Known unknowns:** Cognitive state of incertitude for which the source can be identified, but a probability distribution cannot be applied to determine the probability of a risk event.
- **Unknown unknowns:** Cognitive state of incertitude for which the source of risk cannot be identified and, therefore, the probabilities cannot be applied.

IVANOV extends that the occurrence of an event can also be described non-stochastically. Instead of aleatory variables with known distributions, fuzzy descriptions can be used [8]. The events and environmental conditions will be considered in more detail below as disturbances and change drivers.

3.2 Disturbances

Disturbances refer to specific individual events in factory operations that cause an unplanned impairment or deviation from the desired system state or process flow [56]. They can be distinguished by system boundaries, the place of occurrence, their duration or their frequency of occurrence [47]. The occurrence of an event (disturbance cause) is also referred to as a disturbance variable, which has a random and uncertain effect on a factory and can result in an undesirable effect (disturbance effect) [57]. In order management, events with a disturbing effect are called turbulence seeds, which are caused by the impact of the explained turbulence drivers on the three essential process steps procurement, production and delivery and resulting in possible triggers for turbulence. The morphology of the turbulence seeds shows that time, date and quantity changes apply predominantly to procurement and delivery, while in production, rather changes in the order mix and the availability of the production resources cause turbulences.[58] Disturbances represent causal cause-effect chains, which in practice are often multi-level situations [59]. By affecting factory elements and processes, disturbances can lead to business disruptions, depending on how vulnerable or sensitive the factory is to disturbances [8]. They have a negative impact on the performance of a factory, which means that the overall targets time, cost and quality can be missed [56,37]. In order management, such an operational disruption is regarded as full turbulence, in which the current actual values of relevant characteristic key figures deviate significantly from their mean value. A tolerance derived from different requirements defines the permissible deviation from the target value, which according to H.-H. WIENDAHL is subjectively defined and objectively strained:[58]

- **Objective** turbulence represents an unexpectedly occurred deviation beyond the planned tolerance so that the assumptions made in the planning for the future have failed in their predictability. In contrast to predictable and weak deviations, sudden and strong deviations cause turbulence and, thus, uncertainty within the planning horizon [60]
- **Subjective** turbulence describes an expected deviation due to a turbulence seed, whose relevance is to be evaluated during planning in order to provide sufficient tolerance for the actual occurrence and thus prevent deviations from the plan.

Disturbances or turbulence seeds are, therefore, either known and predictable or unknown and unpredictable. The known events can be modelled with deterministic or stochastic methods, and their disturbance effect can be estimated [57]. Here, the objective view describes the market requirements and determines the theoretically necessary factory configuration. The subjective aspect evaluates the capabilities compared to the requirements and determines the practically realized factory configuration. For example, the greater the volume fluctuations compared to the available volume flexibility, the higher the turbulence. Significant deviations from the idealized flow pattern of the factory result and the lead time of individual orders varies enormously. In the case of full turbulence, the requirements can no longer be met due to the variability of the turbulence drivers. The planning in the classical sense loses its task, and operations cannot be maintained permanently or only with high effort, leading to an operational disruption. [61]

3.3 Change Drivers

Change drivers influence the basic conditions of a factory, place new requirements and thus lead to a strategic need for change [62]. They influence and determine the required values of the change dimensions cost, time and quality as essential production indicators as well as the required quantity and product variants, that must be met for competitive factory operations [39]. Change dimensions are also referred to as receptors, as they represent receiving devices of a system that is sensitive to specific stimuli, which is then passed on: A change in the dimensions by change drivers leads to a need for change in a factory. Some drivers have a direct influence on the factory and its elements. [63] Following KLEMKE, a distinction can thus be made between target drivers as well as process and element drivers [39]:

- **Target drivers** influence the change dimensions and thus place new requirements on the factory. If the changed target values of a dimension cannot be met, a factory adjustment is necessary.
- **Process and element drivers** have an influence on the basic conditions of a factory. When the drivers occur, specific elements of the factory must be adapted to the changed conditions, which in turn can have a negative impact on the target values of all dimensions.

Due to the unpredictable environment, it is difficult to predict which adjustments will be necessary in the future [1]. However, in contrast to disturbances, a predictive ability is assumed in general. That is why

KLEMKE excludes uncertainties which cannot be predicted with approximate accuracy even by technical experts (e.g. natural disasters) [39]. The forecasting ability results from the influence of megatrends, which represent long-term developments with great relevance from an economic, political and social perspective. Due to the influences of megatrends, the environment of manufacturing companies is constantly changing [64]. Change drivers are also referred to as the impact of megatrends on the factory environment [39]. This in turn results in complex cause-effect relationships between megatrends, change drivers and the factory [62]. The interactions between megatrends, depending on their geographic manifestation, determine the probability and extent of change drivers [65]. They can affect factories internally, i.e. from within a company, or externally, i.e. from the environment of a company. The factory elements affected by the change are themselves in a complex multi-level network with dynamic feedback [62]. Change drivers are therefore medium- to long-term uncertainties that are generally known and predictable.

4. Differentiation Of Uncertainty Over The Factory Life Cycle

Using insights gained from the literature review, the short-term disturbances are to be consistently differentiated from the medium- to long-term change drivers in the following. Hereby, a theoretical basis for the alignment of life cycle-oriented factory planning is provided. Due to the increased inclusion of operations during the conceptual design of a factory in life cycle-oriented factory planning, it is particularly important to focus more strongly on possible disturbances and potentially associated operational disruptions, which have a high relevance in the current time. Stress tests of design variants are carried out in order to select the variant that can cope best with uncertainty during factory operations. For this purpose, the term uncertainty is divided into risk and incertitude in the context of a factory life cycle (see Figure 3).

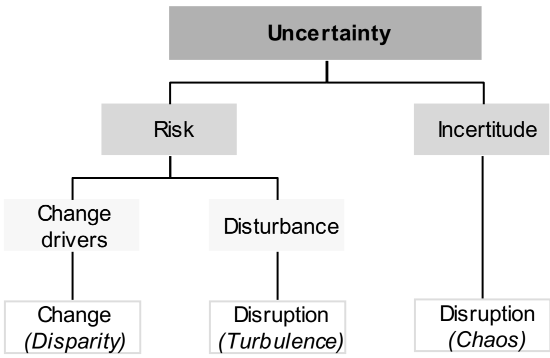

Figure 3: Differentiation of uncertainty over the factory life cycle

Incertitude results from epidemic uncertainty with no knowledge of the origin, probability of occurrence, or possible effect (known/unknown **unknowns**). It is an unforeseen deviation from an outcome. Accordingly, a subjective evaluation can only be made without the expertise or experience that is actually required. In contrast, a risk results from aleatory uncertainty, for which knowledge is available about the probability and distribution of variation in a system and its environment (known/unknown **knowns**). In most practical planning situations, objective probabilities do not exist [51]. Subjective probabilities incorporate the experience and intuition of a factory planner. Therefore, incertitudes are also handled as a risk in real planning situations, using assumptions nevertheless. Otherwise, incertitude would remain completely unconsidered in factory planning.

Risks describe the possible occurrence of different environmental conditions or events as a state of incomplete information, which can lead to a deviation between the target and actual values in controlling. If risks actually occur, a distinction is made between change drivers and disturbances. *Change drivers* can lead to both a positive (opportunity) and negative (danger) deviation. As an environmental condition, they cannot be influenced by factory planning, but they determine the outcome of a decision. In contrast, *disturbances* refer to events affecting individual factory elements that may lead to missed targets. Given their origin in aleatory uncertainty, they are usually known and predictable. As long as a factory is not in a steady state, they are deterministic or predetermined. In the case of reasonably stable processes, they are stochastic or random.

Disturbances can have an immediate effect on the actual values and thus on the current target achievement of factory operation or cause short-term changes in target values. Without further measures, they can lead to *operational disruption*, depending on the vulnerability of a factory. Based on the turbulence classes of order management, *turbulence* gradually arises [66]. In the case of weak turbulence, individual disturbances affect the primary movement of the material flow within a section. The lead time of individual orders deviates significantly and a high level of control effort is required to maintain the flow. Full turbulence affects the entire factory. There is no continuous material flow, which is overlapped by disturbances and can break off leading to a disruption. If incertitude suddenly occurs as an unknown or objectively unpredictable event, it can directly trigger an operational disruption. The event is unexpected, the effect can usually not be absorbed economically so that an unprepared factory is threatened with *chaos*. The material flow breaks off immediately. In contrast, change drivers do not have a disruptive effect and thus have no direct influence on the current processes in factory operation. At the most, they can facilitate the occurrence of disturbances through a change in system state (e.g. ageing behaviour). Instead, they result in new restrictions, potentials for the actual values or requirements for target achievement as new medium- to long-term target values. This prevailing *disparity* is balanced by implemented *changes* that ultimately transform operations and adapt processes to new conditions. Change drivers explicitly refer to future environmental conditions after factory planning is completed. During a factory planning project, uncertainties in environmental conditions are referred to as planning risks. These are assumptions about parameters that are detailed and confirmed during the planning process [67]. Such assumptions pose a risk to the target achievement of a factory configuration.

Life cycle-oriented factory planning therefore combines the preliminary considerations on turbulence from classic factory planning and order management in order to prepare the factory in the best possible way for any kind of uncertainty over the factory life cycle. Factory configurations must be designed differently, depending on whether medium- to long-term changes in environmental conditions (change drivers) or short-term operational disturbances (disruptions) are expected. Ideally, a life cycle-oriented factory configuration manages to maintain target achievement despite the upcoming uncertainties. If target achievement is permanently impaired by disturbances or if the capability of a factory configuration to achieve a target value is insufficient due to a change driver, the current factory life cycle comes to an end and a new factory planning project must be initiated.

5. Discussion and outlook

In summary, future challenges in factory operation can be anticipated based on the developed differentiation of uncertainty. It forms a useful basis for considering the unavoidable uncertainties in life cycle-oriented factory planning. Nowadays, factory planners have to become more aware of possible disruptions and thus of the entire factory operation in addition to possible change drivers. Consideration must be given to whether the capacities and capabilities provided in a factory configuration are sufficient and effective enough for the uncertainties to be expected during factory operation. Future research is needed to make the uncertainties identified in this paper assessable as part of a factory life cycle model in order to be able to select factory planning measures and determine their scope of action depending on the evaluated effect of the uncertainties. This involves a prognosis model in a suitable level of detail, which simulates the temporal behaviour of a factory after the occurrence of uncertainty. Furthermore, explicit design principles based on the strategies of risk management are to be developed in the future for the sophisticated handling of uncertainties.

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References

[1] Heger, C.L., 2006. Bewertung der Wandlungsfähigkeit von Fabrikobjekten. Dissertation. PZH, Produktionstechnisches Zentrum, Garbsen.

[2] Wiendahl, H.-P., Harms, T., Heger, C.L., 2003. Die Fabrik als strategisches Wettbewerbsinstrument, in: Reinhart G., Z.M. (Ed.), Marketchance Individualisierung. Springer, Berlin, Heidelberg.

[3] Gairola, A., 1981. Montagegerechtes Konstruieren: Ein Beitrag zur Konstruktionsmethodik. Dissertation, Darmstadt.

[4] Gebler, M., Cerdas, J.F., Thiede, S., Herrmann, C., 2020. Life cycle assessment of an automotive factory: Identifying challenges for the decarbonization of automotive production – A case study. Journal of Cleaner Production 270.

[5] Herrmann, C., Kara, S., Thiede, S., 2011. Dynamic life cycle costing based on lifetime prediction. International Journal of Sustainable Engineering.

[6] Perlewitz, U., 1999. Konzept zur lebenszyklusorientierten Verbesserung der Effektivität von Produktionseinrichtungen. Dissertation. PTZ, Berlin.

[7] Hingst, L., Park, Y.-B., Nyhuis, P., 2021. Life Cycle Oriented Planning Of Changeability In Factory Planning Under Uncertainty. Proceedings of the Conference on Production Systems and Logistics : CPSL 2021.

[8] Ivanov, D., 2018. Structural Dynamics and Resilience in Supply Chain Risk Management, 1st ed. 2018 ed. Springer International Publishing; Imprint: Springer, Cham.

[9] Hingst, L., Dér, A., Herrmann, C., Nyhuis, P., 2023. Towards a holistic life cycle costing and assessment of factories – Qualitative modeling of interdependencies in factory systems. Sustainability.

[10] Herrmann, C., 2010. Ganzheitliches Life Cycle Management. Springer Berlin Heidelberg, Berlin, Heidelberg.

[11] Herrmann, C., Bergmann, L., Thiede, S., Halubek, P., 2007. Total life cycle management-an integrated approach towards sustainability, in: 3rd International Conference on Life Cycle Management, Zurich.

[12] Helbing, K.W., 2018. Handbuch Fabrikprojektierung, 2., aktualisierte und ergänzte Auflage ed. Springer Vieweg, Berlin, Heidelberg.

[13] Müller, E., Engelmann, J., Löffler, T., Strauch, J., 2009. Energieeffiziente Fabriken planen und betreiben. Springer Berlin Heidelberg, Berlin, Heidelberg.

[14] International Organization for Standardization, 2021. Environmental management – Life cycle assessment – Principles and framework.

[15] Verein Deutscher Ingenieure, 2005. Purchase, operating and maintenance of production equipment using Life Cycle Costing (LCC): VDI 2884.

[16] Hauschild, M.Z., Rosenbaum, R.K., Olsen, S.I., 2018. Life Cycle Assessment: Theory and Practice. Springer International Publishing, Cham.

[17] Dér, A., Hingst, L., Nyhuis, P., Herrmann, C., 2022. A review of frameworks, methods and models for the evaluation and engineering of factory life cycles. Advances in Industrial and Manufacturing Engineering.

[18] Schmenner, R.W., 1983. Every Factory has a Life Cycle. Harvard Business Review 61 (2), 121–129.

[19] Westkämper, E., Constantinescu, C., Hummel, V., 2006. New paradigms in manufacturing engineering: factory life cycle. Annals of the Academic Society for Production Engineering. Research and Development 13 (1), 143–147.

[20] Wiendahl, H.-P., Reichardt, J., Nyhuis, P., 2015. Handbook Factory Planning and Design. Springer Berlin Heidelberg, Berlin, Heidelberg.

[21] Nyhuis, P., Kolakowski, M., Heger, C.L., 2005. Evaluation of Factory Transformability, in: 3rd International CIRP Conference on Reconfigurable Manufacturing, Ann Arbor, USA. May.

[22] Grundig, C.-G., 2018. Fabrikplanung: Planungssystematik - Methoden - Anwendungen, 6., neu bearbeitete Auflage ed. Hanser, München.

[23] Pawellek, G., 2014. Ganzheitliche Fabrikplanung, 2. Auflage ed. Springer Vieweg, Berlin, Heidelberg.

[24] Schenk, M., Wirth, S., Müller, E., 2014. Factory Planning Manual: Situation-Driven Production Facility Planning, Aufl. 2010 ed. Springer Berlin, Berlin.

[25] Verein Deutscher Ingenieure, 2011. Factory planning - Planning procedures: VDI 5200.

[26] Nielsen, L., Schmidt, C., Blume, S., Schmidt, M., Thiede, S., Nyhuis, P., Herrmann, C., 2016. Towards Quantitative Factory Life Cycle Evaluation. Procedia CIRP 55, 266–271.

[27] Wirth, S., Günter, U., David, T., 2000. Durchgängiges Planungskonzept mit ganzheitlicher simulationsbasierter Layoutplanung, in: Vortragsband "Vernetzt planen und produzieren", Chemnitz, pp. 56–61.

[28] Hingst, L., Nyhuis, P., 2022. Controlling Product Variance in a Factory Through the Evaluation of the Factory Life Cycle. Advances in Production Management Systems. Smart Manufacturing and Logistics Systems: Turning Ideas into Action. APMS 2022. IFIP Advances in Information and Communication Technology, vol 663. Springer, Cham.

[29] Hernández, R., 2002. Systematik der Wandlungsfähigkeit in der Fabrikplanung. Dissertation, Hannover.

[30] Spur, G., Stöferle, T., 1994. Fabrikbetrieb. Hanser, München.

[31] Warnecke, H., 1992. Die Fraktale Fabrik: Revolution der Unternehmenskultur. Springer Berlin Heidelberg, Berlin, Heidelberg.

[32] Grote, K., Feldhusen, J. (Eds.), 1995. Dubbel: Taschenbuch für den Maschinenbau. Springer Berlin Heidelberg, Berlin, Heidelberg.

[33] Zahn, E., Tilebein, M., 1999. Führung wandlungsfähiger Unternehmen – eine Herausforderung in neuen Dimensionen. Industrie Management 14 (6), 49–52.

[34] Schneeweiß, C., 1991. Planung: Systemanalytische und entscheidungstheoretische Grundlagen. Springer, Berlin, Heidelberg.

[35] Knight, F., 1921. Risk, Uncertainty and Profit.

[36] Ivanov, D., Sokolov, B., Dolgui, A., 2014. The Ripple effect in supply chains: trade-off 'efficiency-flexibility-resilience' in disruption management. International Journal of Production Research 52 (7), 2154–2172.

[37] Knüppel, K.M., 2016. Modellbasiertes Störungsmanagement in Produktionssystemen. Dissertation, Hannover.

[38] Allianz, 2021. Allianz Risiko Barometer 2021. https://www.agcs.allianz.com/news-and-insights/news/allianz-risk-barometer-2021-de.html.

[39] Klemke, T., 2014. Planung der systemischen Wandlungsfähigkeit von Fabriken. Dissertation, Hannover.

[40] Löffler, C., 2011. Systematik der strategischen Strukturplanung für eine wandlungsfähige und vernetzte Produktion der variantenreichen Serienfertigung. Dissertation, Stuttgart.

[41] Wagner, C., 2012. Kontinuierliche Gestaltung skalierbarer Produktionsstufen. Dissertation, Hannover.

[42] Blumenau, J.C., Kotz, T., 2005. Wandlungsfähigkeit auf Abruf: Bedarfsgerechte Gestaltung und Bewertung stückzahlflexibler Produktionssysteme für die Massenfertigung von Hochleistungserzeugnissen. Zeitschrift für wirtschaftlichen Fabrikbetrieb 100, 42–46.

[43] Khedri Liraviasl, K., ElMaraghy, H., Hanafy, M., Samy, S.N., 2015. A Framework for Modelling Reconfigurable Manufacturing Systems Using Hybridized Discrete-Event and Agent-based Simulation. IFAC-PapersOnLine 48 (3), 1490–1495.

[44] Wulf, S., 2011. Bewertung des Einflusses von Produkt- und Technologieveränderungen auf die Fabrik: Bewertung des Einflusses von Produkt- und Technologieveränderungen auf die Fabrik. Dissertation, Hannover.

[45] Gottschalk, L., König, R., 2004. Bedarfsunsicherheiten durch flexible Kapazitäten beherrschen. ZWF 99, 715–719.

[46] Heinicke, M., 2017. Resilienzorientierte Beurteilung von Produktionsstrukturen. Dissertation, Magdeburg.

[47] Peukert, S.K., 2021. Robustheitssteigerung in Produktionsnetzwerken mithilfe eines integrierten Störungsmanagements. Dissertation, Karlsruhe.

[48] Morse, E., Dantan, J.-Y., Anwer, N., Söderberg, R., Moroni, G., Qureshi, A., Jiang, X., Mathieu, L., 2018. Tolerancing: Managing uncertainty from conceptual design to final product. CIRP Annals 67 (2), 695–717.

[49] Thunnissen, D. Uncertainty Classification for the Design and Development of Complex Systems.

[50] Engelhardt, Alexander, R., Eifler, Tobias, Mathias, Johannes, Kloberdanz, Hermann, Birkhofer, Herbert, Bohn, Andrea, 2011. Linkage of methods within the umea methodology: An approach to analyse uncertainties in the product develmopment procees. INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN.

[51] Laux, H., Gillenkirch, R.M., Schenk-Mathes, H.Y., 2018. Entscheidungstheorie, 10., aktualisierte und erweiterte Auflage ed. Springer Gabler, Berlin, Heidelberg.

[52] Wildemann, H., Baumgärtner, G., 2006. Suche nach dem eigenen Weg: Individuelle Einführungskonzepte für schlanke Produktionssysteme. Zeitschrift für wirtschaftlichen Fabrikbetrieb 101 (10), 546–552.

[53] Wiendahl, H.-H., 2006. Auftragsmanagement im turbulenten Umfeld: Teil 2 – Lösungsansätze. wt Werkstattstechnik online 96 (5), 325–330.

[54] Rogler, S., 2002. Risikomanagement im Industriebetrieb. Dissertation, Wiesbaden.

[55] Winch, G.W., Maytorena, E. Managing Risk and Uncertainty on Projekts, A Cognitive Approch, in: , The Oxford handbook of project management, pp. 345–364.

[56] Heil, M., 1995. Entstörung betrieblicher Abläufe. Gabler Verlag.

[57] Stricker, N., 2016. Robustheit verketteter Produktionssysteme. Dissertation, Karlsruhe.

[58] Wiendahl, H.-H., 2011. Auftragsmanagement der industriellen Produktion. Springer Berlin Heidelberg, Berlin, Heidelberg.

[59] Bormann, D., 1978. Störungen von Fertigungsprozessen und die Abwehr von Störungen bei Ausfällen von Arbeitskräften durch Vorhaltung von Reservepersonal. Günter Marchal und Hans-Jochen Matzenbacher WIssenschaftsverlag, Berlin.

[60] Mintzberg, H., 1994. That's Not "Turbulence," Chicken Little, It's Really Opportunity, in: , Planning Review, pp. 7–9.

[61] Wiendahl, H.-H., 2002. Situative Konfiguration des Auftragsmanagements im turbulenten Umfeld. Dissertation, Stuttgart.

[62] Nofen, D., 2006. Regelkreisbasierte Wandlungsprozesse der modularen Fabrik. Dissertation, Hannover.

[63] Heinen, T., 2011. Planung der soziotechnischen Wandlungsfähigkeit in Fabriken. Dissertation, Garbsen.

[64] Adolph, S., Tisch, M., Metternich, J., 2014. Challenges and approaches to competency development for future production. Journal of International Scientific Publications 12, 1001–1010.

[65] Hingst, L., Dér, A., Herrmann, C., Nyhuis, P., 2021. Evaluation of the influence of change drivers on the factory life cycle. Procedia CIRP.

[66] Westkämper, E., Wiendahl, H.-H., Pritschow, G., Rempp, B., Schanz, M., 2000. Turbulenz in der PPS – eine Analogie. wt Werkstattstechnik online 90 (5), 203–207.

[67] Weig, S., 2008. Konzept eines integrierten Risikomanagements für die Ablauf- und Strukturgestaltung in Fabrikplanungsprojekten. Dissertation, München.

Biography

Lennart Hingst, M.Sc. (*1989) has been a research associate in the factory planning group at the Institute of Production Systems and Logistics (IFA) at the Leibniz University Hanover since 2019. He previously studied technical logistics at the University of Duisburg-Essen (M.Sc.) and holds years of industry expertise.

Prof. Dr.-Ing. habil. Peter Nyhuis (*1957) has been head of the Institute of Production Systems and Logistics (IFA) at Leibniz University Hanover since 2003. Prof. Dr.-Ing. habil. Peter Nyhuis was a member of the German Science Council (2014 – 2018) and has been Chairman of the Science Council of the AiF (GAG3) since 2015. He is also a member of the German Academy of Technical Sciences acatech and the Scientific Society for Production Technology (WGP).

4th Conference on Production Systems and Logistics

Modelling And Control Of Aqueous Parts Cleaning Machines For Demand Response

Daniel Fuhrländer-Völker[1], Benedikt Grosch[1], Matthias Weigold[1]

[1] *Technical University of Darmstadt, Department of Mechanical Engineering, Institute of Production Management, Technology and Machine Tools (PTW), Darmstadt, Germany*

Abstract

With the aim of enabling better utilization of renewable power and reducing the environmental impact of industrial sites, we propose an approach for implementing electric demand response. Cleaning machines provide significant potential for demand response due to their large water tanks, which can be used for thermal energy storage. Furthermore, many batch cleaning machines allow process interruptions without impacting the cleaning result. We show that utilizing inherent energy storage and process interruptions are practical ways to implement demand response.

Hence, we present a mathematical demand response model of an aqueous parts cleaning machine and integrate it in a cyber-physical production system. The mathematical demand response model is used to determine the energy consumption of the machine resulting from the cleaning process and the tank heater. The model is divided into an event-based part describing the individual steps of the cleaning process and a time-based part representing the energy required by the tank heater to satisfy specified tank temperature limits.

In addition to the mathematical model, we present the data model required for communication with the physical machine. We validate the mathematical model and the complete cyber-physical production system including a real machine in a field test in the ETA research factory for their demand response capabilities.

Keywords

carbon neutral production; energy-flexibility; cyber-physical production system; model predictive control; single machine scheduling; data model; inherent energy storage

1. Introduction

Purchasing electricity is currently more expensive than ever for industrial companies. Average annual electricity spot market prices in Germany rose from 28.20 €/MWh in 2016 to 93.35 €/MWh in 2021 and 235.52 €/MWh in 2022 [1]. The latest price increase is caused by the dependence on conventional energy sources such as oil and gas [2]. The worldwide average price for gas already increased by 549 % between December 2020 and one year later. [3]. One way to reduce dependence on fossil fuels is to expand the use of renewable energy. Between 2011 and 2021, renewable generation worldwide has nearly doubled from 402 TW h to 763 TW h [4]. An adjustment of the electricity system is required for the switch to renewable electricity generation. Due to the stochastic nature of renewable electricity generation consumers should adapt to fluctuating generation through the integration of energy storage and by using demand response (DR) as part of demand side integration [5], thus reducing energy costs.

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In previous research we performed an analysis of the DR potential of an industrial aqueous parts cleaning machine [6]. We also developed an automation data model to be used for the communication between DR services and the machine automation in cyber-physical production systems (CPPS) [7]. In [8] we implemented a CPPS based on the automaton data model including a simulation model of the cleaning machine and a simple rule-based DR service to control the tank heater of the machine. The approach shown in the present paper extends this research with a mathematical model for the machine's production schedule. The model integrates the flexibility potentials identified in [6]. We also extend the automation data model to include the newly required information and update the automation structure of the machine.

In section 2 of this article we provide a literature review of industrial process and production scheduling. Then, we briefly describe the cleaning machine and its DR potential in section 3. We subsequently present the DR service in section 4. The data model for interaction between the machine automation and the DR service is shown in section 5. Finally, we apply the DR service to a cleaning machine in a field test in section 6 and draw a conclusion in section 7.

2. Literature

The literature review identified many research articles focused on energy flexible or energy efficient scheduling of single machines. Some exemplary approaches for minimizing the energy cost of production by applying DR are [9], where the schedule is optimized for an unspecified single machine, and [10], where a machining process is considered and multiple factors are optimized, including the cutting speed. Biel et al. [11] provide a comprehensive overview of research in this area, and a more recent review has been published by Bänsch et al. [12].

Most of the previously mentioned research lacks a standardized method for the implementation of the proposed optimization on actual machines in real production environments. The creation of cyber-physical production systems might offer a path towards further proliferation of the proposed scheduling optimizations. In [13], Meissner et al. describe how the development of cyber-physical production systems influences process planning and scheduling. They point out a variety of factors affecting the implementation of data driven process planning and scheduling approaches, such as the interconnectedness of machines and products, big data, and cyber security. The benefits of integrated process planning and scheduling lie mostly in the increased capacity for real-time adaptation of process plans and schedules.

Leiden et al. present an approach for energy and resource efficient operation of plating process chains using a cyber-physical system implementation [14]. They created an agent based discrete-event simulation of the process chain to support planning and operational processes. The authors assert that the implementation as a cyber-physical system led to high process transparency and attest good applicability of their system by utilizing it for decision support as well as direct control of processes [14].

In the literature review we observed a lack of cyber-physical production system implementations which aim to make single machine scheduling with an energy-related objective more attainable. We therefore attempt to fill this gap by presenting a scheduling model with an energy-cost objective which is integrated in a cyber-physical production system.

3. System description and demand response potential

We develop a demand response scheduling model for the aqueous parts cleaning machine MAFAC KEA in the ETA Factory at the Technical University of Darmstadt [15]. The machine has a total rated power of 20.7 kVA. It is equipped with one closed treatment chamber and a 320 l tank for cleaning fluid, which is heated by an electrical tank heater with 10 kW nominal load. The cleaning process duration is 12 minutes and consists of the three energy-relevant process steps *spray cleaning* (600 s), *impulse blowing* (30 s) and *convection drying* (90 s).

We analysed the potential of the cleaning machine for DR measures in [6]. The DR potential analysis of the machine showed that it has high potential to implement the DR measures *interrupt process* and *store energy inherently* defined in [16]. *Interrupt process* means pausing between cleaning processes or between the process steps. By controlling the tank heater with a DR service and using the thermal inertia of the tank as a thermal storage, the heating system can be used to *store energy inherently* [6].

In this study we aim to replace the simple control strategy previously described in [8] with a mathematical optimization model, executed as a model predictive controller (MPC). While we previously presented a simple rule-based approach for controlling just the tank heater, we now design a more sophisticated model for the temperature of the cleaning fluid in the tank, which takes the cleaning stages into account. We also integrate the ability to make the *interrupt process* decision. These changes of the model also require some adaptations of the automation structure. The entire implementation of the cyber-physical production system is based on the eta-utility software framework [17].

4. Demand response scheduling model

To use the cleaning machine for DR we create a mixed integer linear programming (MILP) scheduling model. The model is used as the DR service by executing it in a MPC loop. The objective function of the scheduling model aims to minimize the energy cost of the cleaning machine which depends on the machine's power consumption and the changing energy price. We separate the model into two parts: We develop an event-based approach to model the cleaning process for the DR measure *interrupt process* and a second discrete-time model for the control of the tank heating system to implement *store energy inherently*.

The total energy costs are the sum of the energy costs for every cleaning process event $n \in \{1, \ldots, N\}$, plus the sum of the energy costs for tank heating for every timestep $k \in \{0, \ldots, K\}$, where $N \in \mathbb{N}$ is the total number of cleaning process events and $K \in \mathbb{N}$ is the optimization horizon. Every cleaning process event is defined by its start time $s_n \in \mathbb{N}_0$ and duration $d_n \in \mathbb{N}_0$. The energy costs of each cleaning process event are determined by the time-dependent energy price $c_k \in \mathbb{R}$ for every timestep *k* and the power consumption $p_n \in \mathbb{R}_{\geq 0}$ of the cleaning process event *n*. The energy cost of the tank heater is the product of the tank heaters power consumption $p_{\text{heat}} \in \mathbb{R}_{\geq 0}$, the tank heater state $h_k \in \{0,1\}$, and the energy price c_k. We minimize the costs over the durations of cleaning process events $\mathbf{d} = (d_1, \ldots, d_N) \in \mathbb{N}_0^N$ and the switching state of the tank heater $\mathbf{h} = (h_0, \ldots, h_K) \in \{0, 1\}^{K+1}$, i.e.

$$\min_{\mathbf{d},\mathbf{h}} \sum_{n=1}^{N} \sum_{k=s_n}^{s_n+d_n-1} p_n c_k + p_{\text{heat}} \sum_{k=0}^{K} h_k c_k. \tag{1}$$

4.1 Event-based model of the cleaning process

Each cleaning process event *n* has an associated power consumption value

$$p_n = \begin{cases} p_{\text{int}}, & \forall n = 1, 3, \ldots, N \\ p_{\text{clean}}, & \forall n = 2, 6, \ldots, N-3 \\ p_{\text{dry}}, & \forall n = 4, 8, \ldots, N-1 \end{cases} \tag{2}$$

with $p_{int} \in \mathbb{R}_{\geq 0}$ representing the power consumption in interruption, $p_{\text{clean}} \in \mathbb{R}_{\geq 0}$ during process steps spray cleaning and impulse blowing combined due to the short duration of impulse blowing, and $p_{\text{dry}} \in \mathbb{R}_{\geq 0}$ during drying. n_{start} represents the MPC's process event currently activated on the machine. Since all previous events lie in the past, the starting time s_n of the active event and all prior events is zero, i.e.

$$s_n = 0, \qquad \forall\, n \leq n_{\text{start}}. \tag{3}$$

The start of the next event s_{n+1} is the sum of the start s_n and duration d_n of the anterior event, i.e.

$$s_{n+1} = s_n + d_n, \qquad \forall\, n = n_{\text{start}}, \dots, N-1. \tag{4}$$

The first, last and all uneven events $n = \{1,3,\dots,N\}$ of a process are defined as interruptions. Only the duration of interruptions can be changed, the duration of cleaning and drying events is fixed. Hence the duration is set to

$$d_n = \begin{cases} 0 & , \forall\, n < n_{\text{start}} \\ d_{\text{start}} & , \forall\, n = 2,4,\dots,N-1 \text{ with } n = n_{\text{start}} \\ d_{\text{clean}} & , \forall\, n = 2,6,\dots,N-3 \text{ with } n > n_{\text{start}} \\ d_{\text{dry}} & , \forall\, n = 4,8,\dots,N-1 \text{ with } n > n_{\text{start}} \end{cases} \tag{5}$$

where the duration of past events is zero, the durations of the cleaning and drying events $d_{\text{clean}} \in \mathbb{N}$ and $d_{\text{dry}} \in \mathbb{N}$ and the remaining time of the current cleaning or drying event is $d_{\text{start}} \in \mathbb{N}$. The total process duration is limited by the fixed end time of all cleaning processes $S \in \mathbb{N}$ and the optimization horizon K i.e.

$$s_N + d_N \leq \min(K, S). \tag{6}$$

At the end of each cleaning process, there must be unscheduled time to allow for loading the machine, except when approaching the end time of all scheduled processes S. The duration for loading is specified by:

$$d_n \geq \min(d_{\text{load}}, S), \qquad \forall\, n = 5,9,\dots,N \text{ with } n \geq n_{\text{start}} \tag{7}$$

4.2 Time-based model of the tank temperature

The optimization of the tank heater is time-based, and the operation of the tank heater depends on the temperature inside the machine's cleaning fluid tank $t_k \in \mathbb{R}_{\geq 0}$, which must remain within the hysteresis limits determined by a lower bound $t_{\text{lb}} \in \mathbb{R}_{\geq 0}$ and an upper bound $t_{\text{ub}} \in \mathbb{R}_{\geq 0}$:

$$t_{\text{lb}} \leq t_k \leq t_{\text{ub}}, \qquad \forall\, k = 0,\dots,K \tag{8}$$

The tank temperature at a specific time step is determined by the starting temperature $t_{\text{start}} \in \mathbb{R}_{\geq 0}$, the temperature loss to the environment and to cleaned parts $f_k \in \mathbb{R}_{\geq 0}$ and the temperature increase due to tank heater operation $e_k \in \mathbb{R}_{\geq 0}$.

$$t_{k+1} = t_k + e_k - f_k, \qquad \forall\, k = 0,\dots,K \tag{9}$$

$$t_0 = t_{\text{start}} \tag{10}$$

To determine experimental factors for the heat losses in section 4.3, we need approximate analytical models to integrate them appropriately with the optimization. Therefore, we assume the fluid inside of the tank of the cleaning machine to be a closed homogenous system. There is no exchange of work between the system and the environment, and the heat exchange is isobaric. The conversion from electric energy to heat in the tank heater has an efficiency near one, hence the heat flow into the system by the tank heater is equal to its electric power rating ($\dot{Q}_{\text{heat}} = p_{\text{heat}}$). The positive heat flow of the tank heater into the system leads to a temperature change dependent on the specific heat capacity $c_{\text{p,fluid}}$, the volume V_{tank}, and density ρ_{fluid} of the cleaning fluid and the time step duration $\delta \in \mathbb{N}$. h_k is the decision variable for tank heater operation:

$$e_k = \frac{p_{\text{heat}}\,\delta}{c_{p,\text{fluid}}\,V_{\text{tank}}\,\rho_{\text{fluid}}} \cdot h_k, \qquad \forall k = 0,\dots,K \tag{11}$$

In addition to the heat flow generated by the tank heater, there is a heat flow f_k from the cleaning liquid to the environment and to the cleaned parts. We chose to separate the heat flow to the environment during the operational state of the machine and the heat flow to environment and washed parts during the working state because they differ significantly. Equation (12) yields the heat flow to the environment $\dot{Q}_{\text{env}}$ due to conduction and convection. We did not consider the effects of radiation and judging from the experimental results this simplification is acceptable. The heat flow depends on the surface area A_{tank}, the thermal conductivity between tank and environment $\lambda_{\text{tank, env}}$, the heat-transfer coefficient α_{env} and the environment temperature t_{env}:

$$\dot{Q}_{\text{env}}(t_k) = \left(\lambda_{\text{tank, env}} + \alpha_{\text{env}}\right) A_{\text{tank}} \left(t_k - t_{\text{env}}\right) \tag{12}$$

Assuming an equilibrium between the temperature of the washed parts and the cleaning fluid at the end of the cleaning process, the total change of inner energy of the parts $\Delta U_{\text{parts}}(t_k)$ with specific heat capacity $c_{\text{p, wp}}$, the number of parts n_{wp}, the mass of each part m_{wp} and the temperature when being loaded $t_{\text{wp}} = t_{\text{env}}$ is defined as

$$\Delta U_{\text{parts}}(t_k) = c_{\text{p, wp}}\, n_{\text{wp}}\, m_{\text{wp}}\, \left(t_k - t_{\text{wp}}\right) \tag{13}$$

The third factor contributing to heat loss to the environment is most likely mainly based on forced convection between the cleaning fluid and the walls of the cleaning chamber because of the spray cleaning process $\dot{Q}_{\text{spray}}(t_k)$ with a separate heat-transfer coefficient α_{spray}:

$$\dot{Q}_{\text{spray}}(t_k) = \alpha_{\text{spray}} A_{\text{tank}} \left(t_k - t_{\text{env}}\right) \tag{14}$$

Based on the analytical heat transfer equations (12), (13) and (14), we identify three regression factors to simplify the models. β_{env} describes the heat loss to the environment, β_{parts} describes the heat loss to the parts during cleaning and β_{spray} describes the heat loss due to spray cleaning.

$$\beta_{\text{env}} \cong \frac{\left(\lambda_{\text{tank, env}} + \alpha_{\text{env}}\right) A_{\text{tank}}}{c_{\text{p, fluid}}\, V_{\text{tank}}\, \rho_{\text{fluid}}} \tag{15}$$

$$\beta_{\text{parts}} \cong \frac{c_{\text{p, wp}}}{c_{\text{p, fluid}}\, V_{\text{tank}}\, \rho_{\text{fluid}}} \tag{16}$$

$$\beta_{\text{spray}} \cong \frac{\alpha_{\text{spray}}\, A_{\text{tank}}}{c_{\text{p, fluid}}\, V_{\text{tank}}\, \rho_{\text{fluid}}} \tag{17}$$

Using these factors, we can simplify the above equations and determine f_k, which includes the temperature change of the cleaning fluid during the cleaning process $f_{k,\text{clean}}$:

$$f_{k,\text{clean}} = \left(\beta_{\text{spray}}\delta + \beta_{\text{parts}} n_{\text{wp}} m_{\text{wp}}\right)\left(t_k - t_{\text{env}}\right)\ \forall k = 0, \dots, K \tag{18}$$

Using this in combination with the heat loss to the environment yields the total temperature difference due to losses to the environment and during the cleaning process f_k:

$$f_k = -\beta_{\text{env}}\delta\left(t_k - t_{\text{env}}\right) - \begin{cases} f_{k,\text{clean}}, \text{if } s_n \le k < s_n + d_n, \forall n = 2, 6, \dots, N-3 \\ 0, \text{else} \end{cases} \quad \forall k = 0, \dots, K \tag{19}$$

4.3 Experimental parameter identification

We performed three experiments to determine the β-factors specified in equations (15), (16) and (17). During the experiments we measured the temperature of the environment t_{env} as 22.5 °C. To determine the heat loss to the environment, we heated-up the cleaning machine to a specified temperature, then allowed the machine to cool down for 127 minutes. We then set β_{env} to be equal to the average temperature gradient of the cleaning fluid $\Delta \text{t}_{\text{env}}$ during the measured time interval, divided by the average temperature difference between the cleaning fluid and the environment $t - t_{\text{env}}$ as given by equation (20). β_{spray} describes the temperature gradient $\Delta \text{t}_{\text{spray}}$ during *spray cleaning* without any parts in the machine (only an empty cleaning basket) calculated by equation (21). Finally, we measured the temperature gradient Δt_{parts} while cleaning 42 metal parts each weighing 0.262 kg to determine β_{parts} using equation (22). Prior to cleaning the parts, their temperature was 22.5 °C.

$$\beta_{\mathrm{env}} = -\frac{\mathrm{avg}(\Delta t_{\mathrm{env}})}{\mathrm{avg}(t - t_{\mathrm{env}})} \cong 1.67 \cdot 10^{-5} \tag{20}$$

$$\beta_{\mathrm{spray}} = -\frac{\mathrm{avg}(\Delta t_{\mathrm{spray}} - \Delta t_{\mathrm{env}})}{\mathrm{avg}(t - t_{\mathrm{env}})} \cong 1.72 \cdot 10^{-5} \tag{21}$$

$$\beta_{\mathrm{parts}} = -\frac{\mathrm{avg}(\Delta t_{\mathrm{parts}} - \Delta t_{\mathrm{spray}} - \Delta t_{\mathrm{env}})}{\mathrm{avg}(t - t_{\mathrm{wp}})\, n_{\mathrm{wp}}\, m_{\mathrm{wp}}} \cong 1.03 \cdot 10^{-5} \tag{22}$$

4.4 Additional equations for the implementation of the optimization problem

For the implementation of the model in the Python-based modelling language Pyomo we had to adapt the event-based model of the cleaning process, since it was not natively possible to implement an objective function with variable sum limits. Therefore, we introduce $a_{n,k} \in \{0, 1\}$ which is 1 during the execution of process event *n* at time step *k*. The objective function (1) then becomes

$$\min_{\mathbf{d},\mathbf{h}} \sum_{n=1}^{N}\sum_{k=0}^{K} a_{n,k} p_n c_k + p_{heat} \sum_{k=0}^{K} h_k c_k. \tag{23}$$

To construct $a_{n,k}$ we introduce $\tilde{a}_{n,k} \in \{0, 1\}$ which is 1 during and before the execution of process event *n* at time step *k* and thereby ensure the correct order of the process events, such that

$$\sum_{k=0}^{K} \tilde{a}_{n,k} = \sum_{i=0}^{n} d_i\, , \forall n = 1, \dots, N \tag{24}$$

With the binary help variable $b_n \in \{0, 1\}$ and

$$\tilde{a}_{n,0} = \begin{cases} b_n\, , \forall n = n_{start}, \dots, N \\ 0\ \ , \forall n < n_{start} \end{cases} \tag{25}$$

$$d_n \le b_n d^{up}, \forall n = 1, \dots, N \tag{26}$$

$$\tilde{a}_{n,k} \le \tilde{a}_{n,k-1}, \forall n = 1, \dots, N, \forall k = 1, \dots, K \tag{27}$$

where $d^{up} \gg max(d_{start}, d_{clean}, d_{dry}, d_{load})$, we guarantee that $\tilde{a}_{n,k} = 0$ for $n < n_{start}$ and $\tilde{a}_{n,0} = 0$ or $\tilde{a}_{n,0} = 1$ else. This allows interruptions with a duration $d_n = 0$. Now, we construct $a_{n,k}$ by subtraction

$$a_{n,k} = \begin{cases} \tilde{a}_{n,k}, & \forall n = 1 \\ \tilde{a}_{n,k} - \tilde{a}_{n-1,k}, & \forall n = 2, \dots, N \end{cases}, \forall k = 0, \dots, K \tag{28}$$

and introduce the interruption variable $i_k \in \{0, 1\}$ which is like the tank heater state h_k and defined by

$$i_k = \sum_{n=1}^{N} a_{n,k}\, , \forall n = 1,3, \dots, N, \forall k = 0, \dots, K. \tag{29}$$

Also, we must modify (18) and include $a_{n,k}$ such that

$$f_{k,\mathrm{clean}} = \sum_{i=0}^{n} \left(\beta_{\mathrm{spray}}\delta + \beta_{\mathrm{parts}} n_{\mathrm{wp}} m_{\mathrm{wp}}\right)\left(z_{n,k} - a_{n,k} t_{\mathrm{env}}\right) \forall n = 2,6, \dots, N-3, \forall k = 0, \dots, K \tag{30}$$

where $z_{n,k} = t_k a_{n,k}$, $z_{n,k} = 0, \forall n \ne 2,6, \dots, N-3$ and

$$0 \le z_{n,k} \le t_{\mathrm{ub}} a_{n,k} \tag{31}$$

$$t_k - t_{\mathrm{ub}}(1 - a_{n,k}) \le z_{n,k} \le t_k \tag{32}$$

such that $z_{n,k} = t_k$ if $a_{n,k} = 1$ and $z_{n,k} = 0$, else.

5. Automation structure and data model

We adapt the cleaning machine's automation program to be able to close the control loop and to use the machine for DR measures. For the *interrupt process* DR measure, we add the additional operating state *interrupted* to the machine automation. For communication between the machine's automation system and the DR service, we implement the automation structure and data model described below to standardize the data exchange based on [7,6,8].

The automation program's main system *KEA* extends *System2Point* (see [7] for an in depth explanation of the different classes) and can be set to the two setpoint states *off* or *on* by an external signal which sets the cleaning machine to the machine states *standby* or *operational*. The system *KEA* represents the whole cleaning machine and contains the three subsystems *CleaningChamber*, *Tank* and *InletAirHeating*. The latter two are extensions of *SystemContinuous*, a system with a continuous setpoint, e.g. a tank temperature [7]. The system *Tank* includes the *Actor2Point TankHeater*, the system *InletAirHeating* includes the *Actor2Point InletAirHeater*. The *Actor2Point* class represents an actor with binary setpoint and enables the execution of the DR measure *store energy inherently* by implementing external control by a DR service via OPC UA [7].

We extend the flow control of the cleaning machine such that it can execute the DR measure *interrupt process* [6]. The machine has the states *stand-by, ramp-up, operational* and *working* following [19,18]. We separate the *working* state into the cleaning process stages *spray cleaning, impulse blowing,* and *convection drying* [6]. In the mathematical model, we combine *spray cleaning* and *impulse blowing* into one as described in section 4.1. The DR potential analysis showed that only the stages *spray cleaning* and *convection drying* have a high potential for the DR measure *interrupt process* so we only implemented this option before each of these two stages [6].

The automation data model is used for the communication between the DR service and the machine's automation system. It consists of the automation data specification, an OPC UA data model implemented in the machine automation system, and the automation data dictionary, a JavaScript Object Notation (JSON) file, that includes all information necessary for mapping the OPC UA data to the DR service [8]. To execute the DR measure *store energy inherently*, the extended automation data model includes information about

- nominal load of the tank heater p_{heat},
- current temperature of tank t_{start} and environment t_{env},
- tank temperature limits t_{lb} and t_{ub},
- cleaning fluid density ρ_{fluid} and specific heat capacity $c_{p,\text{ fluid}}$,
- tank volume V_{tank},
- workpiece mass m_{wp},
- number of workpieces n_{wp},
- Boolean setpoint variable to control the tank heater h_k.

For the DR measure *interrupt process,* we include the following data points:

- power consumption operational p_{int}, cleaning p_{clean} and drying p_{dry},
- operating state n_{start},
- remaining step duration d_{start},
- duration of cleaning d_{clean} and drying d_{dry},
- Boolean setpoint variable for interruption.

The information is integrated as a OPC UA data structure as part of the automation data specification in the automation program. The DR service reads the OPC UA data structures denoted in the automation data dictionary and writes the contained information into the DR scheduling model variables. This process is part of the eta-utility framework [17].

6. Field test

We integrate the demand response scheduling model and the automation data model as a cyber-physical production system using eta-utility and apply it to the aqueous parts cleaning machine model MAFAC KEA in the ETA Factory to show its applicability. For the electricity prices we use data from EPEX Spot [8] and take the prices of December 1st 2021 6:00 am to 9:00 am. Since we are only executing a single cleaning process in the field test, we scaled the interval of price changes from 15 to 5 minutes. This would not be necessary for a typical industrial use case, where multiple cleaning processes may be optimized in sequence. The CPPS uses the IBM ILOG CPLEX solver to solve the mathematical model and was executed on a PC with Intel Core i-5 6200U CPU and 8 GB of RAM in 10 s intervals. We analyse a single cleaning process which should be completed within 30 minutes and set the prediction scope for the model to 30 minutes. The workpiece is a control plate for a hydraulic pump. The model parameters are the following:

$N = 5$	$\delta = 10\ \text{s}$	$n_{wp} = 42$	$p_{\text{heat}} = 10\ \text{kW}$
$K = 1800\ \text{s}$	$V_{\text{tank}} = 320\ \text{l}$	$m_{\text{wp}} = 0.262\ \text{kg}$	$p_{int} = 0.2\ \text{kW}$
$S = 1800\ \text{s}$	$c_{p,\,\text{fluid}} = 4.19\,\frac{\text{kJ}}{\text{kg K}}$	$t_{\text{lb}} = 55\ °\text{C}$	$p_{\text{clean}} = 3.43\ \text{kW}$
$d_{\text{load}} = 120\ \text{s}$	$\rho_{\text{fluid}} = 1\,\frac{\text{kg}}{\text{l}}$	$t_{\text{ub}} = 65\ °\text{C}$	$p_{\text{dry}} = 9.35\ \text{kW}$

We reduce S by 10 s for every cycle of the MPC to ensure process termination within 30 minutes.

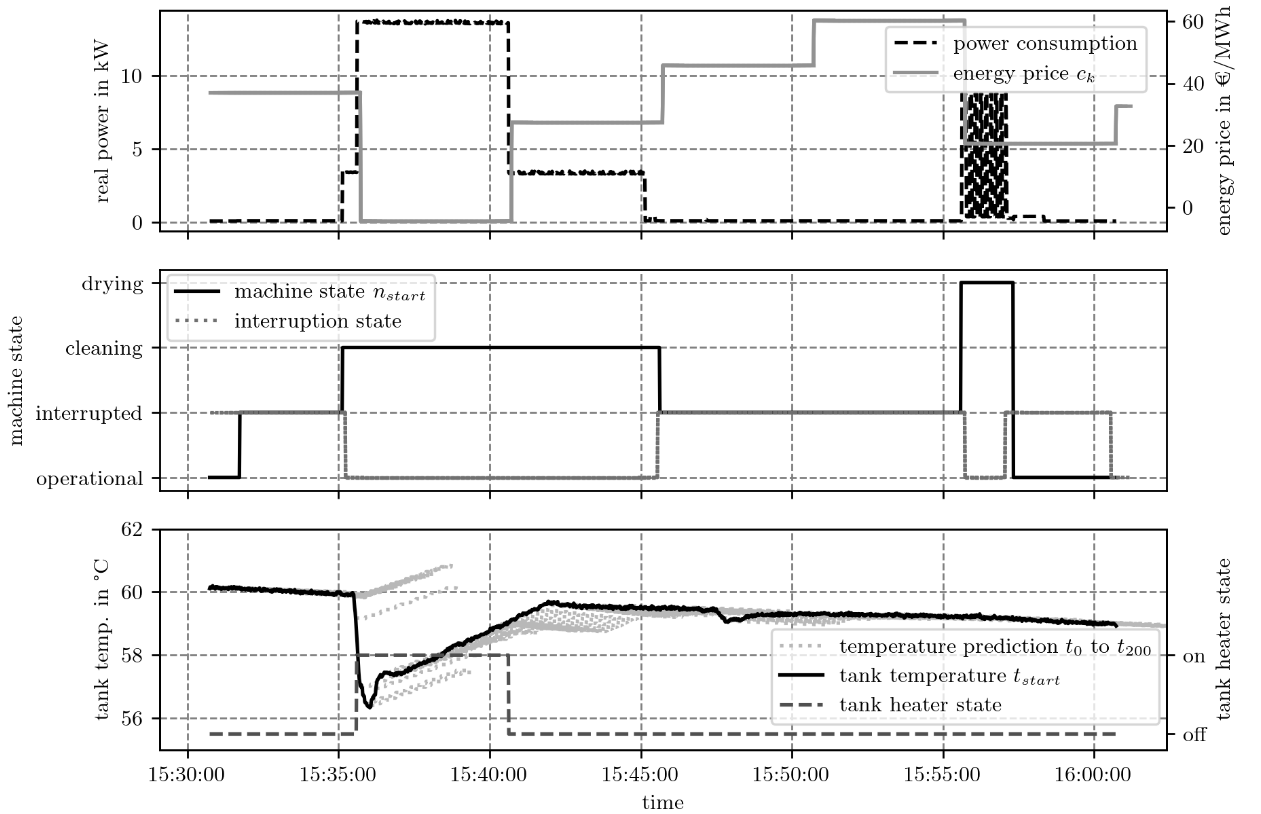

Figure 1: Results of the field test with a duration of 30 minutes. The upper diagram shows the machine's measured total power consumption and the energy price c_k. The middle diagram displays the cleaning process operating state n_{start} and the boolean interruption variable i_k. The lower diagram shows the measured tank heater state, tank temperature t_{start} and tank temperature forecast t_k for 200 seconds.

The results of the field tests are shown in Figure 1. The energy price, displayed in the upper diagram, becomes negative after five minutes which leads the solver to optimize for an increase in the total power consumption during the negative-price-period. The DR service postpones the start of *spray cleaning* by activating the interruption, shown in the middle diagram to utilize the negative price. The tank heater is activated slightly after the start of the cleaning process, visible in the lower diagram. When the energy price increases, the tank heater is deactivated, and *spray cleaning* continues. The DR service interrupts the process again when *spray cleaning* is finished to postpone *convection drying* to a time interval with a lower price at the end of the given period. The cleaning terminates after 30 minutes. In the lower diagram the temperature prediction based on the β-factors is shown in grey. The heat loss to the environment during the first five minutes and at the end of the process is so accurate that the predicted grey temperature values completely align with the actual tank temperature drawn in black. The temperature increase during operation of the tank heater is also predicted accurately (between 15:36 and 15:41), however there are significant dead times after the heater turns on and before the heat transfer stops, which cannot be reproduced by the model. Especially at the beginning of the cleaning process, the temperature drop during *spray cleaning* does not correspond to the real temperature. This is due to a transient response when activating the spray pump. It takes about two minutes for the tank temperature to stabilize after the pump starts. After the transient processes (dead times of the tank heater and response of the cleaning fluid) have settled, the prediction represents the reality accurately. When looking at the cleaning process overall, The model is accurate enough for our the case.

7. Conclusion

In this paper we present a detailed mathematical mixed integer linear programming model which is used as a MPC within the DR service of a cyber-physical production system that uses a cleaning machine for DR. The mathematical model consists of two parts: an event-based model that represents the cleaning process and is used for the DR measure *interrupt process* and a discrete-time model for the tank heating system used to *store energy inherently*. We apply the model to an aqueous parts cleaning machine in a field test and show that the DR service successfully controls the machine depending on a fluctuating electricity price. In the future the model should be used in other field tests to compare an energy-flexible operation implementing DR measures with a conventional operation. The ramp-up process of the tank heating system and the execution of several cleaning processes in a row should also be investigated.

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Appendix

The software code for the presented work is available as an open-source project on GitHub:
https://github.com/PTW-TUDa/cpsl2023-dr-for-cleaning-machines

References

[1] Burger, B., 2022. Annual spot market prices in Germany. Fraunhofer ISE. https://www.energy-charts.info/. Accessed 28 October 2022.

[2] Ganz, K., Wasmeier, L., Kern, T., Roon, S. von, 2022. Merit order shifts and their impact on the electricity price. FfE - Forschungsstelle für Energiewirtschaft e.V. https://www.ffe.de/en/publications/merit-order-shifts-and-their-impact-on-the-electricity-price/.

[3] Brandt, M., 2022. Erdgaspreis steigt innerhalb eines Jahres um 549 Prozent. https://de.statista.com/infografik/26608/durchschnittlicher-preis-fuer-erdgas-in-europa/. Accessed 28 October 2022.

[4] Ritchie, H., Roser, M., 2020. Energy. Our World in Data.

[5] Walther, J., Dietrich, B., Grosch, B., Lindner, M., Fuhrländer-Völker, D., Strobel, N., Weigold, M., 2022. A Methodology for the Classification and Characterisation of Industrial Demand-Side Integration Measures. Energies 15 (3).

[6] Fuhrländer-Völker, D., Magin, J., Weigold, M. Demand Response on Aqueous Parts Cleaning Machines.

[7] Fuhrländer-Völker, D., Borst, F., Theisinger, L., Ranzau, H., Weigold, M., 2022. Modular data model for energy-flexible cyber-physical production systems. 21st CIRP Conference on Life Cycle Engineering 107, 215–220.

[8] Grosch, B., Fuhrländer-Völker, D., Stock, J., Weigold, M., 2022. Cyber-physical production system for energy-flexible control of production machines. Procedia CIRP 55.

[9] Shrouf, F., Ordieres-Meré, J., García-Sánchez, A., Ortega-Mier, M., 2014. Optimizing the production scheduling of a single machine to minimize total energy consumption costs. Journal of Cleaner Production 67, 197–207.

[10] Yusta, J.M., Torres, F., Khodr, H.M., 2010. Optimal methodology for a machining process scheduling in spot electricity markets. Energy Conversion and Management 51 (12), 2647–2654.

[11] Biel, K., Glock, C.H., 2016. Systematic literature review of decision support models for energy-efficient production planning. Computers & Industrial Engineering 101, 243–259.

[12] Bänsch, K., Busse, J., Meisel, F., Rieck, J., Scholz, S., Volling, T., Wichmann, M.G., 2021. Energy-aware decision support models in production environments: A systematic literature review. Computers & Industrial Engineering 159, 107456.

[13] Meissner, H., Aurich, J.C., 2019. Implications of Cyber-Physical Production Systems on Integrated Process Planning and Scheduling. Procedia Manufacturing 28, 167–173.

[14] Leiden, A., Herrmann, C., Thiede, S., 2021. Cyber-physical production system approach for energy and resource efficient planning and operation of plating process chains. Journal of Cleaner Production 280, 125160.

[15] Elserafi, G., 2021. Reinigungsmaschine (MAFAC KEA). https://eta-fabrik.de/ueber-uns/ausstattung/mafac-kea/. Accessed 20 August 2021.

[16] VDI - Verein Deutscher Ingenieure, 2020. VDI 5207 Energieflexible Fabrik. Blatt 1: Grundlagen, 0th ed., Düsseldorf 91.120.10. https://www.vdi.de/richtlinien/details/vdi-5207-blatt-1-energieflexible-fabrik-grundlagen. Accessed 6 September 2020, 44 pp.

[17] Grosch, B., Ranzau, H., Dietrich, B., Kohne, T., Fuhrländer-Völker, D., Sossenheimer, J., Lindner, M., Weigold, M., 2022. A framework for researching energy optimization of factory operations. Energy Informatics 5 (S1).

[18] VDMA, 2019. 34179, Messvorschrift zur Bestimmung des Energie- und Medienbedarfs von Werkzeugmaschinen in der Serienfertigung, 2019th ed. 25.080.01.

[19] ISO - International Organization for Standardization, 2017. Machine tools -- Environmental evaluation of machine tools --: Part 1: Design methodology for energy-efficient machine tools. Beuth Verlag GmbH, Berlin 25.080.01.

Biography

Daniel Fuhrländer-Völker (*1990) received his master's degree in mechatronics in 2016 from Technical University of Darmstadt. He is a research associate at the Institute for Production Management, Technology and Machine Tools at Technical University of Darmstadt. His research focuses on cyber-physical production systems and automation data models for demand response on production machines and industrial supply systems.

Benedikt Grosch (*1992) received his master's degree from TU Darmstadt in mechanical engineering in 2018. He is a research associate at the Institute for Production Management, Technology and Machine Tools at Technical University of Darmstadt since 2018. His research is focused on production control for energy efficiency and energy flexibility. He evaluates data models and strategies for energy-adaptive production control of job shops.

Matthias Weigold (*1977) has been head of the Institute of Production Management, Technology and Machine Tools (PTW) at Technical University of Darmstadt since 2019. Prof. Dr.-Ing. Matthias Weigold directs the research fields of Manufacturing Technologies as well as Energy Technologies and Applications in Production with a focus on digitalization and climate neutrality in production.

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Conceptualization of an AI-based Skills Forecasting Model for Small and Medium-Sized Enterprises (SMEs)

Charlotte Frierson[1], Jana Wrobel[1], Roman Senderek[1], Volker Stich[1]
[1]FIR (Institute for Industrial Management) at the RWTH Aachen University, Aachen, Germany

Abstract

Forecasting-based skills management, which is oriented to the respective corporate goals, is gaining enormous importance as a central management tool. The aim is to predict future skills requirements and match them with existing interorganizational skills. Companies are required to anticipate changes in markets, industries, and technologies at an early stage as well as to identify changes in job profiles within an occupational profile by tapping into and evaluating various data sources. Based on these findings, they can then make informed decisions regarding skill gaps, for example, to implement targeted further training measures. Forecasting-based skills management offers the opportunity to optimally qualify employees for constantly changing tasks. At the same time, however, the targeted development of such skills requires a high level of time, financial and personnel resources, which small and medium-sized enterprises (SMEs) generally do not have at their disposal. In addition, many SMEs are not yet aware of the importance of this issue. Within the framework of research and industrial projects of the Smart Work department at the FIR (Institute for Industrial Management) at the RWTH Aachen University, an AI-based skills forecasting tool will be developed. The goal of the paper is to conceptualize the future machine learning method, that is able to generate individualized skills forecasts and recommendations for SMEs. This is achieved by linking societal forecasts and sector trends with company-specific conditions and skills. In order to generate a corresponding database, the derivation system is made available to various companies (large companies and SMEs) in order to obtain as many data sets as possible. The data sets obtained via the derivation system are then used as training data sets for the machine learning method, with the help of which an automatic derivation of competencies depending on new trends is to be made possible.

Keywords

Skills Management; Changing Markets; Future Skills; Employee Qualification; AI; SMEs; Company-specific conditions; Skill Forecasting; Competencies.

1. Introduction

The world of work is currently undergoing profound change, the central drivers of which are digitization and automation, the complexity and dynamics of markets, and demographic change [1,2]. Increasing complexity and growing dynamics of global markets are leading to massive pressure to innovate, which requires companies to be highly flexible to constantly adapt to changing conditions. Digital technologies enable new forms of communication that fundamentally change social relationships, social structures, and inter- and intraorganizational forms of cooperation [3]. This development was accelerated to a great extent by the COVID-19 pandemic. The digital transformation, which has been driven forward with vigor for years, has turned from a much-discussed future scenario into an everyday working environment. The developments outlined are accompanied by major changes in terms of the competence requirements of employees [4]. New

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competence requirements and even completely new job profiles are emerging, whereby competence is understood as a collection of skills that contribute to successful action [5]. According to a study by Bughin et al., the need for physical and manual skills will decline. Instead, more complex, cognitive skills and technological know-how will be of interest [6]. Against this background, the Organization for Economic Cooperation and Development (OECD) has found evidence in a study that there is already a deficit between the job requirements and the existing competencies of the employees [7]. For this reason, individualized forecast-based competence management, which is oriented to the respective corporate goals, is gaining enormous importance as a central management tool. The aim is to predict future competence requirements and to match them with existing internal competences [8]. Such competence management offers the opportunity to optimally qualify employees for the constantly changing tasks. However, the financial, human and time resources required for this can hardly be found in small and medium-sized enterprises (SMEs) in particular [9,10]. SMEs are thus faced with the challenge of proactively managing the tension between individualized forecast-based competence management on the one hand and resource bottlenecks on the other. Within the framework of research and industrial projects of the Smart Work department at the FIR (Institute for Industrial Management) at the RWTH Aachen University, the goal of conceptualizing a forecast-based assessment procedure for deriving the competencies required in SMEs in the future and, accordingly, developing education contents is pursued. Thus, an active contribution to existing research in the context of skills forecasting and skills assessment in SMEs is made.

2. Economic relevance for SMEs

An essential prerequisite for future-oriented corporate alignment is the early recognition of market trends or megatrends, which can result from various causes (e. g., consumer trends, product trends, social trends, political trends). In order to be able to react adequately to these trends, they must be analyzed continuously and the employees must be qualified at an early stage, taking the new trends into account [11,12]. In this regard, the concept of life-long learning [4] has become established in the specialist literature, through which the further education of employees with regard to changing environmental influences, e. g. in manufacturing companies, is to be sustainably anchored. Against this background, learning is becoming a strategic competitive advantage of companies and should therefore find its way into the company's objectives [13]. If we look at the reasons for the still relatively low learning and competence orientation in SMEs, various scientific-technical and economic aspects can be cited. The existing models of competence forecasting for SMEs are only of limited use. They only provide first action implications for implementation and application. It is therefore often necessary to design a new model that takes company-specific conditions and competencies (currently prevailing and future relevant) into account and compares them with the sector-specific forecasts. However, due to the lack of time, financial and human resources outlined above, SMEs are often not in a position to do this. [9,10]. Against the background of this need for action, the central research question of how and in what form a prognosis-based competence assessment can be carried out in SMEs needs to be answered. The focus lies on the conception of a generally applicable guideline that generates individualized competence forecasts and recommendations for SMEs. Consequently, a high cross-sector innovation potential can be offered: By analyzing future market developments and trends in the field of production technologies, developments, and method, developments relevant to competition can be made transparent at an early stage and communicated to SMEs.

In summary, a multidimensional challenge for SMEs can be identified, which results from the lack of the possibility to analyze market- and megatrends and to determine their effects in a targeted manner for their own business field. In order to carry out and link these analyses with the goal of identifying and balancing the necessary qualification needs of the employees, there are major time, financial and capacity risks. Thus, these risks stand in the way of preventing the loss of the company's market position. Due to the high economic importance of German SMEs [14], a research-based solution is needed to reduce the aforementioned prevention risks in order to enable SMEs to adapt their strategic orientation and thus strengthen their own market position. Therefore, the goal is to develop a tool that enables the determination of market and technology developments and matches existing skills with future needs based on a data-driven trend forecast. As a result, companies receive an overview of the resulting competence gaps, which can be used to derive suitable further training offers.

3. Scientific-technical approach

To delve further into the topic, it is first mandatory to define the concept of competence. The term competence is defined as a collection of prerequisites or skills that contribute to successful action [5]. Competencies include the skills required to perform a task [15]. An example is the European Classification of Skills, Competences, Qualifications and Occupations Platform (short: ESCO) [16]. Its aim is to generate a uniform classification in the subject areas of occupations, skills and qualifications in order to increase efficiency in the European labor market and improve the integration of education into the labor market [16]. The classification comprises five categories. The first category includes skills such as general equipment operation or even basic manual skills. The second category includes skills such as data entry and data processing. Possible activities include providing basic information or maintaining operational and sales designations. In contrast, the third category describes higher cognitive skills. This category includes activities such as managing and maintaining product inventories or complex information processing and interpretation. In addition, the fourth area includes social and emotional skills and the fifth all technological skills. Here, a distinction is made between different technology levels, for example between basic digital skills and advanced IT and advanced data analysis skills.

3.1 Competence forecasting and competence forecasting models

Competence forecasts represent a central control element for the further training of employees [17]. There are, for example, forecasts for the strategic assessment of future competence requirements on the labor market [8]. The goal is to create a balance between the supply and demand of competencies through the anticipation of competencies [8]. A number of different methods and instruments can be found in the literature to anticipate future needs and relevant skills. The most commonly used instruments include employer and employee surveys, sector analyses and general labor market studies [18].

In the literature, the term model is defined as a simplified representation of a section of reality [19,20]. According to Stachowiak, models contain three essential features: Mapping or accuracy, foreshortening, and pragmatism. [21]. Moreover, models represent different elements of reality. Depending on the objective, for example, the structure or even the functioning of a reality can be depicted exactly. At the same time, however, models only represent a section of reality. Furthermore, a model is tailored to an individual purpose of investigation. For this purpose, it is necessary to define for whom and for what purpose the model in question is being developed [21]. As an additional determinant, verification and validation must also be taken into account [22,23]. Accordingly, the aim of competence forecast models is to depict the future working world as realistically as possible. To achieve the most realistic depiction possible, situational (e. g. sector-specific conditions) as well as individual, company-specific conditions should be considered. According to a study by Campion et al., the company context and the individual company goals must be taken into account for the identification of competencies [24]. Furthermore, a combination of different analysis methods is necessary to compensate for method limitations. The third component to be considered is the purpose of the investigation: To ensure successful application, subsequent model verification and validation in companies is required. It is necessary to verify whether the model answers the actual research question and can deliver the desired results [25,23].

In the context of competencies that will be relevant in the future, four models in particular are of interest and are presented in overview form in the following table 1. For better comprehensibility, the models are named after the responsible institutions. They differ in structure, design, and approach.

Table 1: Competence models (own representation)

Pearson and Nesta (2017) [26]	McKinsey & Company (2018) [6]	World Economic Forum (2018) [27]	Stifterverband (2017) [28]
• Status quo analysis (influences and trends) • Discussion and future scenarios • Predictions of activity requirements • Predicion of future relevant capabilities • Results and implications	• Status quo analysis (influences and trends) • Skills classification • Company surveys on the topic of the influence of automation and AI on • Organizations Quantification of activity and capability changes • Results and implications	• Status quo analysis (influence and trends) • Conception of company questionnaire considering relevant dimensions • Presentation of future skills and activities • Results and implications	• Status quo analysis (Identification of prevailing competence challenges) • Conducting company surveys and interviews • Deriving a future skills framework • Results and implications

The four models outlined above represent relevant capabilities for the future. However, while the models of McKinsey & Company and the World Economic Forum (WEF) can be applied to different countries and regions, the models of Pearson and Nesta and the Stifterverband focus on individual countries (UK and USA or Germany). All models consider situational factors (such as sector or region specifics) or identify trends, influencing and changing factors. However, individual, or company-specific factors are not considered separately in the analysis. In addition, although companies are considered as a target group, the results are not directly applicable to companies on an individual basis. Only the models of Pearson and Nesta, McKinsey & Company and the WEF provide initial action implications for implementation and application in companies. The individuality of the (competence) forecasts is also limited. The planned model is expected to close these gaps.

3.3 Machine learnings models or algorithms

Machine learning is a method of teaching computers to learn from data, without being explicitly programmed. It involves using algorithms and statistical models to analyze and make predictions based on data. There are three main types of machine learning: supervised learning, unsupervised learning, and reinforcement learning [29].

In supervised learning, the computer is given a dataset with labeled examples (input and the corresponding desired output) and uses these examples to learn a general rule that can be used to predict the output for new, unseen examples. This type of machine learning is used for tasks such as image classification, speech recognition, and natural language processing. Unsupervised learning, on the other hand, the computer is given a dataset without labeled examples and must find patterns and relationships within the data on its own. This type of machine learning is used for tasks such as anomaly detection, clustering, and dimensionality reduction. Reinforcement learning is a type of learning where an agent learns to make decisions by interacting with its environment and receiving feedback in the form of rewards or penalties. It is used in applications such as robotics, game playing, and autonomous vehicles. [30–32]

Predicting the skills that will be in demand for SMEs in the next five years will be a complex problem, and there is no universal answer when it comes to the best machine learning model or algorithm. However, some models and algorithms that may be well-suited for this problem include:

- **Random Forest:** Random Forest is an ensemble method that combines multiple decision trees to improve the accuracy of predictions. It can be used to identify important features in the data and make predictions about future skills demand.
- **Gradient Boosting Machine (GBM):** GBM is an ensemble method that is particularly useful for predicting a continuous target variable. Like Random Forest, it also identifies important features. It can be used to predict future skills demand for SMEs.
- **Time Series Analysis**: Time series analysis can be used to analyze and forecast trends in the data over time, which can be useful for predicting future skills demand for SMEs.
- **Natural Language Processing (NLP):** NLP can be used to analyze unstructured data such as job postings and resumes, which can be used to predict future skills demand for SMEs.
- **Machine Learning model based on clustering**: Clustering algorithms like K-means, Hierarchical clustering etc can be used to group similar jobs or skills together and then use the group to predict the future skills demand. [30,33]

It is important to note that the best model or algorithm will depend on the specific problem, e. g. industry, region, social transformations, which is to be observed, as well as the characteristics of the data. The performance of the respective models and algorithms using appropriate evaluation metrics need to be evaluated and lastly, the best performing model needs to be selected.

3.2 Working hypothesis

Based on the previously presented research idea for the conceptual design of a prognosis-based assessment procedure for the derivation of future required competencies in SMEs, the following hypotheses can be derived, which will be investigated and processed within the scope of the work packages:

- Information about the existing competencies of employees (also outside their direct field of work) is only available to a limited extent, especially in SMEs.
- SMEs could increase the employability of their own employees through competence forecasts and also expand their business areas in the long term.
- Lack of expertise as well as unidentified skills gaps lead to sub-optimal employee deployment as well as productivity losses.
- In the long term, a competence assessment based on well-founded forecasts could also significantly increase the development opportunities of employees and their satisfaction.

Since forecasting future trends is very time-consuming, SMEs often react late to the need for new or changed competencies and skills. A central prerequisite for targeted training and workforce planning is the recording of existing competencies in the company and their comparison with the required competencies. This requires new IT tools that enable SMEs to comprehensively record the competence profiles of their employees and to reflect technological developments with regard to the requirements. Taking the formulated hypotheses into account, the following overarching working hypothesis emerges:

Overall working hypothesis:

The development and provision of a tool for competency assessment enables SMEs to deploy their employees in a targeted manner and to close existing competency gaps in line with their needs. In addition, the prospective analysis and forecasting of future technology and development trends enables an early response to necessary competence requirements and opens up potential for productivity and efficiency increases across all levels of the company.

4. Method

Within the conceptualization of the AI-based skills forecasting tool, a complex problem will be investigated, which, due to its various main topics, such as

- the trend forecast for sales markets and market developments,
- the networking of people and technology, and
- the competence prognosis and the competence evaluation,

has a high interdisciplinarity. Findings from previous research projects (e. g., the Labor Science Competence Center for Gainful Employment in Industry 4.0 (LIMo) project conducted by FIR (Institute for Industrial Management) at the RWTH Aachen University) are taken into account for further development. The preliminary work from these research projects will be used to determine the necessary data basis for the trend forecast. At the same time, these projects have already successfully integrated new technologies in industry with the help of selection aids and implementation aids, so that the comprehensive results and findings obtained here will be transferred as preliminary work. To achieve the machine learning tool, the process is split up in six steps. In the following chapter, the processing steps are presented in more detail.

4.1 Processing steps

The aim of the first step is to develop a catalog of requirements for the recording and assessment of competencies in SMEs. In a first measure, the required competencies (e. g. technical and methodological competencies, personal competencies, social competencies, activity and action competencies, digital competencies) are to be examined and identified with regard to their relevance to the research objective [34]. Based on this, the methods and software solutions already available on the market for screening the identified employee competencies are to be identified with the help of a market research [35–38]. Subsequently, their industrial suitability is to be discussed and evaluated with the help of semi-structured interviews with experts of partner and application companies and essential obstacles regarding their use in SMEs are to be identified. In addition, the existing solutions are evaluated regarding competence acquisition in SMEs, taking into account the typical problems of SMEs. Finally, the results of the market research and the interviews with experts will be translated into requirements for the methodology to be developed and transferred into a requirements catalog.

The goal of the second step is to develop the competence morphologies, segmentation and classification of competences required to achieve the research objective. This measure is based on the assumption that employees, regardless of their education, have different competencies, the targeted use and promotion of which generate considerable added value for the system as a whole [39]. Within the framework of the competence morphologies to be developed, the relations between the available competences of employees and the value of these competences for the performance of a defined activity are to be highlighted. For this purpose, the operational activities in production and logistics of SMEs are to be clustered into activity groups and each activity group is to be assigned the competencies required to perform its activities. The basis for this is literature research, in the context of which the different activities in production and logistics are summarized as clusters. Subsequently, with the help of further expert interviews and the analysis of job advertisements on job portals and in the environment of the partner companies, the skills required for each activity are identified and related to the activities by means of an assignment table. In addition to technical and methodological competencies, personal, social, activity and action competencies as well as digital competencies must also be considered. At the same time, interviews with experts are to be used to identify the typical training occupations of operational employees and to examine them in terms of the competencies they have learned. Analogous to the first step, the results will also be put into relation to one another with the help of an assignment table.

The third step focusses on development of the concept for enabling SMEs to identify required competencies at an early stage regarding forecast technology and development trends. The starting point in this respect is the derivation of upcoming industrial and sector-specific trends in the short and medium term. As described in the previous chapters, the automotive industry plays a pioneering role regarding technology and development trends, which is to be used to identify future developments and market trends for SMEs. The analysis of these trends will be done by literature research, the results of which will be discussed and verified in interviews with the partner companies of the automotive industry as well as other large companies of the industry. In the interviews, the reaction of the automotive companies to the necessary competence requirements (technical and methodological competence, personal competence, social competence, activity and action competence) will also be examined. In doing so, it will be analyzed to what extent trends from the automotive industry also apply to SMEs in the pure single-item manufacturing sector, or whether there are deviations which may require separate analyses. The result is a reference process for deriving competence and training requirements from market trends. Based on the reference process, a derivation system is then developed that allows users to forecast the competence requirements associated with a market trend. To this end, users are asked various questions about the market trend in question. These questions are to be designed in such a way that their answers provide direct information about the type of trend (technological, social, etc.) and the required competencies. To be able to automatically derive competence requirements in the future, the use of machine learning methods is to be examined for this purpose. Since there is a correlation between market trends and the required competencies, the competencies are to be formalized and qualitatively predicted as a classification question. In order to generate a corresponding database, the derivation systematics will be made available to various companies (large enterprises and SMEs) in order to obtain as many data sets as possible. The data sets obtained via the derivation systematics are then used as training data sets for a machine learning procedure to be selected, with the help of which an automatic derivation of competencies depending on new trends is to be made possible. The development and market trends are to be prepared quantitatively in such a way that they can be processed automatically by a machine learning procedure.

The goal of the fourth step is the development of internal competence screening. In order to be able to compare the existing competencies with the required ones, a standardized system is needed to link the respective competencies with the departments and employees. For this purpose, both the required and the existing competencies must be prepared accordingly. To support users in entering the existing competencies, the conception of the internal assessments is planned for an implementation in Microsoft Excel VBA, which has a high user-friendliness and is based on Excel tables that can be created by any company. The competencies are to be entered via a corresponding user interface, via which the existing competencies can be linked to predefined departments and employees. The competencies entered are to be stored in structured flat tables, with the competencies being uniquely coded via primary keys. For this purpose, in addition to defining the table format, a coding catalog is to be created via which all competencies are assigned to unique primary keys. The competence requirements associated with the market trends were already derived in the third step but must also be transferred to structured tables and coded accordingly using the coding catalog. The subsequent comparison of competencies is performed by an iterative comparison of the primary keys of the required and existing competencies, so that a corresponding algorithm must be developed and implemented in the software. If a required competency is not available, the corresponding primary key is transferred to a separate output format, which provides the user with a clear list of the missing competencies after the comparison is complete.

To ensure the industrial applicability of the developed methodology, the partial concepts developed in the third and fourth step are to be combined in an IT-demonstrator. It should be noted that this must be an environment that is also frequently used by SMEs or can be easily adapted, such as Microsoft Excel or Python. The tool should be designed in such a way that the users can view the source code and adapt it if necessary. Consequently, it should be programmed in an open-source program, so that it can be made available to the economy without barriers and can be adapted as needed. Of particular importance is the design of a user-friendly interface, so that the usability of the tool is guaranteed even without extensive IT knowledge. In addition, comprehensive documentation on the conception, use and implementation of the tool will be provided so that its structure and functionality can be viewed, thus ensuring autonomous use by the users beyond the duration of projects. For the selection of the programming language (Java, C++, Python, VBA) for the software-technical conversion of the derivative systematics therefore an benefit-cost analysis is to be accomplished regarding the pro and cons of the individual programming languages. In order to avoid interface problems, the competence requirements resulting from the questionnaire are to be output as flat Excel tables, which are automatically coded by the application of text mining methods and with the help of the coding catalog.

The methodology developed in the previous steps for recording competencies, forecasting future competency requirements, the targeted use of existing competency profiles and the expansion of competencies among employees, among other things to increase productivity and the economic factor in the company, is to be validated in this step. For this purpose, the screening concept will be applied to at least two partner companies. Various market trends are presented to the companies, from which a market trend suitable for the company's orientation is to be selected. Subsequently, the competence forecast, and the competence screening must be carried out accordingly and the required qualification must be identified. The validation and identification of improvement potentials regarding the methodology and the IT demonstrator, whose implementation is also part of the validation is accompanied scientifically. The sixth step concludes with the documentation of the procedure for competence forecasting as well as for competence screening and the use of the IT demonstrator in the form of a guide.

5. Feasibility and transfer of results

An important goal is the dissemination of the results achieved in the economy, in particular making them known to SMEs; from all sectors. Therefore, specific transfer measures will be implemented, which will be completed in different ways at different times. Nine measures are planned during the term of the project, i. e. the conceptualization of the AI-based skills forecasting tool, which are now presented here with the intended objective. First, project information will be presented on the Internet so that the current status of the work can be tracked. In this way, the websites of the participating research institutions will always reflect the status quo of the research, and additional companies will be attracted to the project. Meetings of the PA are initiated with the aim of discussing the research progress and agreeing on the further procedure. Through industry consultations and strengthening of the economic networks, the approach as well as the acquisition of potentially interested companies is to be optimized in the context of public relations. Measures are also to be taken in the passive information area. For example, results will be presented on knowledge platforms to promote an exchange and transfer of results to the (regional) economy. However, not only the knowledge platforms will be used for the publication of project results, but also the internal magazine of the FIR (Institute for Industrial Management) at the RWTH Aachen University, in which the project will be presented. In the sense of promoting young scientists, bachelor's and master's theses as well as project papers will also be written in the project. This serves to convey scientific knowledge in the subject area, as well as to introduce students to independent scientific work. Other written work, such as interim reports, will be published in professional journals (for example, the “Zeitschrift für wirtschaftlichen Fabrikbetrieb” (Journal for economical factory operation)). Also, the possibilities of project presentations on conferences and congresses are used (e. g. on the GfA conference). Finally, a final report is written, which follows the dissemination of the project results. Through the constant interaction of research and practice, companies are involved in the definition of the competence morphology, which enables the development of a user-friendly demonstrator for competence screening. For validation purposes, tests will be implemented in the environment of the partner companies and needs for improvement will be revealed. The research centers will support the first applications of the demonstrator, which will enable the long-term usability of the results achieved. Furthermore, the finally developed IT demonstrator will be made available to interested companies. In addition, potential users will be able to access the results achieved and transfer them into business practice. In order to avoid additional costs for the companies using the demonstrator, the aim is to design the demonstrator on the basis of software solutions commonly used in SMEs or to develop it on the basis of common or license-free software that also allows adaptation to the individual needs of the users. This enables SMEs to use the competence screening and thus promote it internally without having to incur additional financial expenses.

References

[1] World Bank, 2019. The Changing Nature of Work: World Development Report 2019. World Bank. https://documents1.worldbank.org/curated/en/816281518818814423/2019-WDR-Report.pdf. Accessed 20 July 2021.

[2] Eichhorst, W., Buhlmann, F., 2015. Die Zukunft der Arbeit und der Wandel der Arbeitswelt. IZA Standpunkte (77), 1–18.

[3] Ameln, F. von, Wimmer, R., 2016. Neue Arbeitswelt, Führung und organisationaler Wandel. Gruppe. Interaktion. Organisation. Zeitschrift für Angewandte Organisationspsychologie (GIO) 47 (1), 11–21.

[4] Dworschak, B., Altepost, A.A., Bau, M., Berger, C., Brandt, P., Gerst, D., Jeske, T., Kötter, W., Mühlbradt, T., Senderek, R., Schweppe, K., Ulrich, C., Wischmann, S., Ziegler, J., 2021. Die VDI/VDE-Richtlinie 7100 "Lernförderliche Arbeitsgestaltung": Ein Beitrag zum humanorientierten Management der digitalen Transformation 67. publications.rwth-aachen.de. Accessed 17 February 2022.

[5] Weinert, F.E., 1999. Definition and Selection of Competencies: Concepts of Competence. Max Planck Institute for Psychological Research. https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.111.1152&rep=rep1&type=pdf. Accessed 20 July 2021.

[6] Bughin, J., Hazan, E., Lund, S., Dahlström, P., Wiesinger, A., Subramaniam, A., 2018. Skill Shift: Automation and the Future of the Workforce. Discussion Paper. McKinsey Global Institute (MGI). https://www.mckinsey.com/~/media/mckinsey/industries/public%20and%20social%20sector/our%20insights/skill%20shift%20automation%20and%20the%20future%20of%20the%20workforce/mgi-skill-shift-automation-and-future-of-the-workforce-may-2018.pdf. Accessed 20 July 2021.

[7] OECD, 2016. Getting Skills Right: Assessing and Anticipating Changing Skill Needs. Organisation for Economic Co-operation and Development (OECD). https://www.oecd-ilibrary.org/content/publication/9789264252073-en. Accessed 18 February 2022.

[8] ILO, 2015. Anticipating and matching skills and jobs: Guidance Note. https://www.ilo.org/wcmsp5/groups/public/---ed_emp/---ifp_skills/documents/publication/wcms_534307.pdf. Accessed 20 July 2021.

[9] Kailer, N., Falter, C., 2006. Auswirkungen der Globalisierung auf Lernkultur und Kompetenzentwicklung in kleinen und mittleren Unternehmen. QUEM-Materialen 66. https://www.abwf.de/content/main/publik/materialien/materialien66.pdf. Accessed 20 July 2021.

[10] Mesaros, L., Vanselow, A., Weinkopf, C., 2009. Fachkräftemangel in KMU: Ausmaß, Ursachen und Gegenstrategien. Friedrich-Ebert-Stiftung Abt. Wirtschafts- und Sozialpolitik, Bonn, 51 pp.

[11] Heim, G., 2006. Rating-Handbuch für die Praxis: Basel II als Chance für Mittel- und Kleinbetriebe. Erich Schmidt Verlag, s.l., 214 pp.

[12] Schmidt-Tanger, M., 2012. Change: Psychologische Veränderungsintelligenz im Business. http://gbv.eblib.com/patron/FullRecord.aspx?p=4344457. Accessed 18 February 2022.

[13] Abel, J., 2018. Kompetenzentwicklungsbedarf für die digitalisierte Arbeitswelt: FGW-Studie Digitalisierung von Arbeit 09. FGW – Forschungsinstitut für gesellschaftliche Weiterentwicklung e.V. https://www.fgw-nrw.de/fileadmin/user_upload/FGW-Studie-I40-09-Abel-komplett-web.pdf. Accessed 8 October 2020.

[14] Destatis, 2023. Kleine und mittlere Unternehmen: 55 % in kleinen und mittleren Unternehmen tätig. https://www.destatis.de/DE/Themen/Branchen-Unternehmen/Unternehmen/Kleine-Unternehmen-Mittlere-Unternehmen/aktuell-beschaeftigte.html. Accessed 18 January 2023.

[15] Pankofer, S., Miller, T., 2016. Empowerment konkret!: Handlungsentwürfe und Reflexionen aus der psychosozialen Praxis, Reprint 2016 ed. De Gruyter Oldenbourg, Berlin, Boston, 272 pp.

[16] Europäische Kommission, 2020. ESCO: Europäische Klassifikation für Fähigkeiten, Kompetenzen, Qualifikationen und Berufe. https://ec.europa.eu/esco/portal/skill. Accessed 20 July 2021.

[17] Lorenz, P., 2017. Kompetenzprognosen als zentrales Steuerungselement in der Arbeits- und Qualifizierungspolitik: Impulse. https://www.stiftung-nv.de/de/publikation/kompetenzprognosen-als-zentrales-steuerungselement-der-arbeits-und. Accessed 20 July 2021.

[18] OECD, ILO, 2018. Approaches to anticipating skills for the future of work: Report prepared by the ILO and OECD for the G20 Employment Working Group. https://www.ilo.org/wcmsp5/groups/public/---dgreports/---inst/documents/publication/wcms_646143.pdf. Accessed 20 July 2021.

[19] Ruben, P., Wolter, H., 1969. Modell, Modellmethode und Wirklichkeit. Deutsche Zeitschrift für Philosophie 10 (17), 1225–1239.

[20] Fleischmann, A., Oppl, S., Schmidt, W., Stary, C., 2018. Ganzheitliche Digitalisierung von Prozessen: Perspektivenwechsel - Design Thinking - wertegeleitete Interaktion. Springer Vieweg, Wiesbaden, Germany, 262 pp.

[21] Stachowiak, H., 1973. Allgemeine Modelltheorie. Springer, Wien, 494 pp.

[22] Adam, O., Hofer, A., Zang, S., 2004. Unterstützung von Geschäftsprozessen in Wertschöpfungsnetzen mit Hilfe einer Architektur für kollaborative Szenarien, in: Dadam, P., Reichert, M. (Eds.), Informatik 2004. Informatik verbindet; Beiträge der 34. Jahrestagung der Gesellschaft für Informatik e.V. (GI), Ulm, 20. - 24. September 2004; [Proceedings. Ges. für Informatik, Bonn, pp. 537–542.

[23] Hartig, J., Frey, A., Jude, N., 2012. Validität, in: Moosbrugger, H., Kelava, A. (Eds.), Testtheorie und Fragebogenkonstruktion, 2., aktualisierte und überarbeitete Auflage ed. Springer Verlag GmbH, Berlin, Heidelberg, pp. 143–171.

[24] Campion, M.A., Fink, A.A., Ruggenberg, B.J., Carr, L., Phillips, G.M., Odman, R.B., 2011. Doing Competencies well: Best Practices in Competency Modelling. Personnel Psychology 64 (1), 225–262.

[25] Adamski, D., 2014. Modellbildung, in: Adamski, D. (Ed.), Simulation in der Fahrwerktechnik. Einführung in die Erstellung von Komponenten- und Gesamtfahrzeugmodellen. Springer Vieweg, Wiesbaden, pp. 23–40.

[26] Bakhshi, H., Downing, J.M., Osborne, M.A., Schneider, P., 2017. The future of skills: Employment in 2030. https://futureskills.pearson.com/research/assets/pdfs/technical-report.pdf. Accessed 20 July 2021.

[27] World Economic Forum, 2018. The Future of Jobs Report 2018. World Economic Forum, Cologny/Geneva, 147 pp.

[28] Kirchherr, J., Kieler, J., Lehmann-Brauns, C., Winde, M., 2018. Future Skills: Welche Kompetenzen in Deutschland fehlen. Diskussionspaper. https://www.stifterverband.org/medien/future-skills-welche-kompetenzen-in-deutschland-fehlen. Accessed 17 February 2022.

[29] Janiesch, C., Zschech, P., Heinrich, K., 2021. Machine learning and deep learning. Electron Markets 31 (3), 685–695.

[30] Mahesh, B., 2018. Machine Learning Algorithms - A Review. International Journal of Science and Research (IJSR) 9 (1), 381–386.

[31] Li, Y.-F., Liang, D.-M., 2019. Safe semi-supervised learning: a brief introduction. Front. Comput. Sci. 13 (4), 669–676.

[32] Hoffmann, F., Hosseini, B., Ren, Z., Stuart, A.M., 2020. Consistency of semi-supervised learning algorithms on graphs: Probit and one-hot methods. Journal of Machine Learning Research 21 (1), 1–55.

[33] Raschka, S., 2018. Model Evaluation, Model Selection, and Algorithm Selection in Machine Learning. University of Wisconsin–Madison. http://arxiv.org/pdf/1811.12808v3.

[34] Kipper, L.M., Lepsen, S., Dal Forno, A.J., Frozza, R., Furstenau, L., Agnes, J., Cossul, D., 2021. Scientific mapping to identify competencies required by industry 4.0. Technology in Society 64.

[35] Holtkamp, P., Lau, I., Pawlowski, J.M., 2015. How software development competences change in global settings-an explorative study. J. Softw. Evol. and Proc. 27 (1), 50–72.

[36] Demary, V., Engels, B., Röhl, K.-H., Rusche, C., 2016. Digitalisierung und Mittelstand: Eine Metastudie. https://www.econstor.eu/bitstream/10419/157156/1/IW-Analyse-109.pdf. Accessed 20 July 2021.

[37] Broady-Preston, J., 2009. Structuration and social identity theories. Performance Measurement and Metrics 10 (3), 172–179.

[38] Cohen-Scali, V. (Ed.), 2012. Competence and Competence Development. Verlag Barbara Budrich, Opladen Germany, 1 online resource (146).

[39] Peters, M.L., Zelewski, S., 2007. Assignment of employees to workplaces under consideration of employee competences and preferences. Management Research News 30 (2), 84–99.

Biography

Charlotte Frierson (*1992) is a project manager in the department Smart Work at FIR (Institute for Industrial Management) at the RWTH Aachen University. She is a sociologist and passionate about diversity-oriented skills management and lifelong learning. In her previous work and research activities, she has gained different transdisciplinary experience, e. g. in production, and skills development in the field of diversity management.

Jana Wrobel (*1995) is a junior project manager in the department Smart Work at FIR (Institute for Industrial Management) at the RWTH Aachen University. She is an educational researcher with interests in educational equity and reducing barriers to access. Most recently, she has worked in the field of international human resource management, addressing challenges and opportunities. She is also interested in competence research and optimal support for female employees.

Roman Senderek worked as project manager in several German and Latin American companies before taking up his position as project manager at FIR (Institute for Industrial Management) at the RWTH Aachen University. In 2019 he founded the research group New Work, which eventually grew in 2021 into the Smart Work department at FIR, which focusses on the design of customized teaching and learning solutions as well as human-oriented design that promotes learning in the digitized world of work.

Prof. Dr.-Ing. Volker Stich is head of the FIR (Institute for Industrial Management) at the RWTH Aachen University since 1997. Prof. Dr.-Ing. Volker Stich worked for the St. Gobain-Automotive Group for 10 years and led the management of European plant logistics. His research focuses on operations management, logistics and business applications systems.

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Application of a Reinforcement Learning-based Automated Order Release in Production

Günther Schuh[1,2], Seth Schmitz[1], Jan Maetschke[1], Tim Janke[1], Hendrik Eisbein[1]

[1]*Laboratory for Machine Tools and Production Engineering (WZL) of the RWTH Aachen University, Aachen, Germany*
[2]*Fraunhofer Institute for Production Technology IPT, Aachen, Germany*

Abstract

The importance of job shop production is increasing in order to meet the customer-driven greater demand for products with a larger number of variants in small quantities. However, it also leads to higher requirements for the production planning and control. In order to meet logistical target values and customer needs, one approach is the focus on dynamic planning systems, which can reduce ad-hoc control interventions in the running production. In particular, the release of orders at the beginning of the production process has a high influence on the planning quality. Previous approaches used advanced methods such as combinations of reinforcement learning (RL) and simulation to improve specific production environments, which are sometimes highly simplified and not practical enough. This paper presents a practice-based application of an automated order release procedure based on RL using the example of real-world production scenarios. Both, the training environment, and the data processing method are introduced. Primarily, three aspects to achieve a higher practical orientation are addressed: A more realistic problem size compared to previous approaches, a higher customer orientation by means of an objective regarding adherence to delivery date and a control application for development and performance evaluation of the considered algorithms against known order release strategies. Follow-up research will refine the objective function, continue to scale-up the problem size and evaluate the algorithm's scheduling results in case of changes in the system.

Keywords

Reinforcement learning; agent; automated order release; simulation; job shop production

1. Introduction

Due to a customer-driven increasing demand for higher product variants in correspondingly smaller numbers, flexible structures must enable their production and therefore the importance of job shop production is growing [1]. However, in a job shop production, the products take different routes through the production which complicates the allocation of machine capacities as well as operator and material availabilities to specific orders. To keep track of the order-specific view and simultaneously control the overall system, requirements on production planning and control (PPC) increase [2]. In order to cope with the higher requirements, one recognizable focus of PPC lies in the optimization of throughput times [3] while other logistical target values such as capacity utilization and adherence to delivery date still remain relevant for manufacturing companies [4]. In consequence, PPC processes become more dynamic and advanced [5].

Order-related optimization attempts can be achieved on two levels – on the upper level (order release) considering the logistical chain by starting production orders and on the lower level (sequencing) by

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changing the queue sequence in front of production units [3]. Although the high importance of an optimized order release system on the planning quality is well known [6], it is not yet used as standard today to achieve logistical target values and to reduce ad-hoc control interventions [7]. When focusing on scheduling tasks in a job shop production, discrete-event simulation is suitable for modelling the complex interrelationships and thus the main system behaviour [8]. Especially, in the context of flexible routes and considering unplanned machine downtimes, simulation holds a significant role in solving PPC tasks [9]. Previous paper and recent research on that topic combine simulation with reinforcement learning (RL) as an important field of machine learning [10]. By utilizing current advances in algorithm development with RL and combining this with simulation, a promising tool to effectively solve production scheduling problems is created [11].

In this context, recent approaches put a strong focus on further development from a computer science point of view and do not reflect the realistic complexity and framework conditions of real-world production systems in terms of machines, orders and uncertainties. It becomes important to align those approaches with practical requirements derived from an engineering perspective, e.g. a realistic problem size and representative data set [1]. Therefore, this paper formulates necessary steps for a stronger practical orientation of RL approaches in production scheduling based on the approach presented in [12]. The remaining of this work is organized as follows: In section 2, the studied problem is described, the method for implementing RL-based scheduling problems is specified and it is explained why previous approaches for order release are not yet practice-based enough. A review on order release strategies considering conventional approaches, heuristics and concepts based on RL is given in section 3. The application of a practice-based RL-approach for automated order release is explained in section 4. Finally, in section 5 the work is concluded and important aspects for further research are elucidated.

2. Background

In this section, the main reason for optimizing the representative task of order release is explained and the general principle of RL algorithms as a tool used for production scheduling is introduced. Then, with the rise of promising RL approaches, the need for more practice-based approaches is motivated.

2.1 Order release in the job shop scheduling problem (JSP)

In our previous paper [1], the substantial reasons for focusing on order release as a representative task within production control (PC) have been motivated. As argued, order release marks a "*critical decision point*" [13] for subsequent PC tasks and regardless a widespread use of enterprise resource planning (ERP), advanced planning and scheduling software (APS) [4] and still conventional heuristics, there is further need for optimization in production practice [1]. Especially due to the further increasing importance of job shop production, which has been proven to be NP-hard [5], it becomes necessary to develop advanced methods to solve the known practical problem.

Therefore, this work considers the order release in a job shop production by adapting the typical assumptions [1,14]:

- One operation at a time on each machine and on any job
- An operation of a job can be executed by only the assigned machine
- The next operation of a job can be started after completing its preceding operations
- No alternative routings for a job
- Each machine is available for production according to the machine calendar (in the application phase additional machine breakdowns and order cancellations will be included)
- No restriction on queue length before any machine

2.2 Implementing a RL algorithm for production scheduling

For solving job shop scheduling problems, either basic correlations presented as heuristics or deep problem related knowledge for exact solutions are required [15]. Since such knowledge is not always available and significant effort is required to parameterize expert knowledge, the desire for further advanced approaches has emerged [16]. Model-free RL has proven to be a suitable approach without requiring this expert knowledge [11] by just interacting with the production environment in a "trial and error" scheme [17].

In order to be used in a RL algorithm job shop scheduling problems are modelled as a Markov Decision Problem (MDP). MDPs are characterized by the fact that future states only depend on the present state and action [18]. Since the decision process requires frequent repetitions it is not directly applicable to real production environments and thus needs to be represented by a discrete-event simulation [8,19].

The core idea of reinforcement learning is based on the interaction between a RL algorithm – referred to as agent – and an environment – usually represented by a simulation model (see Figure 1). At each time step, the agent observes the environment described by its state $s_t \in S$ and decides on an action $a_t \in A$ to perform. Subsequently, the taken action leads to the state $s_{t+1} \in S$ and a specific reward for the agent, which over time aggregates to a total reward of $R_t = \sum_{i=t}^{T} r_i$. Those two aspects are combined during the training phase, where the agent tries to learn and adapt an optimal policy $\pi_t(a|s)$ based on the actions it performs and the reward it gets [20]. The learnt policy allows the agent in the following application phase to solve the stated problem. According to the defined objective function, during training phase the RL agent tries to maximize the sum of rewards gotten from its actions in order to solve the stated problem [21]. For the approach at hand, related works suggest the Deep Q-Network (DQN) training method as a suitable approach [11,12].

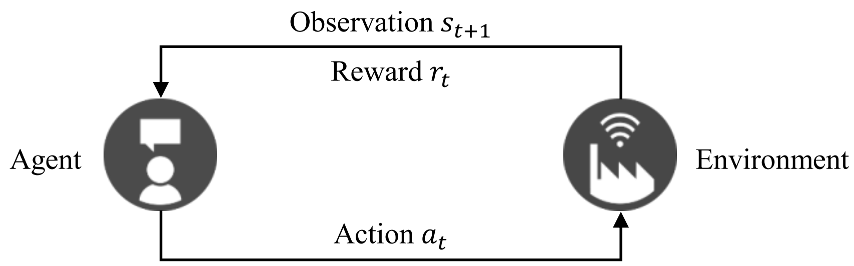

Figure 1: General principle of RL algorithms [20]

Especially in the training phase, the environment is represented by a simulation model, because in contrast to real systems, it reacts reproducibly and thus can be iterated [22]. For training, the agent needs the interface to the simulation model and a set of training data. Complying with the practice requirement claimed in this paper, this should be historical feedback data from an ERP system. For training purposes fast interfaces between the simulation model and the RL agent significantly improves the training time [11]. For the application after the completed training phase, the trained RL agent can apply its improved value function on a production case either still represented by a simulation or a real production.

2.3 Practical application of RL-based production scheduling

As stated in the introduction, this paper is intended to give a more practical direction to the application of RL algorithms in production scheduling. Therefore, the following three sections present what would be required for more practice-based approaches. Similar to other areas e.g. big data analysis, this field of research also benefits from cooperation between data science and engineering, because engineering brings in the necessary production expertise[23].

2.3.1 Problem size and data set

A major challenge for production scheduling approaches is the excessively increasing complexity with the increase in problem size until an approximate realistic production scale of e.g. 200 machines is reached. One problem of RL approaches that prevents user from simply scaling-up the problem size is the state design representing the number of jobs and machines. It can be overcome by using production expertise for state aggregation, function approximation or modelling adaptions in the state-action space [24]. Another requirement for practice-based approaches would be the validation with real production data to ensure transferability to real-life problems [1]. Without focus on features of real production environments, possible influencing factors such as machine breakdowns, order cancellations, sequence dependent setup time, and precedence constraints could thus be unintentionally hidden [24].

2.3.2 Objective function and action space

One important enabler of a performant RL approach is the objective, from which the reward is directly or indirectly derived. Yet, it is noticeable that the total makespan is the most widespread objective [24,11]. Although reliable results in not directly optimized performance measures are achieved as well, a survey of manufacturing companies showed, that due to recent crises, companies are paying more and more attention to on-time delivery as a target for their PPC [7]. Therefore, this paper claims to primarily focus on the value adding measure adherence to delivery date. Here it should be also covered that a new order release method should directly focuses on identification of orders instead of indirectly determining them.

2.3.3 Control interface for development and evaluation

The third missing aspect towards practice-based approaches is a specialized control interface for fast evaluation and algorithm development, by means of evaluation against logistical target values and comparison against classical or adapted control heuristics. Standard control and evaluation interfaces such as Tensorboard or WandB, that are widely used for ML development[25,26], mainly focus on the comparison of different algorithm variants and the performance evaluation of machine learning methods. Certainly, for optimizing the RL method itself, this is an important part of algorithm development, but it misses the special characteristics that must be mapped in production to justify a method even against other less advanced solution options that are not ML based. Therefore, the application presented in this paper integrates the Plant Simulation environment to easily create and compare different scenarios based on common order release heuristics or an optimized solution from the RL agent. With the selected combination of order and machine related graphs an effective analysis of a job shop production is enabled based on production expert knowledge.

3. Related work

In this section, conventional and recent approaches on the job shop scheduling problem are reviewed. Especially the task of order release and approaches with transferable findings are considered in detail. In the second part of the chapter, existing AI-based approaches for order release and order scheduling are specified.

3.1 Conventional approaches and heuristics

A brief overview on order release methods has been given in the previous paper [1]. Two methods that are not advanced but found in many production systems are the instant order release and order release by deadline. Orders are released directly as soon as they have been created or once the planned starting date is reached, regardless any production performance measures e.g. the quantity of orders in production [27]. The constant work in process (Conwip) and the load-oriented order release are two common inventory controlling order release approaches. This includes the two heuristics workload-control and bottleneck-control, where either the workload of all order processing stations or just the stations up to the bottleneck station must be considered. The order release with linear programming differs from the previously presented heuristics in the manner that mathematical optimization is used. A calculation module that can solve linear equations minimizes the target value of an objective function [27]. This is usually used by production software such as ERP or APS, which aim for a direct integration of the order release task into the overall order management process of the organization [4].

3.2 RL-based approaches

Especially in the last two decades, conventional approaches and heuristics have been steadily extended by those based on Artificial Intelligence and here especially the subarea RL [24]. An overview of existing meta-heuristics including learning-based systems is provided in [1]. The reinforcement learning approach introduced by [12] is designed to simultaneously decide on order release and operation sequencing. The Deep Q-Network (DQN) agent tries to minimize the makespan and is evaluated in random simulation instances regarding solution quality, solution speed, and scalability to bigger problems. [28] utilize a deep reinforcement learning approach to determine the release times of the orders in a flow shop with three machines. The reward that the agent receives after every action depends on the number of backorders, current WIP and size of the inventory. The validation results are limited to the simulated case.

Three DQN agents used by [29] independently control three machines to automate scheduling tasks. The model is implemented in MATLAB for training and evaluation purposes and aims to minimize the cycle time spread for three product groups. However, information about the origin of the data is not provided. A centralized learning policy is added to a multiple agent approach by [30]. Individual agents make decisions in a decentralized manner but share a common Q-network. This approach which objective it is to minimize the makespan is validated against 15 generated data sets.

Google DeepMind's AlphaGo Zero algorithm applied to optimize sheet-metal production schedules by [31] interacts with a discrete event simulation and schedules operations to idle machines. The agent aims to jointly minimize tardiness and material waste and is validated using 80 different offline scheduling instances. The multi-step reinforcement learning algorithm introduced by [32] is developed to minimize the total weighted unsatisfied demand in the scheduling horizon. While real industrial datasets are used for evaluation, the validation in this study considers various problem sizes as randomly generated datasets. The approach presented by [33] differs slightly from other reinforcement learning approaches since the DQN agent does not directly decides on the order in this case but selects an operation selection rule and a machine assignment rule. The overall goal to reduce the total tardiness is validated by making assumptions concerning data and by randomly generating test benchmarks. The reinforcement learning mechanism applied in [34] is considered in this paper despite the dispatching focus because of its unique policy transfer. The policy transfer allows it to apply a trained agent in a new factory setting and reduces the effort for model training and data collection. For the validation of the agent aiming to minimize the lateness and tardiness of orders, a simulation based on artificial data is built.

The review on related works supports the three recognized shortcomings of current approaches (see 2.3). First, regarding the problem size it can be seen that when mentioned small instances of 3 to 15 machines are studied and are not usually based on real production data. Using artificial or open-source data sets can help to better fulfil demands on the training data such as data size and independencies but doesn't necessarily support the solution of real-world problems. Second, the mainly used objective is a minimization of the makespan. Only few approaches focus on the adherence to delivery date, customer demand or tardiness. Also regarding action space it is missing, that within action spaces an order is directly chosen for the next scheduling step as a direct consequence from the policy of the algorithm. Lastly, in most cases, no application set-up is described that would facilitate the development and evaluation of algorithms by taking realistic framework conditions on the shop floor with a strong focus on logistic target values into account.

4. Application

This section presents the practice-oriented application approach for an automated order release process, which has been motivated throughout this paper. The main objective aims to optimize adherence to delivery dates. Also, the used online application which allows for a quick validation is introduced.

4.1 Setup of the Application

This approach uses the setup of a RL agent and discrete-event simulation described in our previous paper [1] (see Figure 2). The program architecture of the RL algorithm builds on that of [12] and adapts it in the parts relevant to this paper (see 2.3).

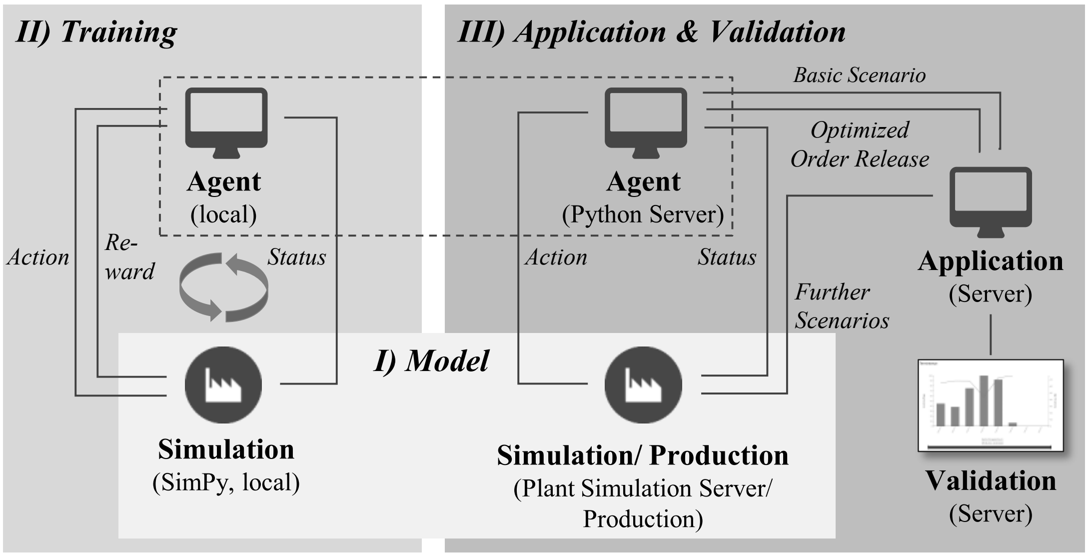

Figure 2: Used setup for the proposed RL approach [1]

In order to model the more-realistic production instance, that is required in this paper, especially the discrete-event simulation in the Plant Simulation environment (see stage III) includes statistically distributed machine breakdowns and order cancellations, the agent must deal with.

4.2 Simulation model and state space

As introduced in the general approach for applying RL algorithms, the current state represented by the state vector provides the agent with all necessary information to decide on his next action. In particular, while some information like work plans and machine lists are loaded once into the simulation environment for its initial creation, data transferred per time step comprises the machine and order status as depicted here:

- **General information:** Current episode, current simulation time
- **Machine status:** Availability, remaining processing time of in-que operations, remaining processing time of the current order
- **Order status:** Machine on which the order is currently processed, downstream machine, processing time of the next process step, remaining processing time of current process step, remaining total lead time of the current order, remaining time until the due date

The general information mainly indicates the simulation progress. In the machine status, for each machine the availability and information on processing times considered with this machine is transferred. Then follow information about each order in production. The vector is successively assembled and its length varies with the number of orders. For calculation of the "remaining total lead time" it is assumed that the waiting times are excluded, so that it is up to the overall system to keep these correspondingly small. By considering the sequence-dependent setup time it is exactly reflected in the calculation of the remaining total lead time.

4.3 Action space

In contrast to [12], in this approach a dependent action space which directly consists of orders to be released or not released at each specific time step is used instead of approximated duration times to which orders must be first assigned. In order to cope with the disadvantage of a dependent action space – its initially defined and constant size – an order release pool has been established which is initially filled with pending orders. The prioritization to fill the order release pool is currently based on the due date of the respective order. In order to be able to link the actions with the corresponding orders in the order pool, each action has an index that matches the index of an order. Once the agent selects an action, the action is used to search for the corresponding order. To depict the case of not releasing any order into the production one more possible action is added into the action space. Besides the possibility of releasing a specific order, the action of not releasing any order is referred to as "No-Op" action.

4.4 Algorithm and reward function

Like the approach of [12], a DQN algorithm learning by experience replay is used with the RL library Stable Baselines. Each step of the agent's experiences is used by the agent in many other steps for weight updates, resulting in a great data efficiency.[35] The biggest change has been done by exchanging a reward on minimizing the makespan to the optimization of adherence to delivery dates (see Table 1). To calculate the reward, the remaining processing time for all orders is determined. An increasing positive and normalized reward is allocated for each order depending on the difference between the remaining time until the due date and the remaining process time. If the difference is negative, the agent receives a negative reward. In addition to this unsteady function, the positive part is multiplied by the value of 10 to enhance positive rewards.

Table 1: Formulation of the algorithm used

Algorithm
Import work plan, list of orders and machine calendar from csv
Initialize state s_0 filled with general information and machine/order status
Define discrete action space
Initialize action space $S \in \{0,1,\dots,M_a\}$ (0,1,…)
Initialize parameters of the DQN library
For episode $e \in \{1,2,\dots,M_e\}$ **do**
Get state vector s_t
Select action from action space
Determine reward r_t
Proceed state to s_{t+1}
End
End

4.5 Control interface and evaluation concept through DAPPS online application

The control interface for rapid evaluation and simple improvement of the RL agent used in this approach is the self-developed online application DAPPS. This tool is based on the approach presented by [36] and has since been further developed and enhanced with more advanced features. DAPPS creates a linkage between the programming and simulation environment and visualizes the agent's order release results by simulating a production scenario. Thus, the agent's decisions on the production environment can be analyzed by comparison against conventional order release scenarios that are simulated as well. By choosing different visualizations of production key figures like adherence to delivery dates, throughput times or Gantt-charts, this helps to quickly derive adjustment possibilities and further develop the algorithms.

The application of the setup presented in this paper, has been conducted on basis of two problem instances: The first with 10 machines and 76 orders, the second with 10 machines and 259 orders. Hypotheses such as the presented objective function or the action space have been derived from expert knowledge and have been directly tested in the DAPPS application with the adherence to delivery dates being the key measure.

As there have been major changes on the problem formulation compared to the first application in [11], the final target of outperform current approaches has not yet been reached. For the smaller data set an adherence to delivery date of 84,21% has already been proven considering maximum freedom the agent got in choosing actions. Then, by applying the second data set with a larger order number, the adherence to delivery dates decreases to 91,89%. Another even larger problem size – with 28 machines and 474 orders – was applied but it emerged that the direct scaling without adjustment in the problem formulation is not purposeful regarding a justifiable training time of around 12 hours. Within the scope of this paper, no solution could be developed yet for the scaling of large problem sizes. Therefore, by using DAPPS as a support system for development, the announced steps (see 2.3.1) must be further carried out here in order to scale the problem.

4.6 Discussion

Within the scope of this paper, we were able to adjust the action space so that the action space is dependent and directly consist of orders to be released. To deal with a dependent action space, we additional add an order release pool. In addition, we are introducing the DAPPS tool to enable an evaluation of release results and a comparison against conventional heuristics such as CONWIP. For the application we use two scenarios with different numbers of orders and 10 machines each. A larger problem size with more machines and 474 orders led to a long training period. The problem of scaling could not be solved within the scope of the paper.

5. Conclusion and further research

This paper elaborates on the usage of reinforcement learning algorithms for automated order release in a practice-based application. Therefore it aims to further develop the reinforcement learning agent presented in our previous paper and introduces the evaluation tool DAPPS. After identifying the shortcomings of current RL approaches, the functionality of our agent and the advancements compared to the previous agent has been explained. Finally, by embedding this practice-based approach into DAPPS, the tool has been presented and the agent been tested on two problem sizes.

The approach can be used in practice, in order release planning to support decision making and thus lead to a better achievement of logistical target values as well as to a reduction of ad-hoc control interventions. The focus of further research must be on an improvement of the problem formulation and on the identification of the computationally intensive component. Finally, the approach has to be validated and the behaviour of the algorithm's decision needs to be evaluated by means of unforeseen disruptions in the production.

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References

[1] Schuh, G., Gützlaff, A., Schmidhuber, M., Fulterer, J., Janke, T., 2022. Towards an Automated Application for Order Release. Procedia CIRP 107, 1323–1328.

[2] Schlegel, T., Siegert, J., Bauernhansl, T., 2019. Metrological Production Control for Ultra-flexible Factories. Procedia CIRP 81, 1313–1318.

[3] Haeussler, S., Stampfer, C., Missbauer, H., 2020. Comparison of two optimization based order release models with fixed and variable lead times. International Journal of Production Economics 227, 107682.

[4] Schuh, G., Stich, V., Reuter, C., Blum, M., Brambring, F., Hempel, T., Reschke, J., Schiemann, D., 2018. Cyber Physical Production Control, in: Jeschke, S., Brecher, C., Song, H., Rawat, D.B. (Eds.), Industrial Internet of Things. Cybermanufacturing Systems. Springer, Cham, pp. 519–539.

[5] Lang, S., Schenk, M., Reggelin, T., 2019. Towards Learning- and Knowledge-Based Methods of Artificial Intelligence for Short-Term Operative Planning Tasks in Production and Logistics: Research Idea and Framework. IFAC-PapersOnLine 52 (13), 2716–2721.

[6] Pürgstaller, P., Missbauer, H., 2012. Rule-based vs. optimisation-based order release in workload control: A simulation study of a MTO manufacturer. International Journal of Production Economics 140 (2), 670–680.

[7] Maetschke, J., Fulterer, J., Janke, T., Zipfel, A., Bank, L., Theumer, P., Mundt, C., Köster, N., Kämpfer, T., Heuer, T., Hiller, T., 2022. PPS-Report 2021. Zeitschrift für wirtschaftlichen Fabrikbetrieb 117 (6), 400–404.

[8] Gutenschwager, K., Rabe, M., Spieckermann, S., Wenzel, S., 2017. Simulation in Produktion und Logistik: Grundlagen und Anwendungen. Springer Vieweg, Berlin, 281 pp.

[9] Panzer, M., Bender, B., Gronau, N., 2021. Deep Reinforcement Learning In Production Planning And Control: A Systematic Literature Review.

[10] Zeng, D., Gu, L., Pan, S., Cai, J., Guo, S., 2019. Resource Management at the Network Edge: A Deep Reinforcement Learning Approach. IEEE Network 33 (3), 26–33.

[11] Kemmerling, M., Samsonov, V., Lütticke, D., Schuh, G., Gützlaff, A., Schmidhuber, M., Janke, T., 2021. Towards Production-Ready Reinforcement Learning Scheduling Agents: A Hybrid Two-Step Training Approach Based on Discrete-Event Simulations, in: Franke, J., Schuderer, P. (Eds.), Simulation in Produktion und Logistik 2021. Cuvillier Verlag, Göttingen, pp. 325–336.

[12] Samsonov, V., Kemmerling, M., Paegert, M., Lütticke, D., Sauermann, F., Gützlaff, A., Schuh, G., Meisen, T., 2021. Manufacturing Control in Job Shop Environments with Reinforcement Learning, in: , International Conference on Agents and Artificial Intelligence. SCITEPRESS - Science and Technology Publications, pp. 589–597.

[13] Roderick, L.M., Phillips, D.T., Hogg, G.L., 1992. A comparison of order release strategies in production control systems. International Journal of Production Research 30 (3), 611–626.

[14] Vinod, V., Sridharan, R., 2011. Simulation modeling and analysis of due-date assignment methods and scheduling decision rules in a dynamic job shop production system. International Journal of Production Economics 129 (1), 127–146.

[15] Gonçalves, J.F., Magalhães Mendes, J.J. de, Resende, M.G., 2005. A hybrid genetic algorithm for the job shop scheduling problem. European Journal of Operational Research 167 (1), 77–95.

[16] Xie, J., Gao, L., Peng, K., Li, X., Li, H., 2019. Review on flexible job shop scheduling. IET Collaborative Intelligent Manufacturing 1 (3), 67–77.

[17] Mnih, V., Kavukcuoglu, K., Silver, D., Rusu, A.A., Veness, J., Bellemare, M.G., Graves, A., Riedmiller, M., Fidjeland, A.K., Ostrovski, G., Petersen, S., Beattie, C., Sadik, A., Antonoglou, I., King, H., Kumaran, D., Wierstra, D., Legg, S., Hassabis, D., 2015. Human-level control through deep reinforcement learning. Nature 518 (7540), 529–533.

[18] Hubbs, C.D., Li, C., Sahinidis, N.V., Grossmann, I.E., Wassick, J.M., 2020. A deep reinforcement learning approach for chemical production scheduling. Computers & Chemical Engineering 141, 1–22.

[19] Waschneck, B., 2020. Autonome Entscheidungsfindung in der Produktionssteuerung komplexer Werkstattfertigungen. Dissertation.

[20] Sutton, R.S., Barto, A., 2018. Reinforcement learning, second edition: An introduction, Second edition ed. The MIT Press, Cambridge, Massachusetts, London, England, 590 pp.

[21] Overbeck, L., Hugues, A., May, M.C., Kuhnle, A., Lanza, G., 2021. Reinforcement Learning Based Production Control of Semi-automated Manufacturing Systems. Procedia CIRP 103, 170–175.

[22] Shannon, R.E., 1998. Introduction to the art and science of simulation, in: Proceedings of the 1998 Winter Simulation Conference. Winter Simulation Conference, Washington, DC. IEEE, pp. 7–14.

[23] Chen, M., Mao, S., Liu, Y., 2014. Big Data: A Survey. Mobile Netw Appl 19 (2), 171–209.

[24] Kayhan, B.M., Yildiz, G., 2021. Reinforcement learning applications to machine scheduling problems: a comprehensive literature review. J Intell Manuf.

[25] Abdi, A.H., Abolmaesumi, P., Fels, S., 2019. Variational Learning with Disentanglement-PyTorch. Journal of Machine Learning Research 1:1-6.

[26] Luus, F., Khan, N., Akhalwaya, I., 2019. Active Learning with TensorBoard Projector.

[27] Lödding, H., 2016. Verfahren der Fertigungssteuerung: Grundlagen, Beschreibung, Konfiguration. Springer Berlin Heidelberg, Berlin, Heidelberg, 679 pp.

[28] Schneckenreither, M., Haeussler, S., 2019. Reinforcement Learning Methods for Operations Research Applications: The Order Release Problem, in: Nicosia, G., Pardalos, P.M., Giuffrida, G., Umeton, R., Sciacca, V. (Eds.), Machine Learning, Optimization and Data Science. Springer International Publishing, pp. 545–559.

[29] Waschneck, B., Reichstaller, A., Belzner, L., Altenmuller, T., Bauernhansl, T., Knapp, A., Kyek, A., 2018. Deep reinforcement learning for semiconductor production scheduling, in: 2018 29th Annual SEMI Advanced Semiconductor Manufacturing Conference (ASMC), Saratoga Springs, NY, USA. 30.04.2018 - 03.05.2018. IEEE, pp. 301–306.

[30] Park, I.-B., Huh, J., Kim, J., Park, J., 2020. A Reinforcement Learning Approach to Robust Scheduling of Semiconductor Manufacturing Facilities. IEEE Trans. Automat. Sci. Eng. 17 (3), 1420–1431.

[31] Rinciog, A., Mieth, C., Scheikl, P.M., Meyer, A., 2020. Sheet-Metal Production Scheduling Using AlphaGo Zero, in: Nyhuis, P., Herberger, D., Hübner, M. (Eds.), Proceedings of the Conference on Production Systems and Logistics, pp. 342–352.

[32] Zhang, Z., Zheng, L., Hou, F., Li, N., 2011. Semiconductor final test scheduling with Sarsa(λ,k) algorithm. European Journal of Operational Research 215 (2), 446–458.

[33] Luo, S., 2020. Dynamic scheduling for flexible job shop with new job insertions by deep reinforcement learning. Applied Soft Computing 91.

[34] Zheng, S., Gupta, C., Serita, S., 2019. Manufacturing Dispatching using Reinforcement and Transfer Learning, in: Brefeld, U., Fromont, E., Hotho, A., Knobbe, A., Maathuis, M., Robardet, C. (Eds.), Joint European Conference on Machine Learning and Knowledge Discovery in Databases, pp. 655–671.

[35] Mnih, V., Kavukcuoglu, K., Silver, D., Graves, A., Antonoglou, I., Wierstra, D., Riedmiller, M., 2013. Playing Atari with Deep Reinforcement Learning, 9 pp.

[36] Schuh, G., Potente, T., Fuchs, S., Schmitz, S., 2012. Wertstromorientierte Produktionssteuerung: Interaktive Visualisierung durch IT-Tools zur Bewertung der Logistik- und Produktionsleistung. wt Werkstattstechnik online 102 (4), 176–180.

Biography

Günther Schuh (*1958) holds the Chair of Production Systems at the Laboratory for Machine Tools and Production Engineering WZL at RWTH Aachen University, is a member of the board of directors of the Fraunhofer Institute for Production Technology IPT and director of the Research Institute for Rationalization (FIR) at the RWTH Aachen.

Seth Schmitz (*1991) studied Business Administration and Engineering (Mechanical Engineering) at the RWTH Aachen University and Tsinghua University. He is Head of the Production Management department at the Laboratory for Machine Tools and Production Engineering WZL at RWTH Aachen University.

Jan Maetschke (*1994) studied Mechanical Engineering (Production Engineering) at RWTH Aachen University in Germany. He is a Research Assistant at the Laboratory for Machine Tools and Production Engineering WZL at RWTH Aachen University and Group Lead of the Production Logistics group in the Production Management department.

Tim Janke (*1993) studied Mechanical Engineering (Production Engineering) at RWTH Aachen University in Germany and Industrial Engineering at Tsinghua University in Beijing. He is a Research Assistant in Production Logistics at the Laboratory for Machine Tools and Production Engineering WZL at RWTH Aachen University and Team Lead Software Development in the department.

Hendrik Eisbein (*1998) studied Business Administration and Engineering (Mechanical Engineering) at the RWTH Aachen University in Germany. He is a Student Research Assistant in Production Logistics at the Laboratory for Machine Tools and Production Engineering WZL at RWTH Aachen University.

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Digital twin and Value Stream Mapping of Warehousing in Era of Industry 4.0

Shiva Abdoli[1]

[1]*School of Mechanical and Manufacturing Engineering/ University of New South Wales,Sydney, Australia*

Abstract

The rapid pace of technological development and high competition make businesses employ proper approaches to assess the effectiveness of their value creation process or supply chains. The dynamic business environment enhances the uncertainty and the risk of not meeting the business goals. Warehouses might be able to address some levels of uncertainty such as demand fluctuations. Yet, inventory accumulation may lead to becoming a source of inefficiency from the lean methodology perspective. Therefore, the application of the lean methodology and its well-known method, Value Stream Mapping (VSM), has not received much attention in the warehouse efficiency assessment context. On the other hand, Industry 4.0 refers to the ongoing fourth industrial revolution promoting connectivity and information sharing with some key enabling technologies, including the internet of things (IoT), simulation, and digital twin. The digital twin technology is considered a strategic technology and offers a practical way for a system performance assessment. This paper aimed to introduce an approach that integrates the VSM method with the digital twin concept. The proposed structured approach can be used for the performance evaluation of a warehouse while adapting to the dynamic nature of warehousing. The developed digital model can be used for real time warehouse performance monitoring and control when connected with the physical warehouse through communication devices. The proposed approach in this paper is applied to a real case to demonstrate its applicability.

Keywords

Industry 4.0; Warehouse; Digital twin; Value Stream Mapping; Simulation

1. Introduction

1.1 Supply chain and warehousing

Businesses experience high competition these days while facing cost increases and higher expectations from customers. Hence, many organizations are seeking solutions for increased value creation, by improving efficiency, reducing waste, and faster time to market. The dynamic business environment introduces uncertainty to supply chains, enhancing the risk of not meeting the goals. Various strategies can be applied to deal with uncertainty, including having warehouses to address fluctuations in supply or demand. Keeping inventories in warehouses may become a source of inefficiency or waste from lean methodology perspective. Warehouses are complex systems because their design knowledge is largescale and multidisciplinary, and they are dynamic systems. Therefore, data and data modelling play key roles in evaluating and consequently improving the efficiency of warehouses, which directly impact the supply chain efficiency from the inventory management perspective. Optimization is one of the most used methods for inventory management in warehousing. However, the complexity of warehouse knowledge and high level of uncertainty and facing various unexpected events may violate some assumptions in optimization models. Hence, an approach is

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required, which can capture the embodied dynamic within supply chains and particularly warehouses. Value Stream Mapping (VSM) is a key method in lean methodology trying to provide a snapshot of value creation in a system (such as manufacturing or warehousing) and gives insights into sources of inefficiency.

1.2 Industry 4.0 and application of digital twin for dynamic performance evaluation

Industry 4.0 refers to the fourth industrial revolution promoting the application of data in value creation. The key enabling technologies of Industry 4.0 are listed as cyber-physical systems, the internet of things (IoT), Artificial Intelligence, simulation, and digital twin [1]. The digital twin application has been studied for production management, robot optimization, quality assurance, and so on [2]. The digital twin concept revolves around developing high-fidelity virtual models reflecting reality [3]. The digital twin offers a practical way to study a system's performance. The connection of the digital twin with the real system (through connection devices such as IoT) allows data exchange between them and controlling the system.

1.3 Objective

This paper aims to integrate VSM as a method for efficiency assessment with the digital twin concept for the dynamic performance evaluation of a warehouse by considering its dynamic and complex structure. The proposed approach can be used as a decision support system to monitor or modify the warehouse planning parameters to increase its efficiency. To this end, this paper aims to introduce a structured approach to define Key Performance Indicators (KPIs) for a VSM model in the warehousing context to be embodied in its digital twin. This paper proposes a modelling approach to develop the warehouse digital twin which is executable and can receive data from the warehouse through communication devices such as IoT and accordingly optimize the warehouse planning/control parameters. The introduced VSM based KPIs are embodied in the digital twin to assure optimization supports meeting the efficiency objectives.

2. Technical concepts

2.1 Warehousing and VSM

Warehouses perform a series of dynamically interacting processes using various resources, so the approach used for their performance assessment must be able to capture such a complex structure holistically. Lean methodology seeks to improve the performance of operations by eliminating waste. VSM is one of the most used lean tools, aiming to visualize the interactions across different processes as resources, products, or information are used and passed through each stage. Such a high-level illustration allows analysing of the Key Performance Indicators (KPIs) of a value chain. Traditional VSM requires modification to capture the uncertainty tied to warehousing and its dynamic nature. This paper aims to integrate VSM with digital twin concept to allow warehouse performance assessment considering its dynamic and uncertain nature.

2.2 Digital twin

The digital twin is an emerging technology and is defined as the digital replica of an object or system, mapping its characteristics and behaviour. Gartner, a global advisory IT firm, suggested the digital twin as a strategic technology trend in 2016. China Association for Science and Intelligent Manufacturing academic consortium proposed the digital twin as a top 10 scientific and technological progress in intelligent manufacturing in 2017 [4]. The digital twin concept was introduced in 2003 at the University of Michigan in a Product Lifecycle Management course [5]. NASA defined it as an integrated multi-physics, multi-scale, probabilistic simulation of a system using physical models, sensor updates, historical, etc., to mirror the life of its flying twin. The first introduced digital twin model included three dimensions: physical, virtual, and data exchange [6]. Later a model was introduced with five dimensions: physical, virtual, twin data, services, and connections [7].

In industry 4.0 context, two types of integration are considered in value creation: horizontal and vertical. The latter addresses integration of systems and elements in an individual node (e.g., warehouse system), they exchange information including real-time data (e.g., collected by sensors) and share their status with each other (e.g., machine-to-machine communication), so the entire system can prepare for future jobs. Horizontal integration means all nodes are networked and cooperate, including warehouses, factories, and customers.

3. Literature review

In this section, only those works are reviewed that have similar scope to this paper. Hence, the works that investigated general application of VSM or digital twin, without their integration are excluded from review. The complexity of warehousing systems made researchers narrow down the scope of warehouse performance assessment, such as layout or operational policy assessment. This paper has a system-level scope, so the studies with a narrower scope are not reviewed here and interested readers are referred to the literature [8].

3.1 VSM for warehouse efficiency assessment

The existing studies that applied VSM at the supply chain level mostly demonstrated a warehouse as an inventory ‘black box’. This does not offer deep insights into the warehouse performance, yet to have a lean supply chain, the performance of the warehouses as key nodes must be assessed and improved too.

Myerson suggested considering the warehouse function as an assembly line constituting several activities. Thus, warehouse efficiency could be improved by improving the tools and equipment availability [9]. Garcia applied VSM in warehousing assuming that the unit load does not change through the warehousing process [10]. However, a significant proportion of industrial warehouses change the unit of receiving consignment to another unit during the processes, which such a change in the unit load requires more careful consideration for a consistent performance assessment through various processes. Dotoli applied VSM to identify non-value-adding tasks in warehousing processes [11]. A mathematical model was developed to rank the identified wastes, called anomaly. The focus of the paper was on ranking anomalies and no structured approach was suggested to define KPI as a basis for comparison. The scope of the paper was only on the production warehouses, and other types of warehousing were only shown as work-in-progress (WIP) in the VSM model with no information about their operational performance. In another work, Bozer defined any increase in inventory level above the determined minimum level, as warehouse inefficiency [12]. However, if customer order reduces considerably, the inventory level will exceed the determined minimum level, or, if the demand increases, the inventory level decreases. Such an increase or reduction in inventory is not an indication of efficiency reduction or improvement in the warehouse.

3.2 Warehousing, VSM, and Digital Twin

Not many studies analysed the integration of VSM with a digital twin in the warehousing context. However, there are some works that studied the application of other industry 4.0 technologies in the warehousing context. Although their scope is different from this paper some of them are explained here.

Leng et al. proposed a digital twin system that used real-time warehousing data to optimize the packing and storage assignments operations. However, the application of this approach was limited to automated high-rise warehouses [13]. In the production system context (not in warehousing), a digital twin-enabled VSM approach was introduced by this reference [14]. That approach was based on developing a simulation model that used the VSM model results to simulate the performance to help finding the bottlenecks and other system problems, and finally, to improve the system parameters. Ali and Phan conducted a literature review on the application of industry 4.0 technologies to achieve sustainable warehousing [15]. Similar to manufacturing systems, they concluded that the application of industry 4.0 technologies in warehousing can support improving operational efficiencies, particularly a fully automated warehouse can achieve high efficiency by reducing energy consumption, waste, resource consumption, and unpredicted machines breakdowns [16]. The economic sustainability of warehousing while applying Industry 4.0 technologies was investigated by this reference [17]. An artificial reality software called "Pickup Simulo" was proposed to provide insights into the efficiency of warehousing activities. The effectiveness of using IoT in terms of data sharing and visibility in warehousing processes such as order picking, loading, and shipping was demonstrated in terms of errors and damages reduction, and consequently reducing resource waste. Likewise, the application of blockchain-enabled digital legend was analysed by this reference [18], concluding improvement in reducing the likelihood of product tempering, consignment rejection, and economic losses. It is agreed that there is a lack of a general approach for digital twin development that can be used in different fields [19].

In conclusion, although VSM has been applied in supply chain and manufacturing system assessment context, but its application has not been studied in warehousing context. On the other hand, given the fact that the digital twin is a new concept, integration of the VSM and the digital twin has not been studied in the literature. This is a research gap that this paper aims to address and the proposed framework as the integration of the VSM and digital twin is a novel contrition by this paper to this field.

4. Digital twin, Simulation, and VSM integration

4.1 Application of VSM in warehousing and KPI modelling

VSM method intends to evaluate a value stream against the overall system objective(s). In warehousing, the ultimate objective is to fulfil customer orders, which their specifications are not known in advance. This uncertainty complicates defining an identical evaluation unit for all processes. An automated warehouse with a seamless connection between a data-driven digital twin, IoT, and cloud technology has potentials to achieve high efficiency in its operation if processes are configured properly, if right data are collected, and analysed such that providing insights for improvement of warehouse performance. Hence, having a proper data model with the proper KPI is crucial for performance. In this section, an approach is proposed for proper modelling of KPIs for efficiency assessment in the warehousing context from the lean methodology perspective.

Dividing the process to the value adding and non-value adding is a principle in lean methodology to identify sources of waste, so by eliminating or reducing the number of non-value adding activities the system can perform more efficient. The former is considered as those that change physical shape/assembly of a product. In warehousing context, there are generally no substantial changes to shape/assembly. Hence, warehousing activities are often not considered to be value-adding. However, warehouses change the item unit type. Warehousing processes can be divided into five abstract classes; receiving, storing, picking, sorting, and shipping [20, 21]. In receiving process, the inbound consignments are accepted and converted into items that can be stored in the warehouse. The value created is transforming inbound items into 'warehouse-able' items (Stock Keeping Units: SKUs). In storing process, warehouse-able items are allocated into storage modules. In order picking process, the customer-requested items are retrieved from the storage modules. In the sorting process, the picked items are qualified to satisfy order requirements and prepared to be shipped. In shipping process, the orders are despatched from the warehouse. Each process has an objective in transferring the item status, receiving transfers the supply consignment to SKUs, storing process transfers SKUs to stored SKUs, picking transfers the stored SKUs to picked SKUs, sorting transfers the picked SKUs to customer order, and shipping transfers the customer order to shipped orders. To identify value-adding activities, this paper suggests modelling the warehouse function based on those five abstract processes. Considering a pool of possible processes and sub-processes, the warehousing function, W_f, can be represented as shown in (1).

$$W_f = \{(\alpha_i, P_i)\}\ ;\ \ i \epsilon \{1, \dots, 5\}, \alpha_i = \begin{cases} 1 \text{ if } P_i \text{ is an enabling process for warehousing function} \\ 0\ otherwise \end{cases} \quad (1)$$

$$P_i = \{(\beta_k, SP_k)\}\ ;\ \ k \epsilon \{1, \dots, k\}, \beta_i = \begin{cases} 1 \text{ if sub} - \text{process k is needed in } P_i \\ 0\ otherwise \end{cases}$$

This paper defines those activities which operate after the item transits to the required status from the abstract process as non-value adding. Each sub-process of a process should be analysed with respect to its abstract process and thus a value-adding activity in one process can be non-value-adding in another. Receiving and shipping processes interact with suppliers and customers respectively, so, they deal with different units for the same item type, respectively supplier consignment and customer order units. The receiving process may encompass various sub-processes to convert the supplier consignment to SKU (e.g., palletizing). As soon as the item unit is converted to SKU, the remaining sub-processes in the receiving process and in storing process operate on an SKU base. Depending on the picking process design, it can operate on SKU or order basis. The sorting process qualifies the picked SKUs to meet the order specification. Hence it also operates on a dual basis, SKU and order. Finally, the shipping process dispatches orders, and this generally operates on an order basis but may include some sub-processes that operate on an SKU basis as well.

The SKU represents the most aggregated level of planning unit in the warehousing context; hence this paper suggests conducting process evaluation using SKU as a base unit. Warehousing processes can be categorized into SKU-based and not SKU-based, which each is subdivided into two sub-categories: '*direct'* and '*variable'*. In the direct sub-category, the process parameters are a direct function of the number of operational units. For example, in the labelling process, the operation time is a direct function of the number of labelled SKUs. In the variable sub-category, the process parameters may vary from one process to another. An example of a variable parameter is the travel distance (and consequently process time) in the picking process, which may vary for different orders depending on requested items in customer orders. There is no need to convert the process operational unit for SKU-based processes. The not-SKU-based processes may operate in one of the following situations:

- Input SKU, output not-SKU: number of inputs (SKUs) can be used to formulate process parameters.
- Input not SKU, output SKU: number of outputs (SKUs) can be used to formulate process parameters.
- Input not SKU, output not-SKU: using 'expected' approach to estimate the average for the number of SKUs in a process (explained below).

Expected: a probability distribution function can be fitted to the variable parameter (e.g., the number of operating SKUs) of a process by using its historical data. Accordingly, the '*expected value'* of the variable process parameter can be used to estimate a process KPI.

For 'direct' type processes, since process parameters are a direct function of the number of operational units, x, the KPIs can be formulated on SKU base. For processes with 'variable' parameters, the KPIs can be calculated with the 'expected' approach as explained din mor detail in the next section.

4.1 Digital twin integration with VSM

Warehouse systems as complex systems demonstrate emerging behaviour as the result of interactions between their individual elements and with their environment [22]. The emerging behaviour or performance of a warehouse system can hardly be formulated with analytical formulation [23]. Simulation is a widely accepted approach for the validation of design or planning parameters. In the industry 4.0 context, simulation can serve many purposes, including scenario analysis and performance assessment. In this section, an approach is introduced to develop a digital twin for a warehouse that embodies the explained KPIs from the VSM perspective while the developed model has simulation capabilities. This helps to observe the possible emerging behaviour of the warehouse because of suggesting changes in the process chain after the VSM application. This makes the digital twin experiment-able that can support the validation of a warehouse plan and as a runtime environment can be used as a test bed to assess the warehouse performance as a function of dynamic interactions prior to applying any changes in the warehouse system.

The Object-Oriented (OO) method is a well-known approach for analysing complex systems [24]. Hence, this research suggests its application in developing the digital twin model of a warehouse. Abdoli introduced OO-based architecting guidelines for the holistic modelling of an engineering system by decomposing the system into processes that deliver its main function as a transformation of an item's state from input to output [23]. Accordingly, a warehouse can be modelled as a class diagram, as a composition of classes representing the warehousing processes. On the other hand, Finite State Machine (FSM) is a formalism that visualizes the structure of a system by its elements and embodies its behaviour by dynamic states defined for its elements. Hence, this research suggests constructing the digital twin in FSM formalism to achieve an experiment-able digital twin, due to the promising features of FSM including system visualization plus its simulation capabilities. Thus, the suggested OO-based approach by Abdoli [23] is mapped to FSM by embodying a nested state structure. The warehouse system is modelled as a parent state decomposed into sub-states embodying its processes, called process-state. In FSM, functions can be defined for a state to model its behaviour, so a function is associated with each process-state to model its dynamic behaviour, called process-functions. A process-function returns the parameters of a process with its outputs (e.g., equipment available capacity, number of operating SKUs), called Dynamic Variables (DVs). Relations between functions (in exchanging DVs) must be defined to embody the interactions between processes. Some variables can be defined in process-functions to return the values of KPIs (e.g., process time) at the end of the simulation.

The digital twin of a warehouse can use both historical and real-time data. An FSM model can receive data in different formats (e.g., XML) from physical objects [25]. This allows the developed digital twin to receive data from the cloud, containing collected data from physical objects (e.g., forklifts) by communication devices (e.g., IoT) or interact directly with them and get data (e.g., storage module status). An FSM model can be used to generate codes (e.g., Programmable Logic Controller) to control physical objects as well [26, 27]. The proposed approach is shown in Figure 1.

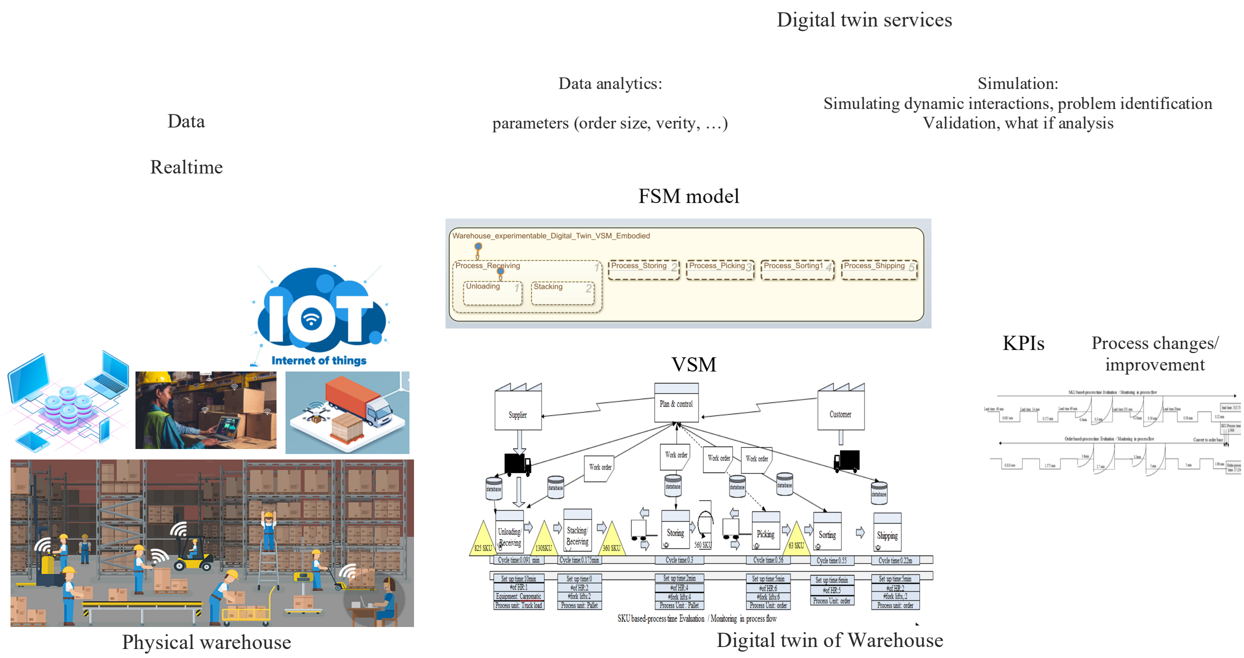

Figure 1: FSM-Digital twin integration with VSM

Embodying the VSM-based KPIs in the digital twin allows capturing the dynamic nature of a process in efficiency assessment. The order picking process is a good example of a process with variable process time and many research formulated that as a function of many parameters as shown in Equation (2), such as a_l: picking aisles length, a_w: picking aisles width, a_h: picking aisles height, T: number of aisles, o_s: order size,

o_{dv}: order diversity [28]. Order diversity can range from one to maximum order size. The former represents a single order line, whilst the latter indicates one single item per SKU in an order. Such formulas can be embodied in the process-function of the order picking process to predict the process time. The process parameters can be deterministic or non-deterministic. The former ones are fixed, such as the number of aisles whereas the latter, such as order diversity or order size, may vary from one order to another. These non-deterministic parameters introduce variability to the process time and leading to have 'variable' the process type as mentioned before. By using historical data, the order profile can be mapped to a probability distribution function. The digital twin has access to historical data or can be connected to physical objects through IoT. The embodied data analytics models in the digital twin can use the available data and fit a probability distribution to the non-deterministic parameter in a warehousing process, such as the order size and variability. The expected value of a random parameter can be used to evaluate a process against the KPIs. For example, after the digital twin fitted a probability distribution to the order size, then the order picking time can be calculated. This logic applies to all variable processes with non-deterministic parameters.

$$Eexpected\ (order\ picking\ time) = \sum_{order\ size=1}^{Order\ size} \sum_{Order\ diversity=1}^{Order\ diveristy=order\ size} P\left(order_{order\ size}, order_{order\ diversity}\right) \times f\left(aisle_{length}, aisle_{width}, aisle_{heigth}, Equipment\ travelling\ time, order_{order\ size}, order_{order\ diversity}\right) \quad (2)$$

According to the introduced approach, all warehousing processes can be evaluated against an identical unit, the SKU. This approach enables the application of a dynamic VSM for holistic warehousing performance assessment. It is preferable to interpret warehousing efficiency with respect to the ultimate objective of the warehousing function, which is satisfying customer orders. Hence, SKU-based KPIs are needed to be transformed into order-based KPIs. Thus, it is suggested to utilize the explained *expected* approach to characterise the order profile by using its historical data. For example, if the storing process time for a single SKU was calculated 5 minutes and the expected order size was 20, then the expected process time for the order can be approximately 100 minutes. The proposed approach stands as a decision support framework, however, the experts still can define some constraints based on the stakeholder objectives. For example, the experts can set a threshold for the minimum value of SKUs to assure having some levels of safety inventory.

4.2 Scenario analysis with digital twin

The executable digital twin allows testing a wide variety of scenarios which may lead to different behaviours and warehouse performance [19, 29]. Such scenarios can be modelled in the FSM model by defining some events or probability functions to model variations from initial assumptions, such as supply frequency or equipment failures. Simulation for what-if assessment can assist in analysing the effects of variations on the warehouse performance within the supply chain. This approach can be applied in any system containing variable processes with non-deterministic process parameters.

5. Case study

The case study warehouse was a distribution centre of a pharmaceutical company. The receiving process needed to change item-unit from supplier consignment to pallet, then from pallet to SKU, and later in the sorting process from SKU to customer order. The receiving process included unloading and stacking sub-processes. The warehouse had an ERP system containing warehousing information including the inventory status, incoming supplier consignment, and customer orders. The unloading process was performed by an automatic Cargomatic, five loads each weekday, each containing 33 pallets of 10 SKUs. Both unloading and stacking are considered value-adding, since they convert supplier consignments to warehouse-able items.

Some example calculations are provided here, and the VSM results are shown in Figure 2. Since the SKU quantity is constant in each load received, the receiving process is formulated on an SKU basis as follows.

Unloading-time for truck load=30 minutes, Unloading-time per SKU=30/33×10= 0.091 minute.

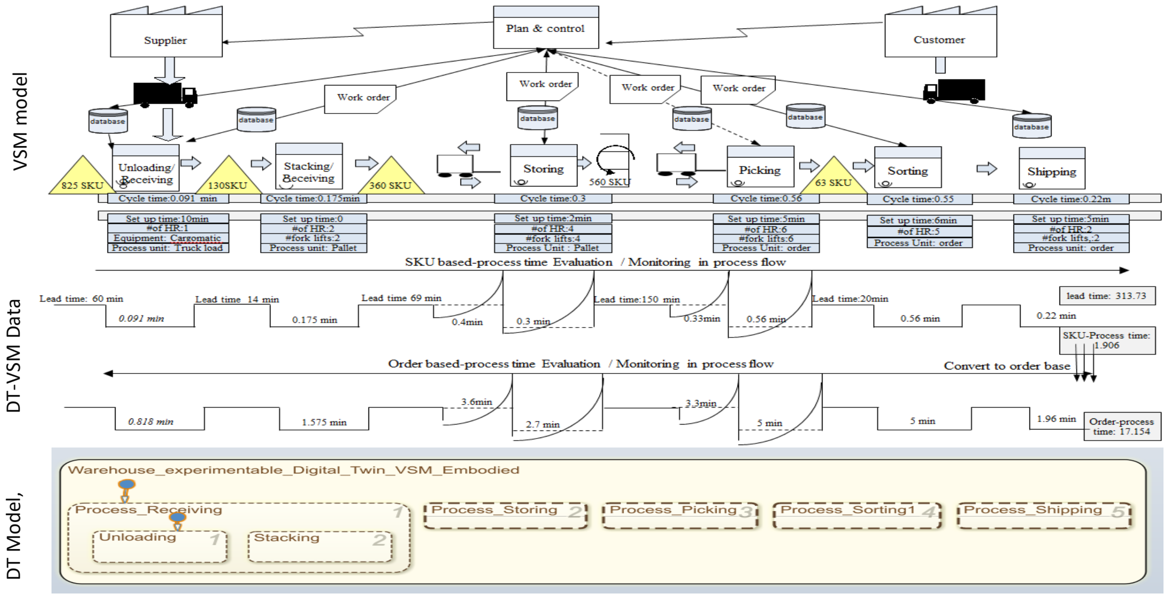

Figure 2: Developed FSM-Digital twin integrated with VSM-KPIs for the case study

In the storing process, an operator needed to drive a forklift to the stacking area and pick SKUs, then drive to the storing area, put them in racks, and come back. The two driving components of this process are considered non-value-added but necessary activities, whilst the positioning of SKUs in racks is considered the main storing process. The transportation and storing process had variable operation time depending on the storage location, (e.g., aisle position and rack height). Using the historical data in the ERP, a Pareto distribution was fitted to the storing process time. In the picking process, an operator needed to pick up ordered items. Likewise, a Pareto distribution was fitted to the picking process by using the ERP historical data. According to the explained approach, the FSM-Digital twin integrated with VSM was developed, as shown in Figure 2. The Pareto diagrams are rotated 90 degrees and the dashed lines show the expected values of each distribution, which can be used for various KPIs estimation. Based on the available data in the ERP, the order size varies from 3 to 11 SKU per order with an average of 9, with larger orders being more common. Hence, the sorting process is converted to an SKU base by considering its expected value of operational units. To demonstrate the order-based KPIs, the process parameters are divided into 9 (average order size).

$\text{Storing} - \text{Process time} =$ 3minutes/pallet $\quad$ $\text{Storing} - \text{Process time}_{-SKU\ based} =$ 3/10=0.3 minutes

$Sorting - Process\ time_{-SKU\ based}$≈0.56 minutes, $Sorting - Process\ time_{-order\ base}$= 5 minutes

The lead time is studied as the main KPI. The lead time before the picking process initiation indicates an SKU's waiting time to progress to successive processes, whereas the cumulative values of lead times after that represent the order lead time. Hence the lead times before the picking process are not converted to order-based values. Based on the developed FSM-digital twin integrated with the VSM model of the warehouse, sorting and picking tend to have the longest processing times, while the transportation elements in the storing and picking imposed the most uncertainty. Hence, combining the storing and picking processes could absorb some variation from both processes. This approach is called the double command storing-picking process and could improve efficiency. The suggested changes in the structure of these two processes could be validated by the digital twin prior to implementation to ensure its applicability. Demonstrating such a future state map is not in the scope of this paper but would follow the same procedures set out in this paper.

6. Results and conclusions

This paper proposed an approach to integrate the VSM as an efficiency assessment with the digital twin concept to allow monitoring and assessing the efficiency of a warehouse.

An approach was introduced for identifying value-adding activities in the application of VSM in the warehousing context, leveraging the traditional VSM to a more dynamic assessment tool that could capture the uncertainty in warehousing processes. An approach was introduced to embody the explained dynamic VSM in the digital twin of a warehouse, developed as an FSM model with simulation capabilities. This can support simulation-based performance evaluation. Such a digital twin can also be used for analysing the impact of possible changes in a warehouse system prior to their implementation. The developed digital twin can use available data including historical data (such as ERP in the case study) or real-time data from communication devices.

A future direction for this research can be an investigation on how the real time data can be used by the developed FSM digital twin model for real-time system improvement. Moreover, automatic model calibration based on VSM results can be investigated as well.

References

[1] T. Ji, H. Huang, and X. Xu, "Digital Twin Technology — A bibliometric study of top research articles based on Local Citation Score," Journal of Manufacturing Systems, vol. 64, pp. 390-408, 2022/07/01/ 2022.

[2] M. Zhang et al., "Digital twin data: methods and key technologies," Digital Twin, vol. 1, no. 2, p. 2, 2022.

[3] Q. Qi and F. Tao, "Digital twin and big data towards smart manufacturing and industry 4.0: 360 degree comparison," IEEE Access, vol. 6, pp. 3585-3593, 2018.

[4] B. He and K.-J. J. A. i. M. Bai, "Digital twin-based sustainable intelligent manufacturing: A review," Advances in Manufacturing, vol. 9, no. 1, pp. 1-21, 2021.

[5] D. Howard, "The digital twin: Virtual validation in electronics development and design," in 2019 Pan Pacific Microelectronics Symposium (Pan Pacific), 2019, pp. 1-9: IEEE.

[6] E. Glaessgen and D. Stargel, "The digital twin paradigm for future NASA and US Air Force vehicles," in 53rd AIAA/ASME/ASCE/AHS/ASC structures, structural dynamics and materials conference 20th AIAA/ASME/AHS adaptive structures conference 14th AIAA, 2012, p. 1818.

[7] F. Tao et al., "Five-dimension digital twin model and its ten applications," Computer integrated manufacturing systems, vol. 25, no. 1, pp. 1-18, 2019.

[8] J. Gu, M. Goetschalckx, and L. F. McGinnis, "Research on warehouse design and performance evaluation: A comprehensive review," European journal of operational research, vol. 203, no. 3, pp. 539-549, 2010.

[9] P. Myerson, Lean supply chain and logistics management. McGraw-Hill Education, 2012.

[10] F. C. Garcia and P. Director, "Applying Lean Concepts in a Warehouse Operation."

[11] M. Dotoli, N. Epicoco, M. Falagario, N. Costantino, and B. Turchiano, "An integrated approach for warehouse analysis and optimization: A case study," Computers in Industry, vol. 70, pp. 56-69, 2015.

[12] Y. A. Bozer and R. Britten, "Developing and adapting lean tools/techniques to build new curriculum/training program in warehousing and logistics," University of Michigan Department of Industrial Operations Engineering2012.

[13] J. Leng et al., "Digital twin-driven joint optimisation of packing and storage assignment in large-scale automated high-rise warehouse product-service system," International Journal of Computer Integrated Manufacturing, vol. 34, no. 7-8, pp. 783-800, 2021.

[14] Y. Lu, Z. Liu, and Q. Min, "A digital twin-enabled value stream mapping approach for production process reengineering in SMEs," International Journal of Computer Integrated Manufacturing, vol. 34, no. 7-8, pp. 764-782, 2021/08/03 2021.

[15] I. Ali and H. M. Phan, "Industry 4.0 technologies and sustainable warehousing: a systematic literature review and future research agenda," The International Journal of Logistics Management, 2022.

[16] N. Mostafa, W. Hamdy, and H. Alawady, "Impacts of internet of things on supply chains: a framework for warehousing," Social sciences, vol. 8, no. 3, p. 84, 2019.

[17] A. Lorenc and T. Lerher, "PickupSimulo–prototype of intelligent software to support warehouse managers decisions for product allocation problem," Applied Sciences, vol. 10, no. 23, p. 8683, 2020.

[18] Y. Ding, M. Jin, S. Li, and D. Feng, "Smart logistics based on the internet of things technology: an overview," International Journal of Logistics Research Applications, vol. 24, no. 4, pp. 323-345, 2021.

[19] A. Löcklin, M. Müller, T. Jung, N. Jazdi, D. White, and M. Weyrich, "Digital twin for verification and validation of industrial automation systems–a survey," in 2020 25th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), 2020, vol. 1, pp. 851-858: IEEE.

[20] S. Abdoli, S. Kara, and B. Kornfeld, "Application of dynamic value stream mapping in warehousing context," Modern Applied Science, vol. 11, no. 1, pp. 1913-1852, 2017.

[21] S. Abdoli and S. J. P. C. Kara, "Designing warehouse logical architecture by applying object oriented model based system engineering," vol. 50, pp. 713-718, 2016.

[22] A. Pyster et al., "Guide to the Systems Engineering Body of Knowledge (SEBoK) version 2.4," The Trustees of the Stevens Institute of Technology, vol. 11, 2021.

[23] S. Abdoli, "A modelling framework to support integrated design of production systems at early design stages," International Journal on Interactive Design and Manufacturing (IJIDeM), 2022/08/08 2022.

[24] G. Booch, R. A. Maksimchuk, M. W. Engle, B. J. Young, J. Connallen, and K. A. J. A. S. s. e. n. Houston, "Object-oriented analysis and design with applications," vol. 33, no. 5, pp. 29-29, 2008.

[25] R. A. Van Engelen, "Constructing finite state automata for high performance web services," in IEEE International Conference on Web Services, 2004: Citeseer.

[26] D. Gritzner and J. Greenyer, "Generating correct, compact, and efficient plc code from scenario-based assume-guarantee specifications," Procedia Manufacturing, vol. 24, pp. 153-158, 2018.

[27] W. Zając, G. Andrzejewski, K. Krzywicki, and T. Królikowski, "Finite state machine based modelling of discrete control algorithm in LAD diagram language with use of new generation engineering software," Procedia Computer Science, vol. 159, pp. 2560-2569, 2019.

[28] "Travel time estimation and order batching in a 2-block warehouse," European Journal of Operational Research, vol. 176, no. 1, pp. 374-388, 2007.

[29] M. Grieves and J. Vickers, "Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems," in Transdisciplinary Perspectives on Complex Systems: New Findings and Approaches, F.-J. Kahlen, S. Flumerfelt, and A. Alves, Eds. Cham: Springer International Publishing, 2017, pp. 85-113.

Biography

Shiva Abdoli is a lecturer in School of Mechanical and Manufacturing Engineering, UNSW. She worked as a researcher in KTH University, Sweden. She received her Ph. D in 2019 from UNSW. After her post-doctoral fellowship, she started as a Lecturer in 2020 at UNSW. She has led industry-based research projects. Her research field includes System design, Industry 4.0, Sustainable Production, and Circular Economy.

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Force Weighting Approach To Calculate Spinal Cumulative Loading For Ergonomic Workforce Planning In Production

Laura Johnen[1], Cathrin Deutz[1], Alexander Mertens[1], Verena Nitsch[1, 2], Christopher Brandl[1, 2]

[1]*Institute of Industrial Engineering and Ergonomics, RWTH Aachen University, Eilfschornsteinstraße 18, D-52062 Aachen, Germany*
[2]*Fraunhofer Institute for Communication, Information Processing and Ergonomics FKIE, Campus-Boulevard 55, D-52074 Aachen, Germany*

Abstract

For the prevention of musculoskeletal disorders (MSD), the evaluation of manual materials handling (MMH) is important. In this context, cumulative loading can be used as an exposure index for the ergonomic assessment of workplaces. However, it was shown in previous empirical studies that most existing methods for calculating cumulative loading fail to completely capture the resulting physiological effects of working conditions on human workers. Therefore, this contribution outlines the development and validation of a novel force weighted approach to calculated spinal cumulative loading that reflects the muscular exposure. Empirical data from 36 individuals were used as the data basis for deriving and validating the calculation method. The results of the validation show a high prediction quality on the basis of the hold-out method. Hence, the method provides relevant indicators for the ergonomic assessment of MMH activities. Thus, it might be a useful tool for workforce planning in production.

Keywords

Ergonomics; Occupational Health; Industrial Engineering; Cumulative Loading; MSD; MMH

1. Introduction

Musculoskeletal disorders (MSD) are a relevant problem worldwide from both an economical and a societal point of view [1]. Moreover, there is empirical evidence which links work-related manual materials handling (MMH) to the occurrence of MSD [2]. Therefore, the assessment of work-related MMH is of central importance for maintaining the health of working humans and preventing work-related MSD in the context of workforce planning in production and manufacturing. In this context, Wells et al. [3] identify the spinal compression force as relevant exposure parameter and recommend the calculation of a cumulative spinal loading value as an exposure index. In essence, the approach of cumulative loading simultaneously considers both the intensity and the duration of the acting spinal compression force and is mostly extended by a weighting factor for the load intensity to account for empirical evidence that suggests a higher relative effect of the load intensity [4,5].

There are several methods for calculating cumulative loading which have in common that they are mostly based on the results of in vitro studies of material failure of human or animal specimens [6]. For regularly occurring work-related physical exposure, however, it has been shown that reversible physiological parameters, such as muscular activity, are much more relevant and should therefore be decisive instead of purely biomechanical limit values [7,8]. Indeed, in previous publications, it was shown that existing methods for calculating cumulative loading are not fully capable of capturing these reversible physiological reactions

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[6,9]. This applies in particular to the parameter muscular activity, which is widely recommended as an indicator for deriving measures in the context of ergonomic work design and workforce planning in production [4].
Consequently, empirical data on the relationship between spinal cumulative loading and reversible physiological reactions, such as muscular activity, are needed. On this basis, an evidence-based optimization of existing methods for calculating the cumulative load of MMH tasks can be derived. Such an optimized method would be a promising approach for ergonomic workforce planning in production. In this way, the data accumulating in the context of advancing digitization can be used to design the work environment in an economical and human-friendly manner by preventing work-related MSD while ensuring economical production. Therefore, the aim of this publication is to present a systematic analysis of the relationship between spinal cumulative loading and work-related muscular activity and, based on this, to develop and validate an optimized calculation method for the calculation of spinal cumulative loading for ergonomic workforce planning. Because of the specific relevance for practical use in occupational health [10], the range of medium intensity levels is focused.

2. Material and Methods

2.1 Participants

The empirical data used to derive the weighted calculation approach were collected in a laboratory study with 36 participants who were financially compensated for their participation. The required number of participants was determined in advance by statistical sample size planning in G*Power for a desired test power of 0.8. The study was approved by the Ethics Committee at the Medical Faculty of RWTH Aachen University (ID: EK 210/21). Participation was limited to individuals who did not currently have, or had not had in the 12 months prior to participation, any cardiovascular or musculoskeletal diseases or conditions. Persons aged 20 to 47 participated, 17 of them identified as male and 19 as female. In addition, age (mean = 25.7 years, SD = 4.9 years), height (mean = 174.8 cm, SD = 9.3 cm), and body weight (mean = 71.2 kg, SD = 12.0 kg) were recorded.

2.2 Empirical data base

The data base used to derive the weighted calculation approach consisted of three different runs of cyclic lifting activities. The load intensities analysed were of medium intensity [10]. The exact levels of external load were chosen so that each would have a different effect on the human body while excluding physical overexertion for individuals without cardiovascular or musculoskeletal diseases or conditions. For this purpose, an ergonomic risk assessment based on the method KIM-LHC (LMM-HHT-E) [11] was carried out in advance and as part of the application to the Ethics Committee.
During all lifting tasks, participants performed an identical two- dimensional, symmetric movement, which is shown in Figure 1, with an external load held in both hands. The trunk inclination was standardised to a range of 0° to 50° with the angle measured between the vertical line and the trunk longitudinal axis as shown in Figure 1. A stretched rope marked the lowest point of the movement. Touching the rope with the forehead signalled reaching of the lowest point. The arms were always perpendicular to the ground. The working pace was set to one lifting or lowering every three seconds and audibly signalled using a digital metronome. This working pace corresponds to a rate typical for occupational practice [12]. Participants completed a short practice session in order to familiarise with the task and pace. With the movement being identical, the three different runs of cyclic lifting activities differed in terms of the external load, as shown in Table 1. The movement was performed as described for 18 minutes in total. The individual lifting activities were each separated by a recovery break of 2 minutes. The participants spent each resting period sitting straight on a chair with the arms placed in the lap and the feet on the floor. The effectiveness in terms of muscular recovery of this resting period has already been shown [9]. The body posture of each participant was recorded at a

rate of 30 Hz using a Kinect sensor (Kinect V2, Microsoft, WA, USA). In the data analysis, the compression force of the intervertebral disc at L5/S1 was calculated for each frame using a biomechanical model validated for material handling in the sagittal plane [13]. As input data, body weight, body height and body posture were used.

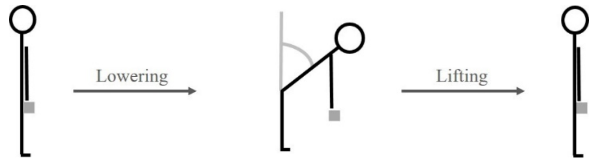

Figure 1: Symmetric MMH in the sagittal plane with marked trunk inclination angle. The arms were always held perpendicular to the ground and the external weight was always held in both hands.

Table 1: The three different runs of cyclic lifting activities that differ in terms of the external load held in both hands.

Condition	External load
1	2 kg
2	4 kg
3	6 kg

With regard to the resulting muscular strain, bilateral muscle activity of the erector spinae longissimus (RES/LES) were collected. Since surface electromyography (EMG) is a suitable estimate for physical stress imposed by dynamic loads [14], the muscle activity was measured using EMG during the lifting/lowering task and the resting period. RES/LES was selected as a representative of the back muscles which are particularly strained during repetitive MMH [15]. To avoid disturbances of the EMG signal during the resting period, which was spent sitting, the chair was without a backrest.

2.3 Mathematical derivation of the force weighted calculation approach

Data from 30 individuals of the study described in 2.2 were used as estimation data to derive the weighting factor, and the remaining data were used as a test data set for validation. The characteristics of the estimation data set were as follows: 13 male and 17 female participants with a mean age (standard deviation) of 24.8 (2.5) years, a mean height of 175.2 (9.7) cm, and a mean body weight of 70.8 (12.2) kg.
The derivation of the equation for the force weighting factor WF_{Force} was divided in two steps. First, based on the load intensity and the resulting muscular strain, an individual strain-load-ratio SLR was calculated by means of Equation (1). Here, the load intensity results from the maximum compressive load within an intensity level. The muscular strain results from the measured electrical muscular activity. The quantification of the electrical muscular activity is explained in detail in section 3. The strain-load-ratio SLR was calculated for each participant and intensity level for both RES and LES. Based on these individual values, average factors for each intensity level and both RES and LES were calculated. The calculation of factors is necessary to use literature-based factors for support points at the lower and upper edges. Since this empirical investigation focusses on the range of medium physical exposures, two additional data points were used in the minimum and maximum range: Following Parkinson & Callaghan [16], the empirically determined maximum compressive strength of the human spine of 6000 N [17] can be associated with a weighting factor of 30. As lower data point, 1 N is selected as a theoretical minimum load. Following empirical evidence from a previous in-vivo study on the relationship between spinal compression force on L5/S1 and electrical muscular activity, it can be stated, that an equivalent weighting of the risk factors load intensity and load duration are unsuitable even in the range of low spinal compression force [9]. Therefore, 1 N is associated with a force weighting factor of 1.01. Both additional, literature-based data points are shown in Table 2.

$$SLR_{Indicator,Intensity\ level} = \frac{Muscular\ strain_{Indicator,Intensity\ level}}{Load\ intensity_{Indicator,Intensity\ level}} \quad (1)$$

Based on the empirical data, the equation for the weighting factor was derived. The known points were plotted to a diagram and a mathematical description of the relationship between acting load and muscular strain was derived using the trend line function in Microsoft Excel 2016 (Microsoft Corporation, Redmond, Washington, USA). This procedure is equivalent to performing a non-linear regression and was chosen in accordance with other published studies [18–20].

Table 2: The two additional, literature-based data points used to derive the mathematical description of the relationship between acting load and calculated strain-load-ratio SLR.

x-axis [N]	6000.00	1.00
y-axis [-]	30.00	1.01

2.4 Validation of the force weighted calculation approach

The hold-out method was used as a method of validation as previously described [21]. While data from 30 individuals of the study described in 2.2 were used as estimation data to derive the weighting factor, the remaining data of six participants were used as test data for validation. The characteristics of these participants were as follows: 4 male and 2 female participants with a mean age (standard deviation) of 30.5 (10) years, a mean height of 173 (6.8) cm, and a mean body weight of 72.7 (12.1) kg. This publication aims to derive an optimized force weighted calculation approach that reflects the muscular strain resulting from work-related MMH. In line with the methodological approach by Yazdanirad et al. [22], the validation was therefore performed as follows: The prediction quality of the new calculation approach was determined based on the correlation between values of the cumulative loading index calculated by means of the calculation method to be verified and the measured resulting muscular strain. For the interpretation of the correlation, a correlation from 0.1 is regarded as low, from 0.3 as medium and from 0.5 as strong [23].

3. Data analysis

To calculate the factors for the optimized calculation approach using Equation (1), both the load intensity and the resulting muscular strain are needed. To quantify the load intensity, the spinal compression force on the intervertebral disc at L5/S1 was biomechanically calculated based on body weight, external load and body posture, as explained in 2.2. Based on this, the maximum spinal compression force on L5-S1 was calculated for each participant and each intensity level (1, 2, 3). Since the movement is cyclic, the maximum compression force is constant within a participant and an intensity level, as shown in Figure 2.

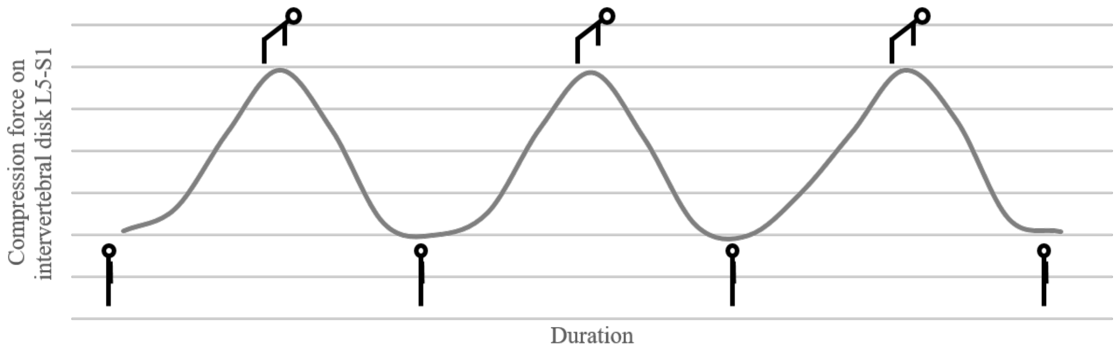

Figure 2: Schematic representation of the cyclic load with associated body positions at the maximum and minimum

To quantify the muscular strain, the area under the curve of the measured electrical muscular activity from RES and LES was determined. The calculation of the area under the curve was performed using the Noraxon MyoMuscle v3.14 software and the Integral calculation function. The resulting unit is thus %MVC • s. The calculation of the integral was chosen instead of an average value in order to represent the complete spectrum of the measured muscular activity.
Prior to the curve-fitting, paired t-tests were used to check whether the average factors over all participants of the estimation data set differed significantly between RES and LES. In case of no significant effect, further evaluation can be performed together for RES and LES. Statistical analyses were performed with IBM SPSS Statistics 28.0.1.0. Significance at the α-level of $p < .05$ was assumed. For the validation, Spearman's correlation coefficient was used, so the data do not need to be normally distributed [24].

4. Results

In this section, the general results regarding the acting load intensity and muscular strain, the calculated factors as well as possible differences between the body sides are presented (section 4.1). Based on both the empirically obtained and the literature-based data points, a new force weighted calculation approach is derived (section 4.2) and validated (section 4.3).

4.1 General results

Paired t-tests between RES and LES show no significant effect of body side on the strain-load-ratio SLR calculated using Equation (1). Average values of both the calculated maximum spinal compression force and the integral of the electrical muscular activity from RES and LES are shown in Table 3 and the resulting strain-load-ratio SLR are shown in Table 5. Statistics of the t-tests are presented in Table 4. Since the body side does not have a statistically significant effect on the calculated factors, a joint equation for the weighting factor WF_{Force} is derived in the next step.

Table 3. Average values of both the calculated maximum spinal compression force and the integral of the electrical muscular activity from RES and LES. This data were used to calculated the ratios shown in Table 5.

Level of intensity	Biomechanically calculated compression force on L5/S1 [N]	Integral of muscular activity [%MVC • s]	
		RES	LES
1	2495.44	7591.56	7444.90
2	2627.14	7983.01	8003.89
3	2792.25	8598.11	8620.40

Table 4. Results of the t-test within each intensity level between RES and LES for the strain-load-ratio SLR.

Pair	Mean	Standard error of the mean	95% confidence interval of difference		t	df	p-value
			Lower	Upper			
$SLR_{,RES,1} - SLR_{,LES,1}$	.05	.16	-0.28161	0.38205	.310	29	.759
$SLR_{,RES,2} - SLR_{,LES,2}$	-.03	.15	-0.33985	0.27747	-.207	29	.838
$SLR_{,RES,3} - SLR_{,LES,3}$	-.02	.15	-0.32536	0.28239	-.145	29	.886

Table 5. Mean (± standard error) of strain-load-ratio SLR calculated using Equation (1).

Body side	Level of intensity		
	1	2	3
RES	3.16 ± .26	3.10 ± .23	3.15 ± .21
LES	3.11 ± .27	3.13 ± .24	3.17 ± .25

4.2 Derivation of forced weighted calculation approach

The resulting data on the relationship between acting maximum spinal compression load in L5-S1 and the strain-load-ratio SLR is shown in Table 6. The two additional data points, which were explained in 2.3, are also included.

Table 6. Points used to derive the mathematical description of the relationship between acting load and relative weighting factor. Since the evaluation is carried out jointly for RES and LES, the three values from the range of medium physical exposure obtained experimentally, are each listened twice.

x-axis [N]	6000.00	2792.25	2627.14	2495.44	2792.25	2627.14	2495.44	1.00
y-axis [-]	30.00	3.15	3.10	3.16	3.17	3.13	3.11	1.01

The plotted data points are shown in Figure 3. With regard to the mathematical description of the relationship between acting load and relative weighting factor, an exponential curve has proven to be the most suitable for the following reasons: In the case of a polynomial function – as used previously [16] – the upper reference value of 6000 N and a factor of 30 would be in the curve, but there would be a global minimum in the range of 1000 N. This means that the weighting factor at 1000 N is lower than the fixed value of the lower guideline value 1.01 and for a load intensity around 1000 N the intensity is weighted lower relative to the load duration. This contradicts the empirical findings on the necessity of a relatively higher weighting of the load intensity to the load duration [4,5,9] and must therefore be avoided. The derived equation for the weighting factor WF_{Force} is also shown in Figure 3 and its coefficient of determination is $R^2 = .97$.
This results in an optimized force weighted calculation approach for cumulative loading given in Equation 2 in accordance with the general form described by [16,25].

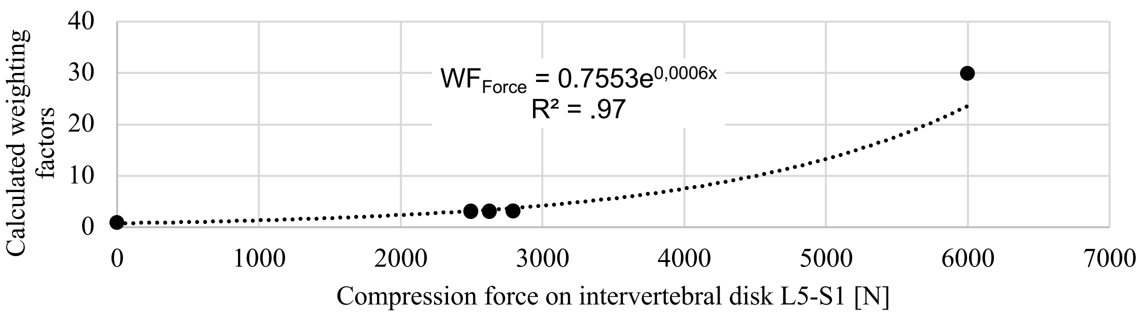

Figure 3. Plotted data points and resulting best-fitting curve to describe the relationship between acting load and load intensity weighting factor.

$$Cumulative\ loading = Exposure\ intensity \cdot WF_{Force} \cdot Exposure\ duration \quad (2)$$

4.3 Validation of forced weighted calculation approach

The results of the correlation analysis are shown in Table 7. Since the correlation coefficient is above 0.5, the correlation between predicted and observed values can be classified as high according to [23].

Table 7. Result of the cross-validation for the evaluation of the forecast quality.

Correlation between	Spearman correlation	p-value
Measured resulting muscular strain - Calculated cumulative loading	.799	<.001

5. Discussion

The objective of this publication was the development and validation of a force weighted approach to calculate cumulative loading. The main motivation was the fact that existing calculation methods are mostly based on the principles of material failure when, in fact, physiological parameters, such as muscular activity, are much more relevant for workplace design for regularly occurring work-related physical exposure [7,8]. However, methods mainly based on the principles of material failure cannot adequately represent these particularly relevant parameters [6]. Therefore, an optimized calculation method based on a new force weighted approach was introduced. For the derivation of the optimized calculation method, the focus was placed on muscular activity, since this parameter is widely recommended as an indicator for measures in the context of ergonomic work design and workforce planning in production [4]. For this purpose, three levels of different load intensity where analyzed. Each level had a different effect on the human body, according to a preliminary ergonomic assessment. Due to additional literature-based upper and lower anchor points, the derived calculation method is also applicable for very high and very low load intensity.

The validation of the optimized calculation method shows very promising results. The prediction quality was determined based on the correlation between values of the cumulative loading index calculated by means of the calculation method to be verified and the measured resulting muscular strain. The results of the correlation analysis show a high correlation (cf. Table 7). For the optimized calculation method, this can be interpreted as a high prediction quality for capturing the physical exposure due to work-related manual lifting activities, and thus as a high quality for ergonomic assessment of physical exposure. As a conclusion of this validation, it can be stated that the overall objective, the optimization of existing methods for the calculation of an exposure index based on cumulative load for a better representation of physiological reactions, has been achieved.

With regard to possible limitations, the following aspect should be mentioned. Due to the literature-based anchor points for very high and very low load intensities, the optimized calculation method is applicable for the entire range from very low to maximum load with regard to the maximum compressive strength of the human spine. However, the calculation method developed here is not intended for exclusive use in the case of very high load intensity in the range of maximum strength of the human spine. If such high loads are present, a general improvement of the workplace to avoid such loads is advisable first, before cumulative loading should be used as a load index for further assessment. Furthermore, it must be mentioned that only a total of five levels of stress were used. Due to time restrictions with regard to the maximum duration of a laboratory study involving participants, it was not possible to investigate even more different levels within the scope of this study.

With regard to the upper anchor point, it must also be noted that the data point (6000|30) does not lie in the approximated curve of the derived calculation formula for the weighting factor WF_{Force}. However, it is also not necessary for the weighting factor to be exactly 30 at an applied compression load of 6000 N. This value

is derived by from experiments on material failure of porcine spine specimen [16]. Since the question of an exact transferability to human bodies still needs verification anyway, this value only serves as a guide value at this point as described. In contrast, it was considered extremely relevant to ensure that the calculated factor WF_{Force} is always above 1. A value of 1 would in fact mean that the two factors load intensity and load duration are weighted equally. This becomes clear when inserting the value 1 in Equation 2. An equal weighting of the exposure factors load intensity and load duration contradicts empirical findings on a relatively higher influence of the load intensity compared to load duration [17,4,5]. Further empirical evidence also explicitly shows that an equivalent weighting of the factors load intensity and duration does not accurately reflect the resulting physical strain but underestimates the influence of higher load intensity [9]. The optimized calculation method presented in this paper takes into account these requirements and thus enables evidence-based ergonomic assessment for work-related MMH.
Furthermore, it should be noted that the optimized calculation method does not take into account any possible sex-specific differences. At the same time, the goal of the optimized calculation method is to better represent the physiological strain resulting from submaximal loading, for which no significant sex-specific differences are to be expected [26]. Moreover, this contribution focuses on the specific exposure case of MMH and the manual lifting activity performed to obtain the empirical data is a symmetrical, two-handed lifting activity. In order to realize a movement execution that is uniform across all test subjects, a very standardized activity was chosen. The derived optimized calculation rule is thus also based on a standardized, simple movement. Still, the derived optimized calculation method is therefore likely not fully suitable for the assessment of very different physical exposure. For example, static muscular work has a completely different effect on the human body than the dynamic muscular work studied here. At the same time, however, dynamic physical work is more frequently encountered in practice [10] and the great relevance of MMH with regard to the prevention of MSE was discussed at the beginning. With regard to other forms of dynamic, physical work that are practically relevant, pushing and pulling of loads can be mentioned [27]. Finally, it has to be noted that possible effects of fatigue were not included in the calculation approach. Since increasing fatigue is likely to have an influence on the muscular activity, further research might be useful with regard to working conditions of longer duration which may lead to physical fatigue.

6. Conclusion

This contribution outlined the development and validation of a calculation method for cumulative loading based on a newly derived force weighted approach. Based on empirical data of 36 individuals and further, literature-based data, a calculation approach was developed. Results of the validation show a high prediction quality for estimating the physical exposure due to work-related manual lifting activities, and thus as a high quality for ergonomic assessment of physical exposure. Further research is needed to extend the presented method to other forms of work-related exposure. Examples of other forms of physical stress that are practically relevant include pushing and pulling of loads.

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References

[1] Maher, C., Underwood, M., Buchbinder, R., 2017. Non-specific low back pain. The Lancet 389 (10070), 736–747.

[2] Heneweer, H., Staes, F., Aufdemkampe, G., van Rijn, M., Vanhees, L., 2011. Physical activity and low back pain: a systematic review of recent literature. European spine journal : official publication of the European Spine Society, the European Spinal Deformity Society, and the European Section of the Cervical Spine Research Society 20 (6), 826–845.

[3] Wells, R., van Eerd, D., Hägg, G., 2004. Mechanical exposure concepts using force as the agent. Scandinavian journal of work, environment & health 30 (3), 179–190.

[4] Gallagher, S., Schall, M.C., 2017. Musculoskeletal disorders as a fatigue failure process: Evidence, implications and research needs. Ergonomics 60 (2), 255–269.

[5] Huangfu, R., Gallagher, S., Sesek, R., Schall, M., Davis, G., 2019. Evaluating the Effectiveness of Estimating Cumulative Loading Using Linear Integration Method, in: Proceedings of the 20th Congress of the International Ergonomics Association (IEA 2018). Springer International Publishing, Cham.

[6] Johnen, L., Mertens, A., Nitsch, V., Brandl, C., 2021. Comparison of Dose Models for the Assessment of Spinal Load and Implications for the Calculation of Cumulative Loading. Proceedings of the 21st Congress of the International Ergonomics Association, 93–100.

[7] Nussbaum, M.A., 2001. Static and dynamic myoelectric measures of shoulder muscle fatigue during intermittent dynamic exertions of low to moderate intensity. European journal of applied physiology 85 (3-4), 299–309.

[8] Waters, T.R., Putz-Anderson, V., Baron, S., 1998. Methods for assessing the physical demands of manual lifting: a review and case study from warehousing. American Industrial Hygiene Association journal 59 (12), 871–881.

[9] Johnen, L., Mertens, A., Nitsch, V., Brandl, C., 2022. Why cumulative loading calculated using non-weighted integration may not be suitable for assessing physical stress of the lower back: an empirical investigation of strain during lifting and lowering tasks. Ergonomics 65 (1), 134–146.

[10] Veerasammy, S., Davidson, J.B., Fischer, S.L., 2022. Multi-task exposure assessment to infer musculoskeletal disorder risk: A scoping review of injury causation theories and tools available to assess exposures. Applied Ergonomics 102, 103766.

[11] Steinberg, U., 2012. New tools in Germany: Development and appliance of the first two KIM ("lifting, holding and carrying" and "pulling and pushing") and practical use of these methods. Work (Reading, Mass.) 41 Suppl 1, 3990–3996.

[12] Marras, W.S., Parakkat, J., Chany, A.M., Yang, G., Burr, D., Lavender, S.A., 2006. Spine loading as a function of lift frequency, exposure duration, and work experience. Clinical Biomechanics 21 (4), 345–352.

[13] Jäger, M., Luttmann, A., 1989. Biomechanical analysis and assessment of lumbar stress during load lifting using a dynamic 19-segment human model. Ergonomics 32 (1), 93–112.

[14] Dolan, P., Kingma, I., van Dieen, J., Looze, M.P. de, Toussaint, H.M., Baten, C.T., Adams, M.A., 1999. Dynamic forces acting on the lumbar spine during manual handling. Can they be estimated using electromyographic techniques alone? Spine 24 (7), 698–703.

[15] Dolan, P., Adams, M., 1998. Repetitive lifting tasks fatigue the back muscles and increase the bending moment acting on the lumbar spine. Journal of Biomechanics 31 (8), 713–721.

[16] Parkinson, R.J., Callaghan, J.P., 2007. The role of load magnitude as a modifier of the cumulative load tolerance of porcine cervical spinal units: Progress towards a force weighting approach. Theoretical Issues in Ergonomics Science 8 (3), 171–184.

[17] Brinckmann, P., Biggemann, M., Hilweg, D., 1988. Fatigue fracture of human lumbar vertebrae. Clinical Biomechanics 3, i-S23.

[18] Afolabi, H.K., Nordin, N.A.H., Nasef, M.M., Harun, N.Y., Ting, T.M., Saeed, A.A.H., 2021. Isotherms for adsorption of boron onto new fibrous adsorbent containing glycidol ligands: linear and nonlinear regression methods. IOP Conf. Ser.: Earth Environ. Sci. 842 (1), 12032.

[19] Agrawal, R., Whalley, R.D., Ng, H.C.-H., Dennis, D.J.C., Poole, R.J., 2019. Minimizing recalibration using a non-linear regression technique for thermal anemometry. Exp Fluids 60 (7).

[20] Jakobek, L., Matić, P., Kraljević, Š., Ukić, Š., Benšić, M., Barron, A.R., 2020. Adsorption between Quercetin Derivatives and β-Glucan Studied with a Novel Approach to Modeling Adsorption Isotherms. Applied Sciences 10 (5), 1637.

[21] Dankaerts, W., O'Sullivan, P., Burnett, A., Straker, L., Davey, P., Gupta, R., 2009. Discriminating healthy controls and two clinical subgroups of nonspecific chronic low back pain patients using trunk muscle activation and lumbosacral kinematics of postures and movements: a statistical classification model. Spine 34 (15), 1610–1618.

[22] Yazdanirad, S., Khoshakhlagh, A.H., Habibi, E., Zare, A., Zeinodini, M., Dehghani, F., 2018. Comparing the Effectiveness of Three Ergonomic Risk Assessment Methods-RULA, LUBA, and NERPA-to Predict the Upper Extremity Musculoskeletal Disorders. Indian journal of occupational and environmental medicine 22 (1), 17–21.

[23] Cohen, J., 1988. Statistical power analysis for the behavioral sciences, 2nd ed. ed. L. Erlbaum Associates, Hillsdale, N.J, 1 Online-Ressource.

[24] Field, A., 2018. Discovering statistics using IBM SPSS statistics, 5th edition ed. SAGE, Los Angeles, London, New Delhi, Singapore, Washington DC, Melbourne, 1070 pp.

[25] Zehr, J.D., Tennant, L.M., Callaghan, J.P., 2019. Examining endplate fatigue failure during cyclic compression loading with variable and consistent peak magnitudes using a force weighting adjustment approach: An in vitro study. Ergonomics 62 (10), 1339–1348.

[26] Daugherty, S.L., Magid, D.J., Kikla, J.R., Hokanson, J.E., Baxter, J., Ross, C.A., Masoudi, F.A., 2011. Gender differences in the prognostic value of exercise treadmill test characteristics. American heart journal 161 (5), 908–914.

[27] BAuA, 2019. Erweiterte Leitmerkmalmethode zur Beurteilung und Gestaltung von Belastungen beim Ziehen und Schieben (LMM-ZS-E): Entwurf zur Praxiserprobung, 12th ed. BAuA/ASER, Dortmund.

Biography

Laura Johnen is Deputy Head of the Department Ergonomics and Human Machine Systems at the Institute of Industrial Engineering and Ergonomics (IAW). She studied Mechanical Engineering and Economics at the RWTH Aachen University. Her research focuses on the assessment of physical strain and identification of risk factors of work-related musculoskeletal disorders to enable evidence-based prevention.

Cathrin Deutz studied Mechanical Engineering at the RWTH Aachen University and worked on the empirical part of this publication in 2021 as part of her master thesis. She is currently a research assistant at the Chair of Production Metrology and Quality Management and information management of RWTH Aachen University. Her research focus is Transdisciplinary Research.

Alexander Mertens is Head of the Department Ergonomics and Human Machine Systems at the Institute of Industrial Engineering and Ergonomics (IAW). In 2012, he received his doctorate in Theoretical Medicine (Dr. rer. medic.) and in 2014 his doctorate in Industrial Engineering (Dr.-Ing.). His research interests focus on designing target group specific user interfaces for mobile information and communication technology.

Verena Nitsch is Director of the Institute of Industrial Engineering and Ergonomics of RWTH Aachen University (IAW) and Head of the Department Product and Process Ergonomics at Fraunhofer Institute for Communication, Information Processing and Ergonomics (FKIE). From 2008 to 2013, she worked as a research assistant at the Human Factors Institute at the Bundeswehr University Munich, where she received her Doctorate of Engineering in 2012 and was appointed assistant professor of Cognitive Ergonomics in

2013. Her research interests include the human factors engineering of multi-modal human machine interfaces, human-machine interaction with highly automated systems and the effects of digitization on human working conditions.

Christopher Brandl is Head of the Department Ergonomics and Human Machine Systems at the Institute of Industrial Engineering and Ergonomics (IAW) as well as research group leader at the Department Product and Process Ergonomics at Fraunhofer Institute for Communication, Information Processing and Ergonomics (FKIE). In 2017, he received his doctorate in Industrial Engineering (Dr.-Ing.). His research interests focus on the analysis of work-related stress and strain indicators, in particular by means of metrological systems.

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Implementation-specific Barriers And Measures For Chatbots In B2B Customer Service

Daniela Greven[1], Kathrin Endres[2], Shugana Sundralingam[1],Volker Stich[1]

[1]*Institute for Industrial Management at RWTH Aachen University, Aachen, Germany*
[2]*International Performance Research Institute, Stuttgart, Germany*

Abstract

The use of chatbots has hardly been established in B2B companies to date and involves various challenges. The goal of this paper is to identify the biggest barriers to the successful implementation of chatbots in B2B customer service and to develop measures to overcome them. The barriers are identified by conducting expert interviews within the framework of Eisenhardt's case study research. These are examined through a socio-technical analysis focusing on people, technology, and organization. By means of systematic literature research and in-depth interviews with German chatbot providers and customers of chatbots, measures for overcoming the barriers are identified. Using interviews with experts from German chatbot providers, the responsible stakeholders of each measure according to the RASCI Responsibility Matrix are determined. A total of 46 implementation barriers and 100 measures to overcome these barriers are identified. The study shows that there are major barriers in the areas of people, technology, and organization of a socio-technical system that can cause the implementation of a chatbot to fail. A holistic view is therefore essential. The results provide firms with a guideline on how to overcome potential barriers during chatbot implementation in B2B customer service.

Keywords

Chatbots; socio-technical analysis; B2B customer service; implementation success factors; implementation barriers

1. Introduction

A 24-hour service with a simultaneous cost saving are by no means contradictory requirements. The continuous development of technologies enables companies to digitize and automate processes such as customer service [1]. One of the most promising technologies of recent years is the so called chatbot, which establishes a 24/7 service for employees and customers, thus increasing their satisfaction and reducing costs. Chatbots are computer-based systems that simulate a natural text-based dialogue. In the B2C sector, chatbots are already in use as innovative and digital service assistants for customer service.[2] In customer communication, chatbots can be used at various touchpoints. Touchpoints represent customer contact points where customers come into touch with products or a company.[3] Chatbots can either be provided as a separate app, integrated into existing systems, such as a company's own website, or in messaging platforms [4]. In order for chatbots to perform its activities, it must be connected either to a database or knowledge base or via interfaces to internal company systems [5].

The implementation of chatbots opens up numerous potential benefits for companies. These will in the following be summarised in the four categories of data, money, quality, and time. Potential benefits in the data category deal with the improvement of customer behaviour, data, and the user experience. The main

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aim here is to use the collected data to make statements about customer needs and the further development of products and services. The money category includes potential benefits for increasing the source of revenue and staff savings. Accordingly, the use of chatbots can support lead generation and increase sales through cross-selling effects. Based on collected data, customers can, for example, be provided with personalised information on further articles. Since chatbots can already solve many of the customers' concerns, the employees are disburdened so that they can focus on their actual value-adding activities. The quality category contains potential benefits that relate to the positive impact of chatbot implementation on everyday service quality. A higher quality of service can be made possible, for example, by the immediate accessibility and fast response time of customer enquiries. In addition to accessibility, chatbot implementation also favours the development and expansion of international service business through multilingual, fast, and targeted interaction. The last category, time, describes potential benefits that deal with the use of chatbots and the associated time savings.

Despite these evident potentials, chatbot implementation in B2B customer service has so far hardly been widespread compared to B2C customer service. The landscape of mechanical and plant engineering is characterised by a large number of small and medium-sized enterprises (SMEs). SMEs in particular are holding back on chatbot implementation because the implementation concepts are not yet fully developed and the high complexity and costs of the systems exceed existing budget and resource constraints.[6] However, SMEs in particular could benefit from the previously mentioned advantages of chatbots, for example in supporting internationalisation.

One major challenge in chatbot implementation, especially for SMEs from the mechanical and plant engineering sector, is the lack of mature implementation concepts that take into account the requirements of B2B service. In addition to the selection of a suitable deployment scenario, it is particularly important to consider implementation barriers that can arise during the introduction of chatbots. The implementation barriers as well as the knowledge how to overcome these barriers are crucial for the success or failure of chatbot implementations. By taking barriers into account at an early stage as part of forward planning, negative effects of implementation barriers can be reduced or eliminated through proactive measures [7]. In accordance with the challenges presented, the research question "How can chatbot implementations be successful?" will be investigated in the following.

To overcome the implementation barriers, a catalogue of measures is to be developed that provides a comprehensive overview of potential barriers that can occur on a technical, organisational, and human level during the introduction of a chatbot with contains measures to eliminate them. Companies with the goal of a chatbot implementation should be able to use the catalogue of measures directly at the beginning of an implementation project to identify potential barriers at an early stage, as well as during the project to help resolve problems that have already occurred. In order to reduce or prevent the negative effects of barriers, measures should be listed for each barrier, which serve as early countermeasures for the user. In addition, to ensure that companies can implement the measures in a targeted manner, responsibilities for each measure should be assigned to different roles. After the presentation of the potential benefits and challenges of chatbot implementation, the next step is to look at related scientific work that deals with a similar problem. This is followed by a description of the methodology used to create the solution, the development of the catalogue of measures. Finally, the results and the benefits of the catalogue of measures are explained based on an example.

2. Related Work

The occurrence of potential barriers does not only play a role in the implementation of chatbots in the company, but also in the implementation of other technologies or digitalisation projects. In the following, some publications are discussed regarding to this topic area.

In their study, [8] deal with challenges that industrial companies encounter when introducing Industry 4.0 applications, in contrast to the barriers listed in the literature. With the aim of filling this knowledge gap, the study surveyed 253 industrial companies regarding this issue. According to [9], the large number of failed projects for the introduction of robot-assisted process automation (RPA) is due to a lack of understanding of the technological possibilities. They therefore discuss challenges and measures to overcome them when implementing RPA. [10] address the issue of user integration in AI-based services and the associated barriers. [11] and [12] focus on the design of human-like interaction of AI-based chatbots and its impact on customer experience and acceptance. [13] and [14] examine factors that complicate or facilitate customer acceptance of chatbot implementation.

Although the previously mentioned publications deal with the challenges of introducing technology and, in the case of chatbots, with the barriers of customer acceptance, they do not take a holistic view of potential implementation barriers and the possibilities of successfully overcoming them. In the process of change through chatbot implementation, it is important to ensure that employees and customers accompany the technology implementation and that both technical and organisational challenges are included. Careful consideration needs to be given to which tasks are automated by chatbots and how certain task areas are handed over to employees. [15]

3. Methods

The research process underlying the catalogue of measures is based on a systematic literature research and a validation by means of expert interviews. The catalogue of measures was constructed in three steps using different methods. In the first step, implementation barriers of a chatbot introduction were identified together with relevant stakeholders. In the second step, corresponding measures were allocated to these barriers using a systematic literature research. In the last step, expert interviews were used to validate and supplement the individual measures and a RASCI classification was created to clearly assign roles for the successful implementation of the measures. The individual steps and methods used are explained in more detail below.

3.1 Fields of action and implementation barriers of a chatbot implementation

In the investigation of the implementation barriers of chatbot introductions, a new field of research is entered. A direct exchange between experts enables a comprehensive view of implementation barriers from different perspectives and generates new knowledge. The identification of implementation barriers was therefore workshop-based with German companies consisting of chatbot users and chatbot providers. Following Osborn, workshops are used for creative problem solving of area-specific problems and questions [16]. The use of workshops as a research methodology aims at obtaining practice-relevant and objective data about the field in question. The approach is characterised by interaction and the consideration of different perspectives, which is why it is particularly suitable for researching new, unknown issues.[17] Consequently, by conducting workshops with experts in a particular field, the aim can be to capture expert judgements to synthesise, integrate or build consensus between experts [18]. The focus on providing knowledge and facts in the workshop ensured that all relevant content regarding potential implementation barriers was recorded by the experts and constructively questioned in stimulating discussions. The introduction of chatbots requires cooperation at the organisational, technical, and human levels in a company. For this purpose, an application example from industry for the use of chatbots was examined incrementally in the workshop with the experts in small groups and subjected to a socio-technical examination with the help of the People-Technology-Organisation (PTO) analysis. The PTO analysis is a socio-technical system approach in which every interaction between the fields of action of people, technology, and organisation is analysed. The three fields of action have a reciprocal relationship, therefore companies should consider technical and organisational as well as expectations and experiences of people while implementing chatbots.[19] The socio-technical systematisation of the implementation barriers was based on the classification of the barriers into these three fields of action. The experts were asked to analyse and collectively discuss the application example based on their knowledge and experience regarding potential implementation barriers. Through the direct exchange between the experts, who were composed of both chatbot providers and chatbot users, implementation barriers could be identified from different perspectives and systematised using the PTO analysis.

3.2 Overcoming measures in the catalogue of measures

Since interdisciplinary areas such as psychology, sociology, technology, and computer science must be taken into account when overcoming the barriers to the introduction of chatbots [20], a systematic approach is of great importance. The identification of effective measures for overcoming the previously identified implementation barriers was carried out through a systematic literature research according to [21] and [22]. For this purpose, mainly search terms were used which are thematically related to overcoming implementation barriers. A systematic literature research is a central component of scientific work and is indispensable in order to gain an understanding of a specific topic. Consequently, the search for overcoming measures requires different search terms, which can be narrowed down by a targeted search strategy. Therefore, not only publications were considered that addressed specifically the introduction of chatbots. Publications dealing with overcoming the barriers of numerous Industry 4.0 applications from different sectors were also included. Subsequently, a collection of the measures listed in the literature was conducted. These were simultaneously assigned to the implementation barriers systematised according to the fields of action. In addition, overcoming measures were recorded by means of expert interviews. The experts validated and adapted measures that had already been recorded or added an alternative measure.

3.3 Definition of responsibilities through RASCI matrix

For a successful implementation of the coping measures, a clear overview of all stakeholders and their functions is crucial. The implementation of chatbots in a company requires the involvement of different cross-functional departments. Accordingly, the implementation of the measures involves interdisciplinary teams with people from different departments of the company who cover different areas of responsibility due to their specific roles. [20] To ensure the successful implementation of the various measures, they were specified using the RASCI matrix. RASCI is an acronym for the functions Responsible, Accountable, Supported, Consulted, Informed and is a further development of the well-known RACI model [23]. The aim of the RASCI matrix is to define a clear overview of a comprehensible distribution of roles for the fulfilment of intended tasks for all those involved in a process or project [24], [25]. In the following the five functions are described: Responsible (R): The person in charge is responsible for the implementation of the task and is also involved in the operational implementation. Accountable (A): This role is accountable for the task. Support (S): This role assists the person responsible for implementation in the execution of the task. Consulted (C): The consulted role performs an advisory function and is involved in the processing of the task. Informed (I): The person holding the informed role should be informed about the progress and outcome of the task. The RASCI matrix is a very effective tool for openly documenting the division of tasks and defining clear roles and responsibilities regarding the successful implementation of a specific task [25].

Since the area of function allocation is about practice-oriented application knowledge, a qualitative method, the expert interviews, was chosen to capture this. Expert interviews are particularly suitable for generating a better understanding of the research area and recording the know-how of the interviewees. The use of a semi-structured guide ensures that all relevant aspects are addressed in the interview. The allocation of the functions to the different roles according to the RASCI matrix was performed by using in-depth interviews with chatbot experts on the provider and user side. A total of twelve interviews were conducted over a period of six months and lasted an average of 60-90 minutes per interview partner. Following the purpose of the research, explorative questions were asked during the interviews in order not to guide the respondents in a certain direction by asking questions. As a result, each measure in the catalogue was analysed in terms of its implementation by identifying functions according to the RASCI matrix for roles within and outside the company. Therefore, a table with all measures was used as a guide in the interviews and at the same time to document the important interview statements.

4. Results

The implementation barriers are presented as a table together with the identified overcoming measures with assignment of functions to roles according to the RASCI matrix. The implementation barriers systematised according to the PTO analysis as well as the corresponding measures are listed in the rows. In addition, all functions involved are listed in the columns, which in turn are divided according to buyer and supplier. The functions are also subdivided according to the categories IT, project team, service customer and specialist departments. The listed functions assume, due to their role, certain tasks in the implementation of the overcoming measures.

The catalogue of measures contains 46 implementation barriers and 100 measures to overcome them, whereby some barriers have been assigned several measures. These are shown in Table 1. The RASCI assignment can be accessed freely available on the internet.

Table 1: List of Implementation barriers and overcoming measures

No	Category	Implementation barrier	Measure
1	People (customer)	Service customers perceive companies as dismissive/disinterested	Establish clear communication strategy between chatbot and customer (process definition, exit strategy)
			Analyse the service customer's communication to design user-friendly dialogues and designs
			Make sure service provider informs service customer about chatbot launch project through website, social media etc.
2	People (service provider)	Rejection attitude and reservations of employees towards the new technology (e.g., AI)	Ensure cultural acceptance of automation at management level and communicating the reasons behind it
			Conduct design and feedback workshops to demonstrate capabilities and limitations of the chatbot
			Create recognition and reward systems to encourage proactive engagement
3	People (service provider)	Choice of chatbot platform (app, browser, on-site, etc.)	Reviewing system requirements for standalone and server operations
			Create internal inventory of the IT infrastructure (predefined by the provider)
4	People (service provider)	Choice of interaction device	Examine the system requirements for the single workstation and server operation
			Analyse the end devices used when using the website
5	People (service provider)	Lack of human contact	Define exact process and conduct a controlled test run with customer
			Design chatbot not as a replacement but as a complement to human service channels (augmentation; user-friendly dialogs and designs)
6	People (service provider)	Employees initiate independent solutions, leading to shadow IT	Prevent shadow IT and proliferation of "islands of automation"
			Ensure a required IT infrastructure for chatbot project combined with clear guidelines
7	People (service provider)	non-existence / ignorance of personal benefits	Communicate the company's rationale for chatbot deployment
			Establish communication platforms (e.g., forum) to enable intra-organizational exchange of experiences
			Communicate the benefits of chatbot implementation to employees early in the process (e.g., less repetitive tasks)
			Transparently explain the changes in the employee's job description
8	People (service provider)	Process reliability of employees	Provide supporting materials, such as process documentation, instructions for action and consultative support
9	People (service provider)	Excessive employee expectations of the chatbot	Define and continuous communicate of a purpose
			Involve employees at an early stage of the chatbot design phase
			Implement internal event formats for initial information (e.g., board or department conferences, market booths, internal company trade shows, etc.)
10	People (service provider)	Uncertainty of digitally inexperienced users in dealing with the chatbot	Design a chatbot that can be operated by digitally inexperienced users
11	People (service provider)	Further development of the chatbot's dialogs	Involve a conversation designer in the chatbot implementation as a permanent role
12	People (service provider)	Untrained employees to maintain the chatbot	Provide developer resources for continuous support of the chatbot (guideline value 1 FTE á 20 automation implementations)
			Provide training programmes, training opportunities and certification
			Purchase external service
			Redesign talent development: train digitization specialists instead of generalists
			Create contingency plans ("error handling") and fallback solutions for employees ("exception handling")
			Establish a responsible project team to survey chatbot implementation (content and technical maintenance)

No	Category	Implementation barrier	Measure
13	People (service provider)	Fear of loss of status, decision-making authority, and-or activity	Communicate the benefits of chatbot implementation to employees early in the process (e.g., less repetitive tasks) Establish active change management to identify and eliminate employee resistance at an early stage Involve all stakeholders early to ensure internal customer support (e.g., management, works council, IT, line) Ensure cultural acceptance of chatbot introduction at management level Explain the changes in the employee's area of responsibility transparent
14	People (service provider)	Excessive feature set at launch leads to employees being overwhelmed	Prototype continuously as the chatbot expands to new business contexts Explain the changes in the employee's area of task transparent
15	People (service provider)	Collaboration between chatbot buyer and provider does not work	Conduct a workshop to develop a joint concept and determine what is possible and what is not Agree on clear distribution of roles and tasks, forms of cooperation, forms, and rhythms of communication Establish escalation levels contractually (special termination rights in case of problematic cooperation) Establish an open-minded culture with open exchange of advice and information, instead of silo thinking
16	Organisation (service provider)	Lack of target definition of the chatbot introduction	Communicate and define the company's rationale for chatbot implementation Focus on long-term value, not quick wins Ensure strategic alignment of chatbot implementation with business goals
17	Organisation (customer)	Chatbot deployment for wrong reasons	Ensure strategic alignment of the chatbot implementation with the business objectives
18	Organisation (service provider)	Choice of chatbot technology	Conduct potential workshop - what is possible, which use cases?
19	Organisation (service provider)	Time and financial restrictions	Provide the necessary financial and human resources Transparent communication between customer and provider
20	Organisation (service provider)	Missing/incorrect further development of the chatbot	Assign a project manager to monitor, manage and control the set-up, implementation, and further development of the chatbots
21	Organisation (service provider)	Qualified personnel for chatbot maintenance	Hire service analysts to provide first line support Hire solution architects to support IT infrastructure required for technology deployment Provide developer resources to continuously support the chatbot Conclude a support contract with provider
22	Organisation (service provider)	Follow-up costs for operation and maintenance	Demand transparent pricing policy from the provider
23	Organisation (service provider)	Excessive expectations of the benefits of chatbot deployment	Establish understanding that the chatbot implementation not only raises quantitative but also qualitative potentials
24	Organisation (service provider)	Excessive feature set at launch leads to non-assessability of benefit	Continuous prototyping when extending the chatbot to new business contexts Build understanding that automation not only raises quantitative but also qualitative potentials
25	Organisation (service provider)	Non-involvement of affected roles and organizational units	Conduct regular department head roundtables and information provision via internal newsletters
26	Organisation (service provider)	Unclearly defined processes of the organization	Hire process controllers to manage, coordinate and control the processes adopted by the chatbot Hire of process developers for design, development, test, and support of chatbot solutions Define and document the process to describe the process scopes (not) to be automated
27	Organisation (service provider)	Unclear division of tasks between employee and chatbot	Communicate intended impact on jobs at an early stage of the process Define process with clear division of tasks and responsibilities between employee and chatbot
28	Organisation (service provider)	New complex processes spanning organizational units	Establish process or business analysts to perform feasibility assessments and create process definitions
29	Organisation (service provider)	Lack of or unclear responsibility for the chatbot	Define a target operating model with clear roles and responsibilities for the chatbot
30	Organisation (service provider)	Responsibility for maintenance work	Provide developer resources for continuous support of the chatbot Create contingency concepts ("error handling") and fallback solutions for employees ("exception handling")
31	Organisation (customer)	Customer query not resolvable by chatbot	Hire of service analysts for first-line support Define escalation mechanisms (clear communication strategies, exit strategy) Adapt processes to suit chatbots to avoid too frequent intervention by employee Test a minimum viable product to eliminate exceptional situations
32	Organisation (service provider)	Legal restrictions on data processing	Ensure compliance with data protection guidelines, IT security
33	Organisation (service provider)	Poor IT security	Ensure compliance with IT security
34	Organisation (service provider)	Access rights management to data	Ensure compliance with authorization concepts Ensure compliance with IT security
35	Organisation (service provider)	Lack of data generation of chatbot interaction and unstructured data	Hire test analysts to perform business process-oriented tests and audits Set up an overview board between interfaces (e.g., chatbot and CRM) Define interfaces, ensure correct entity extraction and slot filling in conversation design and technical development

No	Category	Implementation barrier	Measure
36	Organisation (service provider)	Maintenance of databases accessed by the chatbot	Hire process controllers to manage, coordinate and control the processes taken over by the chatbot
			Create requirements catalogue to be provided to the customer in advance
			Maintain central knowledge database with all data accessed by the chatbot
37	Organisation (service provider)	Incorrect data entry by service customers	Ensure willingness to cooperate through transparent data collection (why is the data needed)
38	Technology	Requirement of customers to the chatbot as to the employee	Use the chatbot according to requirements, strength, and functions
39	Technology	Customer has the same requirement for employees as for the chatbot	Develop clear communication strategy between chatbot and customer
40	Technology	Limited capabilities of the chatbot lead to frustration	Use the chatbot according to requirements, strength, and functions
			Clear communication of the capability on the part of the provider
41	Technology	Chatbot language is not well received	Integrate a conversation designer as a fixed role
			Analyse users' communication (Wizard of OZ method)
42	Technology	Lack of optimization and customization options	Conduct a support contract to the customer with constant analysis
43	Technology	Unstructured data analysis of chatbot data collection.	Ensuring log files (log files) in which all activities of a software robot are written down (important in the context of a later audit)
44	Technology	Incompatible/closed interfaces	Involve IT early to ensure a robust IT infrastructure
			Test integration capability for interaction with in-house applications
45	Technology	Redundant IT systems in one company	Involve IT early to ensure a robust IT infrastructure
			Test the software solution in a controlled experiment
46	Technology	Completeness and interpretability of information	Test of the software solution in a controlled experiment

The assignment of the RASCI letters to the roles provides information about which roles are involved with which function in the implementation of the listed measures. The presentation and application of the catalogue of measures for the elimination of barriers in the context of a chatbot introduction will be illustrated with an example (see Figure 1).

Implementation barrier	Measure	Chatbot-Buyer									Chatbot-Provider			
		Service Customer		Project Team				Departments						
		Key User	…	Product Owner	Process Owner	Project Manager	…	Management	…	Project Manager	Developer	Customer Support	…
Rejection attitude and reservations of employees towards the new technology (e.g., AI)	Ensure cultural acceptance of automation at management level and communicate the reasons behind it	I			A	R		C		S		S	
	Conduct design and feedback workshops to demonstrate capabilities and limitations of the chatbot	S				R		A		S	S		
…	…												

R : Responsible **A** : Accountable **S** : Support **C** : Consulted **I** : Informed

Figure 1: Example of the catalogue of measures

The introduction of chatbots requires the integration of the chatbot functions into the existing workflow in the company. For this reason, it must be ensured that all employees involved are included in the change process and accept it. A potential cultural barrier to this is the rejection attitude and reservation of employees towards the new technology. One measure to eliminate or reduce the barrier under consideration is to ensure cultural acceptance of automation at management level and communicate the reasons behind it. A shared awareness of the problem and understanding of the goal thus achieved will contribute to employees also developing a desire for change and realising and understanding the benefits of the technology introduction for their company as well as for themselves personally. [7] The responsible implementation of the measure is primarily carried out by the project manager (R) on the side of the chatbot-buyer, as they act as a role model and can represent and shape the commitment for the whole company. The project manager must support the project both through their position as well as their behaviour [25]. The project manager (S) and the customer support (S) on the side of the chatbot-provider should also support the implementation of the measure. Through their experience and expert knowledge, they can assess whether the buyers' motivations and intended benefits are a good basis for a successful chatbot implementation. For this measure the management (C) needs to be consulted to jointly work on the communication strategy. The key users (I) will be informed through this measure.

Another measure listed in the catalogue to overcome the described barrier is to conduct design and feedback workshops to demonstrate capabilities and limitations of the chatbot. These workshops are designed to demonstrate the benefits and limitations of the new technology, to receive feedback from employees and to promote a constructive attitude. In this way, all participants are informed from the beginning about the capabilities and limitations of the chatbot solution for the company and the employees concerned. The implementation of workshops is approved by the management (A) of the chatbot-buyer. The project manager (R) of chatbot-buyer is responsible for the implementation of the measure, based on their knowledge of the strategic objective of the chatbot implementation, the intended use and benefit as well as the resources available to the company. The project manager of the chatbot-provider (S) fulfils a supporting function here, as they have the corresponding expertise and can take the feedback from the workshops as a suggestion for improvements. In addition, the chatbot-provider's developer (S) plays a supporting role in the implementation of the measure, as they are the contact person for technical questions regarding functionality and technical requirements for the chatbot implementation.

The early realisation of these measures can ensure that the employees accept the new technology and integrate it into their process routines, which prevents a relapse into old behavioural patterns [14].

5. Discussion

The developed catalogue of measures provides a comprehensive overview for dealing with implementation barriers. The overview enables project participants to prepare for potential problems at the beginning of a chatbot implementation project and to take countermeasures at an early stage. At the same time, the user is enabled to identify potential barriers already in the planning phase. This helps to ensure that the cost and deadline targets of a chatbot implementation are not exceeded by facilitating project entry and avoiding unexpected project delays. Furthermore, through proactive measures, employees and customers can be convinced of the new technology and taken along during an implementation, which creates the necessary acceptance within and outside the company and enables a sustainable deployment of the new technology. Negative effects of potential implementation barriers can thus be effectively prevented [7].

In summary, the catalogue of measures should not be understood as a rigid template for dealing with implementation barriers. Companies with the intention of a chatbot implementation should rather use it as a guideline for orientation during the implementation process.

Further research is required for large companies, on barriers caused, for example, by slow processes and organizational inertia. For SMEs from the mechanical and plant engineering sector, more extensive research is required for a complete guide to the introduction of chatbots that goes beyond addressing possible barriers to introduction with corresponding overcoming measures. An adequate implementation concept must accompany the company from project initiation to implementation and the incremental further development of the chatbot deployment. For this reason, the research project "Chatbot in Service" investigates further aspects of chatbot implementation such as the identification and prioritisation of potential implementation scenarios, a provider and technology screening for chatbot implementation, the quantification of potential benefits as well as the collection of factors influencing acceptance and measures for overcoming them.

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References

[1] Neufeind, M., O'Reilly, J., Ranft, F., 2018. Work in the digital age: Challenges of the fourth industrial revolution.

[2] Fotheringham, D., Wiles, M.A., 2022. The effect of implementing chatbot customer service on stock returns: an event study analysis. J. of the Acad. Mark. Sci., pp. 1–21.

[3] Kushwaha, A., Kumar, P., Kar, A., 2021. What impacts customer experience for B2B enterprises on using AI-enabled chatbots? Insights from Big data analytics. Industrial Marketing Management (98), pp. 207–221.

[4] Smutny, P., Schreiberova, P., 2020. Chatbots for learning: A review of educational chatbots for the Facebook Messenger. Computers & Education 151, 103862.

[5] Muischnek, K., Müürisep, K., 2018. Human language technologies- the Baltic perspective: Proceedings of the Eighth International Conference Baltic HLT 2018. IOS Press, Amsterdam, Netherlands.

[6] Waack, J., 2019. Umfrage: Wann kommen die B2B-Chatbots? https://blog.ec4u.com/umfrage-wann-kommen-die-b2b-chatbots/. Accessed 22 October 2022.

[7] Schulte-Zurhausen, M., 2014. Organisation, 6th ed. ed. Franz Vahlen, München.

[8] Meißner, A., Glass, R., Gebauer, C., Stürmer, S., Metternich, J., 2017. Hindernisse der Industrie 4.0 – Umdenken notwendig? Zeitschrift für wirtschaftlichen Fabrikbetrieb 112 (9), pp. 607–611.

[9] Götzen, R., Stamm, J. von, Conrad, R., Stich, V., 2022. Understanding the Organizational Impact of Robotic Process Automation: A Socio-Technical Perspective, in: Camarinha-Matos, L.M., Ortiz, A., Boucher, X., Osório, A.L. (Eds.), Collaborative Networks in Digitalization and Society 5.0, vol. 662. Springer International Publishing, Cham, pp. 106–114.

[10] Janssen, A., Grützner, L., Breitner, M., 2021. Why do Chatbots fail? A Critical Success Factors Analysis. International Conference on Information Systems (ICIS), Austin.

[11] Rapp, A., Curti, L., Boldi, A., 2021. The human side of human-chatbot interaction: A systematic literature review of ten years of research on text-based chatbots. International Journal of Human-Computer Studies 151, 102630.

[12] Kushwaha, A.K., Kumar, P., Kar, A.K., 2021. What impacts customer experience for B2B enterprises on using AI-enabled chatbots? Insights from Big data analytics. Industrial Marketing Management 98, pp. 207–221.

[13] Mozafari, N., Weiger, W.H., Hammerschmidt, M., 2022. Trust me, I'm a bot – repercussions of chatbot disclosure in different service frontline settings. Journal of Service Management 33 (2), pp. 221–245.

[14] Brachten, F., Kissmer, T., Stieglitz, S., 2021. The acceptance of chatbots in an enterprise context – A survey study. International Journal of Information Management 60, 102375.

[15] Abbas,S., Lokman,M, Ameedeen,A. Modern chatbot systems: a technical review., in: Proceedings of the Future Technologies Conference (FTC) (Ed.), vol. 2, pp. 1012–1023.

[16] Osborn, A.F., 1979. Applied imagination: Principles and procedures of creative problem-solving, 3., rev. ed., [Nachdr.] ed. Scribner, New York.

[17] Ørngreen, R., Levinsen, K., 2017. Workshops as a Research Methodology. The Electronic Journal of e-Learning (15), pp. 70–81.

[18] Niederberger, M., Wassermann, S., 2014. Methoden der experten- und stakeholdereinbindung in der sozialwissenschaftlichen forschung. Springer VS, Wiesbaden.

[19] Ulich, E., 2011. Arbeitspsychologie, 7., neu überarbeitete und erweiterte Auflage ed. vdf Hochschulverlag AG an der ETH Zürich; Schöffer-Poeschel Verlag, Zürich, Stuttgart.

[20] Zhang, J.J.Y., Følstad, A., Bjørkli, C.A., 2021. Organizational Factors Affecting Successful Implementation of Chatbots for Customer Service. Journal of Internet Commerce, pp. 1–35.

[21] Brocke, J., Simons, A., Niehaves, B., Riemer, K., 2009. Reconstructing the Giant: On the Importance of Rigour in Documenting the Literature Search Process, Italy.

[22] Cooper, H.M., 1988. Organizing knowledge syntheses: A taxonomy of literature reviews. Knowledge in Society 1 (1), pp. 104–126.

[23] Mrzyglocka, J., Kott, J., Kott, M., 2019. Communication management model- case study in the project of energy efficiency improvement using the RASCI matrix. Department of Operations Research and Business Intelligence, Wroclaw University of Science and Technology.

[24] Hightower, R., 2009. Internal controls policies and procedures. Wiley, Hoboken, N.J.

[25] Baker, D.A., 2010. Multi-company project management: Maximizing business results through strategic collaboration. J. Ross Publ, Fort Lauderdale, Fla.

Biography

Daniela Greven (*1995) has been a Research Associate and Project Manager at the Institute for Industrial Management at RWTH Aachen University since 2020. She studied Business Administration and Engineering specializing in Mechanical Engineering at the RWTH Aachen University. In her research, she focuses on industrial service and digital business models.

Kathrin Endres (*1996) is a Research Associate at the International Performance Research Institute in Stuttgart, Germany. She studied International Business at the Friedrich-Alexander-Universität in Nuremberg and Economics at the Ulm University in Ulm. In her research, she focuses on industrial application fields as well as management of intelligent technologies.

Shugana Sundralingam (*1994) is a Scientific Research Student Assistant at the Institute for Industrial Management at RWTH Aachen University since 2022. She studied Business Administration and Engineering specializing in Mechanical Engineering and focuses in her research on industrial service and digital business models.

Prof. Dr.-Ing. Volker Stich (*1954) has been head of the Institute for Industrial Management (FIR) at the RWTH Aachen University since 1997. Prof. Dr.-Ing. Volker Stich worked for over 10 years for Saint-Gobain Sekurit and lead the management of European plant logistics. In addition, he was responsible for the worldwide coordination of future vehicle development projects.

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Maturity SCAN 4.0 - An Analysis And Discussion Of Results From The Scanning Of Digital Capabilities Adopted In Argentinian CPG Companies

Lourdes Perea Muñoz[1], Marcel Hagemann[2] , Lucila Palandella[1], Paz Cagliari[1]

[1]Facultad de Ingeniería, LIDTUA-CIC-Centro de Industria 4.0 / Universidad Austral, Pilar, Argentina
[2]Industrie 4.0 Maturity Center Gmb/ RWTH University, Aachen, Germany

Abstract

Industry 4.0 is a new dynamic paradigm for manufacturing companies, being studied by academia and evolving at the same time as companies are trying to leverage its potentials. Readiness and maturity models have been developed to assess Industry 4.0 adoption, diagnose the current state of companies regarding digital transformation and help them understand how to move from the current situation to a desirable future one. However, these models are generic, based on general principles of Industry 4.0 and do not consider the particular challenges and potentials of each industry and company. In practice, the success of Industry 4.0 implementation depends on how companies manage to match the concepts and technologies with specific potentials in the context of their strategy.

For this purpose, a study within companies of the same industrial sector is proposed. It serves as first step of "customization" of industry 4.0 concepts to help companies identify their specific benefits. The results of the study within 30 companies in the Consumer Packaged Goods sector in Argentina is presented. It combines the findings from surveys and self-assessments based on a proven maturity model with workshops and semi-structured interviews within a group of managers who are responsible for digital transformation, IT and Operations in their companies. In addition to an initial evaluation of the current Status quo, the analysis focusses on the main challenges and needs of the sector and possible actions to address them.

Keywords

Industry 4.0; Maturity Models; Readiness Assessment; Consumer Packaged Goods; Challenges

1. Introduction

Industry 4.0 (I4.0) is a new paradigm which is being adopted by companies around the world and has captured the interest of governments as an opportunity to make companies more competitive in today's highly changing environment. Since its first denomination as ‘Industry 4.0’ in Germany 2011[1], academic attention has evolved, from defining the term, settling its frontiers for different areas of application, and its technology enablers, to establish the implications from a company´s perspective. Therefore, the promising potentials of the fourth 'revolution' need to be translated to a realistic and affordable 'evolution' path.

For manufacturing companies, the ultimate goal of I4.0 is mostly based on transforming data into actionable knowledge, turning companies into agile, flexible and learning organizations, while enabling them to generate greater value. Thus, achieving digital maturity is a complex process; in which organizations must develop digital capabilities, not only from a technological point of view, but also from a holistic vision that takes into account people, culture and organizational structure [2].

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It is clear that such a complex process calling for the transformation of the company at all levels, in all processes and in the long term, requires specific tools to be sustained. This has given rise to prolific and still booming research on maturity models (MM), roadmaps and methodologies, which are aimed at helping companies, put the vision into action. MMs, in the context of I4.0, promise to guide the adoption of I4.0 technologies at the organization level [3]. MMs offer a generic, but detailed, step-by-step evolution, from early stages to full maturity of I4.0, allowing companies to diagnose their current situation and derive the actions to be taken to move forward in this process. Understanding at what stage organizations are, and what their pain points and challenges are, is the first step towards the structured pursuit of higher stages.

Despite the advances in the comprehension of what I4.0 stands for in a manufacturing company, and the common expectation of its general potential benefits, not all industries are adopting these enabling technologies at the same ease and it is necessary to understand what the reasons behind these differences are [1]. This demands a more specific approach, going to the practical arena to learn about the particular challenges related to the enterprise size [4], context of a geographic region or of an industrial sector.

In Argentina, the I4.0 concept started to develop around 2016. During 2018/19 relevant studies were published to show the initial situation of companies at the country, mainly focused on technological and context factors [5] [6] and based on surveys to executives regarding technology adoption and barriers to implementation, but, with neither a MM to support it nor a holistic understanding of the progress degree of companies. The results of these studies have been useful information for the strategic planning of productive development at a national level. Today, a different scenario can be observed, partly accelerated by the COVID-19 context, partly as result of governmental and institutional promotion, and partly because of the natural pressure from the international competitive scenario. Today many companies have a generalized understanding of the I4.0 concept and; the main concern is how to implement it.

The I4.0 implementation process is context dependent, and will be different for each company. It is necessary to examine each case to better define the company objectives. The need to measure the progress and success, as well as the need of benchmarking against competitors, is part of the industrial environments [1].

Two aspects are crucial: the motivation (to guarantee the movement) and the know how (to move in the correct direction). This study presents an analysis of the maturity state of companies in the Consumer Packaged Goods (CPG) sector in Argentina, with a dual purpose: i) to shed light on the potential that I4.0 can present to the sector and help companies understand where this specific potential lies (motivation) ii) to assess the internal development of digital capabilities in the companies in order to understand which actions should be taken to promote its development in an effective way (know how).

1.1 Maturity Models

As stated above, MMs help an individual or entity reach a more sophisticated maturity level in people/culture, processes/structures and/or objects/technologies following a step-by-step continuous improvement process. Roadmaps are plans that match short-term and long-term goals with specific technology solutions to help meet those goals [4].

Angreani et al [3] offers a systematic literature review of existing frameworks, indexes, roadmaps, readiness and maturity models for manufacturing and logistic sectors. They analysed 17 models as a result of a quality assessment selection that measures: i) research aims, method, and theoretical foundation, ii) structure accuracy and iii) practice orientation. They conclude: Almost all of the selected MMs have a perfect score in research aims, methods, and theoretical foundations. Regarding structure accuracy, most have good scores in modeling maturity levels, but there is a great dispersion in the scope of dimensions. Only five of the models, include the nine dimension categories in the review (strategy; leadership; customers; products; operations; culture; people; governance; technology). Practical orientation seems to be the main gap.

Different visions arise when referring to Industry 4.0, its specific requirements and the conditions to achieve the highest levels of maturity. Although, technology is always considered as an essential enabler of I4.0, there are differences in the relevance that authors assign to it. While some of them focus, even exclusively, on this aspect [7][8][9], others present a holistic approach that incorporates other organizational dimensions such as corporate strategy, structure, culture and human resources [2][10][11]. Schuh et al [2] manages to clearly translate their holistic vision to six "value based" development stages. This approach enables companies to plan and implement the road towards I4.0 maturity in a way that ensures continuous value creation throughout the transformation process. Another strength of this model is that it is based on a well-established management framework, enabling a deep understanding of the capabilities to develop in the main structural areas of an enterprise: Resources, Culture, Organization and Information Systems. Although [3] ranks it low in practical orientation, this tool has been successfully implemented in many projects around the world proving its usability [12]. For these reasons, the tool selected for this study is a simplified but detailed version of the "Industrie 4.0 Maturity Index" (Maturity SCAN 4.0).

1.2 Industry 4.0 in the CPG sector

No literature related to the I4.0 evolution in CPG industries, from our concern, has been found. However, there is some literature for associated industries like "food and beverage", one of the most representative of the CPG sector. The largest part relates to specific technology implementation. Hassoun et al [13] presents a complete state of the art in the Food Processing 4.0, highlighting the potential of the fourth industrial revolution technologies to improve quality and safety of processed food products, reduce production costs and time, save energy and resources, as well as diminish food loss and waste. They also highlights the value of the most promising technologies, such as the industry of robotics, smart sensors, artificial intelligence, the internet of things (IoT), and big Data, as the main enablers of the I4.0 in the sector, and its applications.

Konur et al. [14] presents the design, development and implementation of I4.0 in a traditional food manufacturing company as a case study, in which they have successfully utilized some emerging technologies, including IoT, big data analytics, machine learning and cyber-physical systems, and have reached some positive results on improving efficiency, productivity, and consistency. They also outlines some generic lessons useful to other similar SMEs, as the role of retrofitting in extending the life of current production facilities, and the cultural change in having academics and employees work together. The costs and benefits of this implementation are not shared.

In practice, the success of I4.0 implementation depends on how companies manage to match the concepts and technologies with specific potentials in the context of their strategy. Despite general benefits are shown in many publications and whitepapers, the majority of companies struggles in the identification of their own potentials, as this study proves. Our study is intentionally focused on companies of the same industrial sector. It allows taking a first step towards "customization" of I4.0 concepts, helping companies identify their specific benefits. It also provides them with a benchmark of the peer group.

2. Research Methodology

The research questions established for this study were:

- RQ1: What is the current maturity level of the companies in the CPG sector?
- RQ2: Which are the sector's current main pain points and challenges with respect to their Digital Transformation?
- RQ3: Which are the possible actions related to I4.0 implementation to overcome the pain points and address the challenges?

To answer these questions, a methodology for the identification of the sample and the definition of the project's phases was selected.

2.1 Sample identification

The CPG sector in Argentina is highly concentrated in a few companies. To give an order of magnitude, 74% of the turnover of gondola products corresponds to 20 companies. In order to guarantee the success of the project, not only the participation of a representative sample of the companies was required, but also the selection of the participants' profiles. Given the characteristics of the chosen tool, high seniority within the company, knowledge of the business and involvement in the planning or execution of the digital transformation were required. To ensure the validity of the answers only the following profiles were considered appropriate: digital transformation director (when existing), or both the operation and IT (Information Technology) director. For this reason, the consulting firm NUMAN (specialized in industrial recruiting) was invited to participate in the project. Out of a total base of 130 medium and large companies (more than 50 employees), the positive response rate was 30. From each enterprise, more than one participant with different roles signed up. Despite the fact that the study was conducted in Argentina, 66% of the enterprises were multinational and 34% were national. The number of employees gives an overview of the size of companies: 57% had more than 650 employees, 16% between 250 and 650, and the remaining 27% between 60 and 250 employees. With regard to the product portfolio, participants could be assigned as follows: Food and beverage 80%, Personal Care 13%, Baby Care 10%, Home Care 7% and Pest control 7%.

2.2 Phases of the methodology

A three-phase methodology was applied (Figure 1):

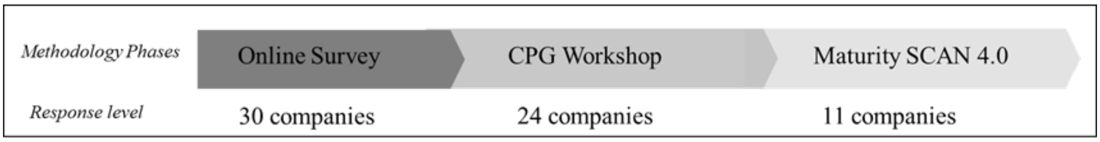

Figure 1- Three-phase methodology

- First Phase: consisting of an online survey, containing questions related to different aspects associated to I4.0: i) Importance and meaning, ii) Expectations and potentials, iii) Focus areas including pain points iv) Structural changes
- Second phase: A workshop with the leaders from the invited companies was conducted. The following topics were discussed: i) I4.0 Motivation and CPG Industry Challenges; ii) Digital Transformation Management and Description of "Maturity SCAN" tool. iii) Implementation challenges and practical experiences.
- Third phase: The "Maturity SCAN 4.0" was used to finish the first stage of the project, and to complete the diagnosis needed to answer the research question related to current maturity status.

2.3 Maturity SCAN 4.0

The "Maturity SCAN 4.0" is a tool specifically developed to assess the maturity level of manufacturing companies; based on the theoretical framework from ACATECH [1]. This framework outlines the evolution towards I4.0 in 6 maturity levels clearly defined and characterized (1. Computerization, 2. Connectivity, 3. Visibility, 4. Transparency, 5. Predictability, 6. Adaptability). In order to assure a holistic approach, the tool assesses the companies' maturity in four different structural forces, each of them includes two principles: Resources (Digital capability / Structured communication); Information Systems (Integration of IT systems / Information processing); Organizational Structure (Organic internal organization / Dynamic collaboration in value networks); Culture (Social collaboration / Willingness to change). The "Maturity SCAN 4.0", evaluates 77 capabilities which are assigned to three typical I4.0 development areas of manufacturing companies: Integrated Business Processes (33 capabilities), Agile Organization (22 capabilities) and Digital Shop Floor (22 capabilities). At the same time, each capability is associated with a company's process: overall process, production, production planning, quality, logistics and maintenance.

3. Results

In this section, we present the most significant results. The maturity status of a company (or area, or process) is expressed by a number between 1 and 6, corresponding to the maturity levels described above. This number represents an average of the scores obtained by each participating company for each capability, at the level of aggregation chosen for the analysis. Values presented as percentage are indicating the share of companies from the total sample that have given answers to a specific aspect.

3.1 Maturity SCAN 4.0

An answer to the first research question (RQ1) can be given based on the results of the Maturity Scan 4.0. A general analysis shows that the companies that completed the SCAN questionnaire are positioned, on average, between level "2. Connectivity" and "3. Visibility". This implies that companies are completing the last level of basic digitalization while taking the first steps towards I4.0 implementation. In order to better understand the development level of companies, results are analysed in three different directions and levels of aggregation of data: i) evolution level of structural forces and its principles; ii) maturity status regarding the three scenarios iii) analysis of individual capabilities. This analysis enables the identification of areas with opportunities for improvement. In order to best capitalize the value per of a maturity stage, a homogenous development of capabilities is needed.

3.1.1 Analysis of structural forces and its principles.

When analysing the four structural forces and its principles, the lowest scores must be noted for "Resources" and "Information systems" (see Figure 2). Average scores between 2,0 and 2,2 show that companies still face considerable gaps in the computerization of processes and the consistent connectivity of resources and IT systems. In consequence, they struggle in gathering and communicating data from equipment, employees and goods but also in exploiting the available data in a suitable way to support decision processes. All this is in alignment with the main challenges and pain points that companies selected in the previous online survey: 50% expressed difficulties in automatically generating data due to an aging equipment, and 37% admitted to have adopted different technologies along time, which made the integration difficult.

A more advanced maturity score, can be observed in the dimensions "organizational structure" and "culture". This seems natural for the principle of "dynamic collaboration in value network" (2.8), considering the key role of the supply chain coordination in the sector where the ultimate goal is to place the product in the latest consuming point and different collaborative planning techniques have been put into practise in the previous decades. The highest score of 3,0 with respect to the "Social Collaboration" [Fig. 2] indicates the increasing introduction of an open communication culture and a trained use of IT systems supported through appropriate incentives, that contributes to an agile exchange of information within the organization.

3.1.2 Analysis of Scenarios

Many participants showed a very narrowly constrained understanding of the term I4.0 as "digitalization of the shop floor" delimiting the digitalization of the factory from projects carried by the IT area. This matches with difficulties in integration between IT/OT (Operational Technology) which was expressed by 30% of the companies as one of their main pain points. Looking at the three scenarios helps connect technology-focused projects with the main principles behind I4.0: The digital shop floor, An agile organization, and the integration of business processes through IT.

The results in Fig. 2 show that companies are in average just completing the Connectivity level (2) with respect to the Digital shop floor scenario, which is characterized by the operational work on or with machines, where products are manufactured or assembled. The core challenge in this scenario is to replace manual information flows with automated information flows based on better data availability. Main pain points mentioned in the survey are difficulties in automatically generating data due to aging equipment (50%) and a high manual effort in the planning and control of production processes (27%).

With regard to the scenarios “Agile Organization” and “Integrated Business Processes”, companies are already on average already advancing towards visibility (2.7, and 2.3 respectively). The core challenge related to the Agile Organization scenario is the flexibilization of traditional organizational structures, which are generally rigid and hierarchical and the implementation of agile methods. Despite the higher score, still a 30% of companies mentioned the implementation of more agile methods as a pain point.

The core challenge related to the scenario of “Integrated Business Processes” is to reach a harmonized IT landscape in order to make information available across the company and therefore promote its value-adding use in decision processes. The main pain points that companies mentioned, associated to this scenario, are difficulties in IT/OT integration (30%); a low level of management integration between areas (27%), challenges of integrating machine control and information exchange (23%) and a low level of integration among clients and suppliers (20%).

Analysis of structural forces and its principles.

Structural Force	Principle	Average
Resources	Digital Capability	2,0
	Structured Communication	2,2
Organizational Structure	Organic Internal Organization	2,4
	Dynamic Collaboration in Value Networks	2,8
Culture	Social Collaboration	3,0
	Willingness to change	2,7
Information Systems	Integration of IT Systems	2,1
	Information Processing	2,1

Analysis of scenarios

Scenario	Average
Digital Shopfloor	2,0
Agile Organization	2,7
Integrated Business Proce	2,2

Analysis of processes

Process	Average
Overall Process	2,5
Production	2,3
Production Planning	2,2
Quality	2,2
Maintenance	2,2
Logistics	2,1

Figure 2- Current I4.0 Maturity Status of companies in the CPG sector (structural forces, scenarios and processes).

3.1.3 Analysis of Capabilities

As mentioned previously, the “Maturity SCAN 4.0” tool considers 77 capabilities to be assessed. The average results show that 56 capabilities were scored on average in the Connectivity level (2) aligned with the overall result. In order to achieve a homogenous development and advance to level 3, all capabilities should be at level 2 first.

From the organizational point of view, a greater progress can be stated; three capabilities have already reached the Visibility level [Fig.3]:

- Change Management in the Overall process; this means that changes (e.g., in processes, systems used, or organisational structure) are communicated openly and driven forward by a core team.
- Databased decision processes in the Overall process; this means that current and historical data are used to support the decision-making process.
- Communication Culture in the Overall process; this means that communication between areas and hierarchies is promoted through regular exchange (e.g., shop floor meetings at different levels).

It shall be mentioned, that aspects associated with the organizational structure are more difficult to measure and the higher scores may be biased through the participants perception. Another possible explanation is the previous rise of the Lean Manufacturing culture within the region.

Eighteen capabilities are on average still on the lowest maturity level of Computerization [see Fig. 3]; the majority of them are close to reaching the Connectivity level. Companies should focus on the following capabilities, which are hampering the maturity progress:

- Use of machine interface in the Quality process; this means that Interfaces of measurement equipment are not used. Quality data is documented manually.
- User interface in Quality and in Maintenance process; this means that in both processes there are only a few user interfaces dedicated to process-internal IT systems. Information is prepared to a very limited extent, e.g., paper-based information transmission.

The importance of these weaknesses is sustained by the outcome of the survey, since 31% of participants mentioned Quality Assurance as one of the main goals for the implementation of I4.0. Further capabilities that have not yet reached level 2, are associated with technology.

Analysis of capabilities

Capabilies Level 2.Connectivity	Process	Average
Data Storage	Overall	2,4
User interface	Logistics	2,0
Provision of information	Quality	2,1
Transparency of IT systems	Overall	2,1
Interdisciplinary skills of employees	Overall	2,2
Communication interface: Human/Human	Production	2,6
Project management	Overall	2,6
Incentive systems	Overall	2,7
Use of IT systems	Overall	2,9
Data analytics	Production	2,2
Decision Support (IT)	Maintenance	2,0
Target-oriented KPI	Production	2,3

Analysis of capabilities

Capabilities Level 3.Visibility	Process	Average
Change management	Overall	3,2
Databased decision processes	Overall	3,1
Communication culture	Overall	3,1

Capabilities Level 1.Computarization	Process	Average
Use of machine interface	Quality	1,4
	Logistics	1,8
	Production	1,9
User interface	Maintenance	1,7
	Quality	1,7
	Production	1,8
Communication interface: Human / Machine	Production	1,8
Provision of information	Production	1,8
IT competencies of employees	Production	1,8
	Quality	1,8
	Maintenance	1,9
	Production P	1,9
	Logistics	1,9
Identification of material	Quality	1,8
	Logistics	1,9
Decision support	Quality	1,8
	Production P	1,9
Resilience	Overall	1,9

Figure 3- Current I4.0 Maturity Status of companies in the CPG sector (results for selected capabilities)

3.2 Technology implementation

Regarding technologies, the ones with the highest level of implementation are Data Analytics (29%), Cloud Computing (29%), IoT solutions (21%) and Robotics (18%). These technologies are also the ones that are being assessed mostly in an experimental phase along with Artificial Intelligence (AI) [See Fig. 4]. This is consistent with the maturity level stated above: Sensors (IoT) allow connectivity and data collection specially in elderly machinery and connectivity; Cloud Computing allows data storage from different sources; Data Analytics allows data analysis and visualization. Moving a step forward, some companies (7%) are starting to work more intensively with AI.

3.3 Motivation and main challenges

The second research question (RQ2) can be mostly answered based on the previous survey, enriched with the results from the workshop.

The CPG sector faces the challenge of obtaining profitability from very short margins of the products. As the prices are commonly fixed by the market in a very competitive environment, companies need to work on their costs and expenses accounts. That is the main source for the companies to seek higher productivity. In parallel, markets are getting more complex, with higher degrees of specialization of customers' needs/ tastes, and required quality standards. When being asked about the motivation of implementing I4.0, 85% of the company's target efficiency, 54% speed & flexibility and 31% Quality Assurance.

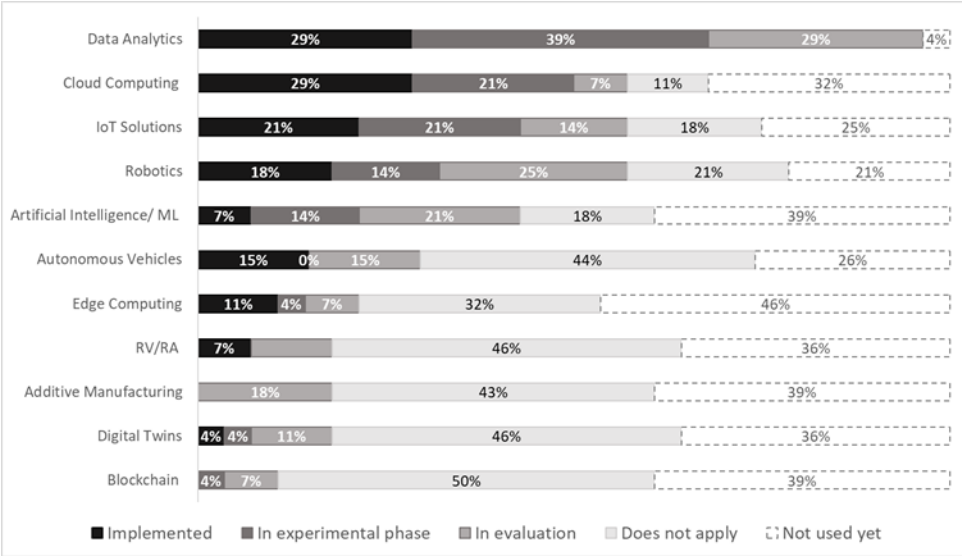

Figure 4 - Degree of adoption of different I4.0 technologies

I4.0 principles provide possible solutions to the before mentioned challenges. Nevertheless, in order to promote the digital transformation, a company needs to find a clear position with respect to the following three aspects: i) Motivation: why should companies adopt this new paradigm? ii) Management: how to adapt the organization, people and culture? and iii) Technology: which solutions are suitable?

Motivation: Companies of CPG sector are already aware of the general benefit of I4.0: 70% of the companies expect an essential impact on their P&L (profit and loss account) and consider it a competitive advantage. In contrast, only 37%, declare to have already identified the specific potential in the enterprise while 39% have begun only few I4.0 projects as they`re lacking a clear idea of its ROI in their own company. Specific challenges related to the identification of concrete potentials, and ROI approximation must be addressed.

Management: 43% of companies expressed challenges through immature management aspects hampering the digital transformation process. This involves the lack of standardization of processes and lack of understanding regarding information relevance to the business. Change management is another issue with 27% of participants remarking the need to change on employee mind-set and 27% the integration between various entities and teams. In addition, during the workshop, leaders of the sector highlighted the lack of support from the top management when it comes to investing in Digital Transformation projects, which is closely related to difficulties in estimating the ROI of interdependent projects that are generally evaluated in a separated manner.

Technology: Companies need to find an individually suitable set of technologies that make relevant information from all company areas and levels available during decision processes. Current challenges expressed by the participants refer mainly to the automated generation of data due to the age of the equipment (50%), achieving higher degrees of integration between IT and OT (37%) as well as the heterogeneity of the technologies in use (37%).

4. Conclusions

The results from the Maturity SCAN 4.0 indicate that Argentinian CPG companies are currently, in average between I4.0 maturity stage 2. Connectivity and 3.Visibility, which implies that they are moving from the most incipient stages of digitization to those where the potentials of I4.0 start to pay off. A large part of the challenges is related to the company's way of planning and managing their digital transformation. Some conclusions are presented regarding the current state of the companies, their challenges and possible actions. In Fig. 3, these aspects are summarized. The analysis presented indicates that:

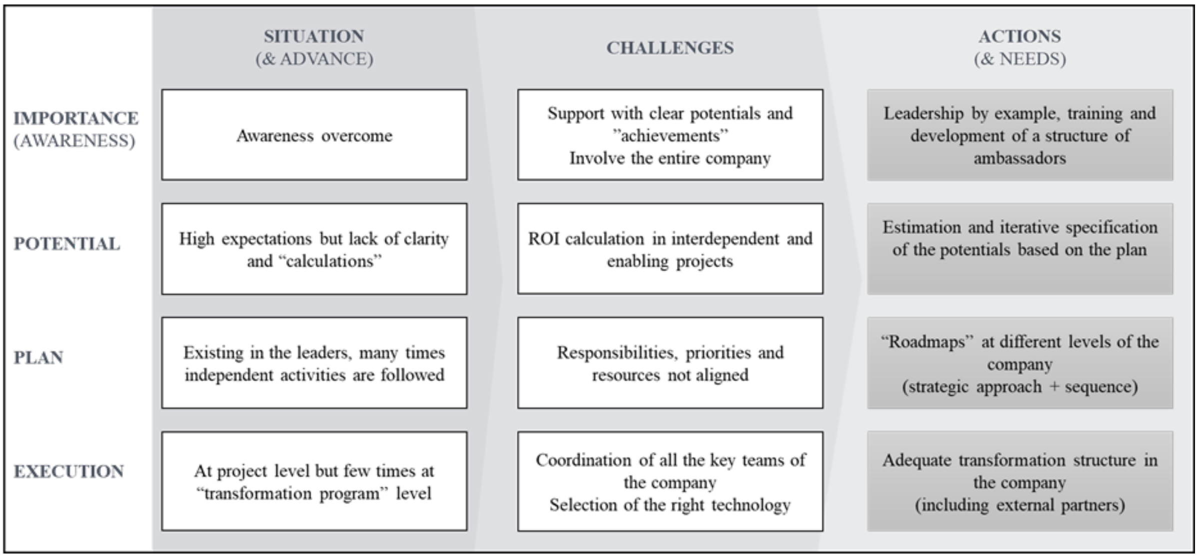

Figure 3: Summary of the current situation, main challenges and proposed actions for companies in the Argentinian CPG sector

A certain level of **awareness** is already reached; there is a good understanding of the importance and generic potentials of I4.0. However, awareness quickly drops when moving away from the personnel directly involved in the topic. The challenge is to increasingly involve the entire organization, which requires a strong leadership focus on a consistent up and down communication of application examples and success stories, the training of employees at all levels and organizational alignment between different departments and from shop floor to top floor.

High expectations on the **potentials** combined with a lack of a clear method for calculating ROI make it difficult to properly prioritize projects. The projects are not isolated but interdependent with each other, some of which have only a limited value on their own while enabling the implementation of other projects with a higher potential. The overarching calculation of the ROI for several projects together is only promising based on a consistent Roadmap that defines sequence and interdependencies of the projects. Although some leading companies declare to have a plan, the majority still lacks it and therefore promotes isolated activities driven by individual motivation from different areas of the company.

Changing this situation requires a holistic view on the ROI and the potentials on program instead of project level, raising awareness at all levels of the company and developing an organization that supports the development and execution of a centrally aligned **plan**, a “Digitalization Roadmap”. In short, the roadmap as consistent, complete, global plan coordinates activities at different levels: corporate, production plant or process and needs to define how the projects are related to each other, in which sequence they are to be addressed and how they contribute to the strategic approach: the goals to be achieved.

Even less companies have found a satisfactory approach for the **execution** of their digital transformation programs. On application level, the execution is hampered through the before mentioned challenges such as eldery of machinery, different legacy technology regarding this machinery, different plant situations in different sites of the company, and difficulties of IT/OT integration. This underlines the need for better centralized alignment of activities based on the “Digitalization Roadmap”. In order to use them successfully as steering tool, the establishment of responsibilities, priorities for certain projects, coordinated deadlines (start and end of a project) and a corresponding allocation of resources is required on the organizational level.

References

[1] V. Alcácer, C. Rodrigues, H. Carvalho, and V. Cruz-Machado, “Tracking the maturity of industry 4.0: the perspective of a real scenario,” *Int. J. Adv. Manuf. Technol.*, vol. 116, no. 7–8, pp. 2161–2181, 2021, doi:

10.1007/s00170-021-07550-0.

[2] W. Schuh, G., Anderl, R., Gausemeier, J., Hompel, M., & Wahlster, "Industrie 4.0 maturity index. Managing the Digital Transformation of Companies," 2017.

[3] L. S. Angreani, A. Vijaya, and H. Wicaksono, "Systematic literature review of industry 4.0 maturity model for manufacturing and logistics sectors," *Procedia Manuf.*, vol. 52, no. 2019, pp. 337–343, 2020, doi: 10.1016/j.promfg.2020.11.056.

[4] S. Mittal, M. A. Khan, J. K. Purohit, K. Menon, D. Romero, and T. Wuest, "A smart manufacturing adoption framework for SMEs," *Int. J. Prod. Res.*, vol. 58, no. 5, pp. 1555–1573, 2020, doi: 10.1080/00207543.2019.1661540.

[5] J. Pastorino, "Estudio de digitalización en Argentina," 2018.

[6] M. Rapetti, "Travesía 4.0: Hacia la Transformación Industrial Argentina," 2019.

[7] R. Anderl and J. Fleischer, "Guideline Industrie 4.0," *VDMA Verlag*, p. 32, 2015, [Online]. Available: industrie40.vdma.org.

[8] S. S. Geissbauer R, Vedso J, "Industry 4.0: Building the digital enterprise." Retrieved from PwC Website, 2016.

[9] Allen-Bradley, "The Connected Enterprise Maturity Model," *Ind. Conectada 4.0*, pp. 1–12, 2014, [Online]. Available: http://www.rockwellautomation.com/rockwellautomation/innovation/connected-enterprise/maturity-model.page?

[10] A. Schumacher, S. Erol, and W. Sihn, "A Maturity Model for Assessing Industry 4.0 Readiness and Maturity of Manufacturing Enterprises," *Procedia CIRP*, vol. 52, pp. 161–166, 2016, doi: 10.1016/j.procir.2016.07.040.

[11] J. Lee, S. Jun, T. W. Chang, and J. Park, "A smartness assessment framework for smart factories using analytic network process," *Sustain.*, vol. 9, no. 5, pp. 1–15, 2017, doi: 10.3390/su9050794.

[12] G. Schuh, R. Anderl, R. Dumitrescu, A. Krüger, and M. Ten Hompel, "Using the Industrie 4.0 Maturity Index in Industry - ACATECH," 2020.

[13] A. Hassoun *et al.*, "Food processing 4.0: Current and future developments spurred by the fourth industrial revolution," *Food Control*, vol. 145, no. June 2022, p. 109507, 2022, doi: 10.1016/j.foodcont.2022.109507.

[14] S. Konur, Y. Lan, D. Thakker, G. Morkyani, N. Polovina, and J. Sharp, "Towards design and implementation of Industry 4.0 for food manufacturing," *Neural Comput. Appl.*, vol. 0123456789, 2021, doi: 10.1007/s00521-021-05726-z.

Biography

Lourdes Perea Muñoz (*1981) is an associate professor and researcher at the Engineering Faculty in Austral University, Argentina. Dra. Ing. Perea Muñoz is co-founder of the Centre for Industry 4.0 at Austral University where she has coordinated research and outreach activities since 2020. She has lead the Digital Transformation Program for SMEs 4.0 carried out together with the National Government in 2019.

Marcel Hagemann (*1991) is Senior Consultant and responsible for LatAm at the Industrie 4.0 Maturity Center, Germany. He has led more than 25 Industry 4.0 maturity diagnosis and roadmap development projects at international level in different industries. He holds a Master's degree in Mechanical Engineering and Business Administration from RWTH Aachen University in Germany.

Lucila Palandella (*1982) Lucila Palandella is a member of the "Centre for Industry 4.0" of the Austral University; focused in investigation activities and transfer projects. She is also a specialist consultant in IT Project Management.

María Paz Cagliari Loyola (*1998**)** is a recent Industrial Engineering graduate and works at the Center for Industry 4.0 since April of 2022. She is also a graduate assistant in the subjects of Supply Chain, Operative Investigation and Operations at Austral University. Before that, she was an intern in General Motors.

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Design Principles For The Organization Of Sales Of Smart Product Service Systems

Günther Schuh[1], Wolfgang Boos[1], Lennard Holst[1], Benedikt Moser[1]
[1]*Institute for Industrial Management (FIR) at RWTH Aachen University, Aachen, Germany*

Abstract

Industrial companies are moving from a product driven to a solution driven business by offering smart product service systems (Smart PSS). In addition to an existing portfolio of physical goods and technical services, companies develop new digital services and combine all three offerings to an integrated solution business. While the development of new digital offerings does not pose any major challenges for companies and is rather well researched, the successful sale of Smart PSS does. Due to changing customer requirements and value propositions of a solution, the sale of Smart PSS requires new design principles for the sales organization compared to the simple sale of physical goods or technical services. While there are already many publications on the topic of industrial sales in research, the description of Smart PSS in particular represents a new field of research. The combination of both topics is therefore not only interesting from a theoretical point of view, but also has a high practical relevance and impact for industrial companies.

This paper therefore describes on the one hand, which characteristics can be used to derive typical customer requirements and on the other hand, which effects these requirements have on the sales organization. The design principles give recommendations for the organizational structure, the resources, the information systems and the culture of the company depending on the addressed customer type. In order to identify and describe both the customer requirements and the design principles, two morphological frameworks were developed based on a literature research and semi-structured interviews with industrial companies. The paper gives an outlook on the different characteristics of the design recommendations and describes first best practices for the successful transformation of the sales organization.

Keywords

Smart Product Service Systems; Smart Servitization; Design Principles; Sales Management; Sales Organization; Morphological Framework

1. Introduction

The transformation of companies from product to solution providers and the introduction of digital technologies play a major role. Digital services such as machine monitoring or remote services not only offer companies the opportunity to distinguish. This development challenges companies to exploit the opportunities for long-term competitive advantages [1]. To avoid becoming the subcontractor of a new type of system integrator, companies must leverage their expertise and advantages from the product and service business to smart product service systems (Smart PSS) [2]. Studies show that 80% of the top performing companies offer a combination of products, traditional services and digital services and are thus successful, while only 30% of the followers do so [3]. Smart PSS combine physical products, traditional services and

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digital services to meet individual customer needs [4][5][6]. The focus is always on the physical product, which is supplemented by additional services. Smart PSS are "smart" because they carry characteristics of digital technologies that make products intelligent, increase the capabilities and value of physical components and optimize the flow of information between customer and provider [7][8]. However, the expected added value potentials have not yet been generated [9]. A study by an association of German mechanical engineering companies with around 530 companies found that the challenge lies less in technical development than in the strategic organization of the sales of digital services [1]. Likewise, *Leoni and Chirumalla's* findings show that the transition to becoming a provider of digital services not only involves technical development and data collection, but also requires new qualifications, processes, organizational structures, and partnerships [10]. *Belz and Lee* describe the need to create appropriate organizational conditions in terms of responsibilities, processes, and qualifications for the emerging broadening of sales [11][12]. There appear to be contradictions between the requirements from the sales of Smart PSS and the current organizational design in sales. Research contributions on Smart PSS still do not adequately address sales organizations. There is a lack of a holistic view of the design of the sales organization Smart PSS depending on the customer type. The purpose of this paper is to contribute to this research gap and to derive design recommendations for companies with which they can meet the challenges.

2. Research Background

2.1 Sales Organization

As a functional organizational unit, sales is part of the operational value chain in companies [13]. Its task is to sell products and services with the aim of satisfying the needs of customers [14][15]. According to the marketing mix, sales represents the fourth component for achieving marketing plans, in addition to product, price and communication policy [16]. *Belz et al*. point out that when selling complex services to customers with high demands, marketing is part of sales and not vice versa [19]. In sales between companies, a distinction can be made between different sales channels. In direct distribution, services are sold directly to a customer by the supplier, while in indirect distribution, the service is sold to an economically and legally independent distribution company, which then sells it to the customer [20]. In the context of this paper, the focus is limited to direct sales, since other sales channels result in extended requirements for the sales organization and industrial companies are characterized by direct sales due to their product complexity [21]. B2B sales is characterized by four features [18]. First, in contrast to B2C, offerings are not consumed in B2B, but further processed and/or invested to generate new offerings. Secondly, the demand for the supplier's offerings is derived from the demand for offerings from his customer. Therefore, this is referred to as derived demand. The complexity of the offering and the decision-making process leads to several people from different departments being involved in the purchasing process on both the customer and supplier side. Finally, the degree of formalization of demand and processes is linked to requirements and guidelines for the provision of services.

2.2 Smart Product Service Systems

The term Smart Product Service Systems generally describes a bundle of offerings consisting of a combination of partial offerings of products, services and digital services for customer-oriented problem solving [20]. In the scientific literature, there are other approaches to define product service systems that have this basic idea in common [21][22]. Thus, product service systems are also characterized by their modularity, from which customer-specific offerings can be developed. For the customer, the added value of Smart PSS compared with the purchase of individual partial services lies in the integration of the components. Providers of Smart PSS effectively different from competition while simultaneously increasing the customer's willingness to pay [20]. A definition by *Chowdhury et al*. is used in this paper: Smart PSS can be defined in terms of the combinations and interactions between smart technologies, physical products, digital and non-digital services, and digital business models [8]. An overview of definitions of the terminology mentioned in this subsection is also provided by *Liu et al*. [23]. The strategic transformation of a company from the sale of physical products to the sale of PSS is described as servitization or smart servitization [24][25].

3. Methodology

The derivation of design principles for the organization of sales of smart product service systems follows a five-step approach as shown in fig. 1 based on the procedure of *Welter* [32] to derive consistent types and design recommendations which was also used by *Ansorge* [29] and *Kolz* [34].

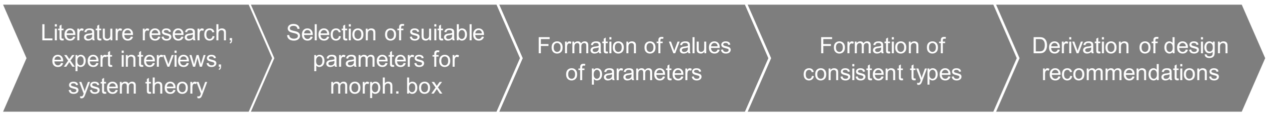

Figure 1: Procedure to derive a framework for the organization of sales of smart product service systems

First, existing frameworks to describe sales organizations of smart product service systems of eight authors (e.g. *Binckebanck* [26], *Belz a. Weibel* [27] *Storbacka et al.* [28]) were analyzed. The authors define varying segments, which in their opinion represent the structure of a sales organization. Based on this literature research, an initial system based on system theory and model building was created that represents the relevant scope of the interaction system between supplier and customer [29][30]. To further deepen the insights gained from the literature and to expand them with insights relevant to practice, semi structured expert interviews were conducted with managers from industrial companies [31]. Based on the interviews and the literature reviewed, two morphological boxes were developed. These describe on the one hand the customer side as a relevant external factor for sales and on the other hand the organization of sales itself. The morphological boxes each consist of characteristic features and their characteristics and are described in detail in the following chapter. Based on the morphological boxes, different consistent types are subsequently formed using the Fit-concept and recommendations for practice developed on their basis.

4. Results

4.1 System Theoretical Reference Framework

The aim of the systems theory study is to identify and elaborate elements and their relationships for organizing the distribution of integrated digital service systems. Following the structure of the regulatory framework for the management of industrial services, the three sub-areas of corporate structure, processes and development form the top level [20] (s. Fig. 2).

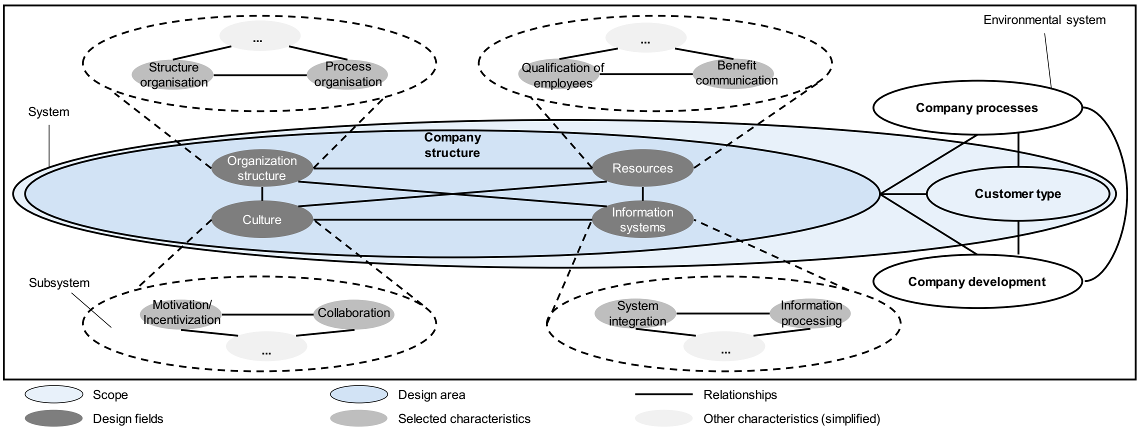

Figure 2: Graphical representation of the system-theoretical reference frame

These three systems are influenced by the customer type system, which describes the customer side from the supply-demand relationship between supplier and customer. That is the customer type has influence on the organization of the other systems and stands therefore in relationship to these. In the area of consideration of the paper lies the company structure, the customer type and the relationship between these two systems. However, the focus is on the supplier side, so although the customer types are in the scope of consideration because they must be considered in the design of the sales organization, the customer side and its design are not considered in detail. The design area as a subset is thus limited to the corporate structure, which must be set up appropriately for the customer type. Both sides of the interaction model are presented and described in more detail in the following chapters via two individual morphologies.

4.2 Morphological framework and consistent types of customer requirements

Based on the literature review and expert interviews and the customer characteristics described therein, this chapter presents the customer morphology and the consistent types (s. Fig. 3).

Components of the performance system	① Physical product	② Phys. product + services	③④ Phys. product + service + dig. services	
Service strategy	① Make (own contribution)		②③④ Buy (external reference)	
Cooperation intensity	① Low	② Partial	③ Distinct	④ Completely
Individualization of services	① Comb. of standardized services	②③ Individual customer-specific partial services	④ Completely customized service system	
Digital affinity	① Skeptical	②③ Interested	④ Convinced	
Demand for digital services	①②③ Push demand		④ Pull demand	
Revenue model for digital services	①② Free Add-on	③ Single transaction	④ Recurring transaction	
Customer review	①② Not a key customer		③④ Key customer (Key Account)	

① Sceptical product customer ② Interested product customer ③ Interested digital customer ④ Convinced digital customer

Figure 3: Morphology and consistent types of customer characteristics

The *components of the product service system* describe the customer's interest in and willingness to purchase individual partial services. Partial services can be physical products, traditional services, and digital services. The components of the service system also depend on the *service strategy* pursued by the customer. In particular, the question of in-house service or external procurement must be clarified. The characteristic of *collaboration intensity* that is willing to pay indicates the form of collaboration for which a customer is willing to pay. A company is only successful if there is a fit between collaboration intensity and willingness to pay [33]. *Individualization of services* describes the extent to which the customer demands a service system consisting of highly standardized or specific, customer-specific partial services [34]. The *digital affinity* of the customer and the decision-makers plays an important role in the acquisition of digital subservices. According to Gartner, this describes "a set of beliefs, mindsets, and behaviours that help employees achieve faster and more valuable results from digital initiatives" and is strongly influenced by corporate culture [35]. *Demand for digital services* is used to describe the difference between customers with push and pull demand, following the push and pull method from customer acquisition. The *revenue model for digital services* describes the price mechanism that customers are willing to pay when purchasing digital services, depending on their willingness to pay [34]. *Customer review and categorization* is applied in various forms to identify key customers. These key customers, also known as key accounts, are indispensable to the company because of their revenue, their customer value, their reference effect, their future potential, their function as a development customer, or other quantitative and qualitative factors [35].

Based of the morphological framework four different consistent types of customer requirements were derived with the characteristics mentioned in Fig. 3. The first type of customer is the sceptical product customer. His PSS consists only of physical products. Both classic services and digital services are of no particular interest to him. Compared to the first, the service system of the second customer type is expanded to include classic services for maintenance, repair, training and financing. This interest is closely linked to the service strategy for external procurement of such services. The distinguishing feature of the third customer type is that digital services are now part of the PSS. Like the second customer type, this customer uses external procurement for classic services and digital services. This means that components such as remote monitoring or smart factory solutions are also part of the external service strategy. The fourth customer type also describes a customer who purchases a service system consisting of all three components. The service strategy is also focused on the external procurement of classic services and digital services, so that the customer largely dispenses with independent maintenance and the development of its own digital solutions. Instead, it relies on close cooperation with the provider not only to obtain all partial services, but also to achieve the most comprehensive integration possible. This integration refers both to the integration of the Smart PSS and to the integration into its value chain.

4.3 Morphological framework and consistent types of sales organization

The other side of the interaction model represents the corporate structure of the offering company and is described in the following morphology (s. Fig. 4). The system of the company structure divides thereby into the four subsystems organizational structure, resources, information systems and culture. The *organizational structure* serves as the structuring of a company into organizational units and responsibilities. Organizational units describe the grouping and assignment of (partial) tasks to human task bearers. The *process organization*, on the other hand, describes the goal-oriented planning of work and information processes [36]. Sales in industrial companies is a "*people business*". Sales employees are the link between the company and the customer and play a decisive role, particularly in the sale of smart product service systems. Therefore, the *qualification of employees* in the sales organization is an important aspect [37]. A service is only successful in the long term if the customer has a perceivable benefit. Therefore, *benefit communication* is an important factor in the distribution of service systems [38]. For sales, the *integration of information systems* is very significant to have a holistic information base available in real time in fluctuating markets with dynamic customer requirements [39]. In the sales of product service systems and smart product service

Org. structure	Organizational structure	① Product-focused	② Service-integrated	③ Completely separated	④ Moderated	⑤⑥ Fully integrated
	Process organization	⑤ Free workflow	①②③ Sequenced workflow	④⑥ Flex. reconfiguration of existing processes		
Resources	Qualification of employees	① Technical expertise	② Expertise in processes	③ Expertise in customer business	④⑤ Expertise in solution selling ⑥	
	Benefit communication	① Product & technology oriented	②③ Performance-oriented	④⑤⑥ Customer results-oriented		
Informat. systems	System integration	① Passive Customer Data Base	②③ Active Customer Data Base	④⑤⑥ Integrated Customer Data Platform		
	Information Processing	① Descriptive	②③ Predictive	④⑤⑥ Prescriptive		
Culture	Motivation/ Incentivisation	Laissez-Faire Leadership	①③ Transactional leadership	④⑤⑥ Transformational leadership		
	Collaboration	⑤ Ad-hoc collaboration	①③ Trying out collaboration	② Controlled collaboration	④⑥ Optimizing collaboration	

Real types: ① Typical product provider ② Typical service provider ③ Separated partial service provider

Ideal types: ④ Orchestrating solution provider ⑤ Independent solution provider ⑥ Integrated solution provider

Figure 4: Morphology and consistent types of the supplier side as a framework for the organization of the sales

systems, in particular, numerous disciplines and experts are involved who must provide their input for the development of the system at the appropriate time [40]. In many companies, systematic *information processing* is still poorly developed compared to information collection. However, the systematic evaluation of customer information offers the opportunity to identify buying habits, churn intentions or potentials by bundling products [39]. In addition to the organizational structure, an informal organization exists in every company and can be influenced by the management culture. This is because it addresses values, norms and the way of working together, so that there is a great influence on the corporate culture [41]. In this context, the *motivation and incentivisation* describe the behavioural control of employees, which is created by the leadership behaviour and the personal appearance of the superior [42]. Another important aspect of the informal structure that shapes the culture is *collaboration*. Collaboration is understood as the working together of individuals and groups on a common project or a task that can only be solved together to achieve a defined goal. Collaboration is particularly necessary for cross-functional work or for new subject areas. This achieves results that the individuals could not have achieved on their own. It is an integral part of a culture that promotes innovation [43].

When considering the types of sales organization, a distinction is made between real and ideal types. Real types represent reality and can be determined empirically. Ideal types are created by abstracting phenomena from reality and are mental models. The first three types represent descriptive real types that are or were common in this form in companies. The last three types, on the other hand, are to be regarded as ideal-typical target images for the sale of integrated digital service systems, whose implementation and suitable design recommendations are shown [44]. The first type of sales organization is based on a product-focused organizational structure. As the name suggests, the focus of the PSS is on the classic product area, which has characterized many machine manufacturers over the years and in which they have a great deal of expertise. Compared to the first type, the organizational structure is service-integrated, so that the digital business is in the traditional customer service. In comparison to the two types presented above, the digital business is represented as a separate unit with positions in the regional structure. This means that there are responsible salespeople for all three business units. However, they offer their services separately from one another, as integration is given little attention and there is no overarching customer-oriented link for integration between the business units and the customer. The orchestrating solution provider shows a first ideal-typical design of the sales organization. The basic idea is based on a customer-oriented process organization with a moderator as process owner. The moderator forms the front end to the customer and integrates the individual business units in the back end in a needs-oriented and targeted manner, so that the distance between the units is closed by the moderator [3][44]. The fifth type identified is based on the idea of a project organization that can serve as an efficient sales organization for companies or regions in which the development and establishment of permanent processes to integrate all business units would be too costly and the hierarchies are flat. This is especially true for smaller companies. Due to the uniqueness of the projects, a free workflow is offered. The sixth type makes sense if the teams are not only formed for one-off, time-limited projects, but the team organization is used permanently and as the decisive structural organization. This is particularly suitable for complex integration projects with strong customer involvement and third-party participation. In order to efficiently manage and implement such a team organization in the long term, basic processes must be established [36].

4.4 Fit between customer types and types of sales organization and design principles

Now that the previous two chapters have identified and described four customer types and six types for sales organization, the two sides are jointly analyzed with the help of the fit concept. For this purpose, a distinction is made between the three degrees of effectiveness - beneficial (+), obstructive (-) and neutral (o) - to describe the fit between the individual types. The result of this analysis can be seen in Figure 5.The figure shows that only the three ideal types can fulfil the requirements of all four customer types in a beneficial or at least neutral manner, while the existing real types exclude the digitally convinced customer. The focus of the design principles in this paper is therefore on showing how companies can succeed in developing in the direction of these ideal types. Many companies are at the beginning of their transformation. They are product providers with a functional and/or divisional organizational structure.

Fit between customer types and types of sales organization			Types of customer characteristics			
			Sceptical product customer	Interested product customer	Interested digital customer	Convinced digital customer
Types of sales organization	Real types	Typical product provider	+	o	-	-
		Typical service provider	o	+	o	-
		Separated partial service provider	o	o	+	-
	Ideal types	Orchestrating solution provider	o	o	+	+
		Independent solution provider	o	o	o	+
		Integrated solution provider	o	o	o	+

Figure 5: Fit between customer types and types of sales organization

Therefore, the existing organization must be broken up in this first phase. Employees must be made aware of the need for change so that they are convinced to participate. Existing processes and structures must be discarded and questioned. A clear sales strategy and target picture must be presented so that the direction of development and the required steps become clear. Customer segments and priorities for the new strategy must be defined. It is important to align sales with the corporate strategy and to involve the sales staff in the implementation. The intermediate phase is the most important stage for building new structures, processes and capabilities for a new shared vision. In addition to reducing hierarchies and shifting responsibility to employees, this can be done by setting up a separate solution selling unit that is responsible for selling integrated digital service systems independently of the existing organization [45]. It is not subject to the organizational restrictions and initially develops solutions with a limited number of key customers. The type *independent solution provider* is suitable for describing this separate solution selling unit. In the final step, the experiences and best practices from the intermediate phase are used to carry the new culture into the company and solidify it. This is done by deploying the employees from the previously autonomous unit as transformational leaders in the company as a whole. The resources are gradually developed throughout the company through further qualification. The processes developed and tested on a small scale by the independent unit can now serve as a starting point for processes that can be flexibly reconfigured. The best practices and information exchange help the employees of the existing organization to change. The organizational structure can either evolve into a matrix process organization, so that the traditional functional and divisional structure is structured more strongly around the customer on the basis of processes, or it can be designed holistically as a team organization, using the separate solution selling unit as an example. In the advanced phase, this corresponds to the ideal types of *orchestrating and integrating solution providers*. The organizational structure thus depends on the choice between these two ideal types. The types are suitable in different cases depending on the initial situation and company structure.

5. Discussion and conclusion

In this paper, design principles for the organization of sales of Smart PSS have been presented to fill the gap that currently exists in both research and practical applications. For this purpose, the interaction model was first shown in a systemic representation based on a literature review and expert interviews. Based on this, the two sides of the interaction model between customers and providers were each described using a morphology with eight characteristics.

The next step in the research process is now the formation of exemplary types on both the customer and supplier side. Based on these types, it is important to see which types from both sides harmonize with each other and thus promise the greatest possible success in the sale of smart product service systems. It should be noted, however, that the customer side is to be regarded as an external factor and is difficult or impossible to influence. Accordingly, the customer side sets the requirements to which the sales organization on the supplier side must respond. The complexity of this interaction increases with the complexity of the smart product service system offered, since many features and value propositions must be served. This paper can only lay the foundation for approaching both the requirements of the customer side and the response of the provider side in a structured manner and deriving corresponding design proposals for the organization of sales of smart product service systems. The need for this arises not only from the existing gap in the scientific literature, but from the need for practical solutions from industrial companies.

References

[1] Kowalkowski, C.; Sörhammar, D.; Tronvoll, B.: Digital Servitization: How Manufacturing Firms Can Enhance Resource Integration and Drive Ecosystem Transformation. In: The Palgrave Handbook of Servitization. Publ.: M. Kohtamäki; T. Baines; R. Rabetino; A. Z. Bigdeli; C. Kowalkowski; R. Oliva; V. Parida. Springer International Publishing, Cham 2021, p. 27-39.

[2] Sklyar, A.; Kowalkowski, C.; Tronvoll, B.; Sörhammar, D.: Organizing for digital servitization: A service ecosystem perspective. In: Journal of Business Re-search (2019) 104, p. 450-460.

[3] Leiting, T.; Rix, C.: KVD-Service-Studie 2020. Vertrieb von Services und Smart Services. Publ.: G. Schuh; J. Frank; M. Schröder; V. Stich, Dorsten/Aachen 2019.

[4] Lerch, C.; Gotsch, M.: Digitalized Product-Service Systems in Manufacturing Firms: A Case Study Analysis. In: Research-Technology Management 58 (2015) 5, p. 45-52.

[5] Coba, C. M.; Boucher, X.; Gonzalez-Feliu, J.; Vuillaume, F.; Gay, A.: Towards a risk-oriented Smart PSS Engineering framework. In: Procedia CIRP (2020) 93, p. 753-758.

[6] Stich, V.; Hicking, J.: Smartifizierung von Maschinenbauprodukten mittels einer ziel-orientierten Methode. In: HMD Praxis der Wirtschaftsinformatik 56 (2019) 3, p. 542-556.

[7] Schuh, G.; Zeller, V.; Hicking, J.; Bernardy, A.: Introducing a methodology for smartification of products in manufacturing industry. In: Procedia CIRP 2019 (2019) 81, p. 228-233.

[8] Chowdhury, S.; Haftor, D.; Pashkevich, N.: Smart Product-Service Systems (Smart PSS) in Industrial Firms: A Literature Review. In: Procedia CIRP (2018) 73, p. 26-31.

[9] Schuh, G.; Boshof, J.; Dölle, C.; Kelzenberg, C. M. B.; Tittel, J.: Subskriptionsmodelle im Maschinen- und Anlagenbau. In: Internet of Production-Turning Data into Value. Statusberichte aus der Produktionstechnik 2020. Publ.: T. Bergs; C. Brecher; R. H. Schmitt; G. Schuh. Fraunhofer-Gesellschaft 2020, p. 282-301.

[10] Leoni, L.; Chirumalla, K.: Exploring Dynamic Capabilities to Facilitate a Smoother Transition from Servitization to Digital Servitization: A Theoretical Framework. In: The Palgrave Handbook of Servitization. Publ.: M. Kohtamäki; T. Baines; R. Rabetino; A. Z. Bigdeli; C. Kowalkowski; R. Oliva; V. Parida. Springer International Publishing, Cham 2021, p. 165-180.

[11] Belz, C.: Verbreiterung der Aufgabe des Verkaufs verunsichert Kunden. In: Sales Excellence 23 (2014) 1, p. 18-25.

[12] Belz, C.; Lee, Y.-C.: Cross-Selling überwindet Distanz. In: Führung von Vertriebsorganisationen. Publ.: L. Binckebanck; A.-K. Hölter; A. Tiffert. Edition Sales Excellence. Springer Fachmedien Wiesbaden, Wiesbaden 2020, p. 125-145.

[13] Notté, K.: Wissensmanagement im Vertrieb. Springer Fachmedien Wiesbaden, Wiesbaden 2013.

[14] Homburg, C.; Wieseke, J.; Bornemann, T.: Implementing the Marketing Concept at the Employee-Customer Interface: The Role of Customer Need Knowledge. In: Journal of Marketing 73 (2009) 4, p. 64-81.

[15] Hesse, J.; Huckemann, M.: Erfolgsfaktoren des Vertriebs. In: Exzellenz in Dienstleistung und Vertrieb. Konzeptionelle Grundlagen und empirische Ergebnisse. Publ.: D. Ahlert; H. Evanschitzky; J. Hesse. Gabler Verlag, Wiesbaden 2002, p. 61-88.

[16] Homburg, C.: Marketingmanagement. Strategie-Instrumente-Umsetzung-Unternehmensführung. 7., überarbeitete und erweiterte Auflage. Springer Gabler, Wiesbaden 2020.

[17] Belz, C.; Lee, Y.-C.; Huckemann, M.; Weibel, M.: Sales Excellence Development – Sparten- und länderübergreifende Verkaufsentwicklung. In: Führung von Vertriebsorganisationen. Publ.: L. Binckebanck; A.-K. Hölter; A. Tiffert. Edition Sales Excellence. Springer Fachmedien Wiesbaden, Wiesbaden 2020, p. 337 – 354

[18] Kleinaltenkamp, M.; Saab, S.: Technischer Vertrieb. Eine praxisorientierte Einführung in das Business-to-Business-Marketing. 2., überarb. u. erw. Auflage 2021. Springer Fachmedien Wiesbaden GmbH; Springer Gabler, Wiesbaden 2021.

[19] Ulaga, W.; Reinartz, W. J.: Hybrid Offerings: How Manufacturing Firms Combine Goods and Services Successfully. In: Journal of Marketing 75 (2011) 6, p. 5-23.

[20] Schuh, G.; Gudergan, G.; Senderek, R.; Wagner, D.: Leistungssysteme. In: Management industrieller Dienstleistungen. Publ.: G. Schuh; G. Gudergan; A. Kampker. Springer Berlin Heidelberg, Berlin, Heidelberg 2016, p. 105 – 139

[21] Baines, T. S.; Lightfoot, H. W.; Evans, S.; Neely, A.; Greenough, R.; Peppard, J.; Roy, R.; Shehab, E.; Braganza, A.; Tiwari, A.; Alcock, J. R.; Angus, J. P.; Bastl, M.; Cousens, A.; Irving, P.; Johnson, M.; Kingston, J.; Lockett, H.; Martinez, V.; Michele, P.; Tranfield, D.; Walton, I. M.; Wilson, H.: State-of-the-art in product-service systems. In: Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 221 (2007) 10, p. 1543-1552.

[22] Valencia, A.; Mugge, R.; Schoormans, J.; Schifferstein, R.: The Design of Smart Product-Service Systems (PSSs): An Exploration of Design Characteristics. In: International Journal of Design (2015) 9, S. 13-28.

[23] Liu, L.; Song, W.; Han, W.: How sustainable is smart PSS? An integrated evaluation approach based on rough BWM and TODIM. In: Advanced Engineering Informatics (2020) 43.

[24] Vandermerwe, S.; Rada, J.: Servitization of business: Adding value by adding services. In: European Management Journal 6 (1988) 4, S. 314-324.

[25] Kaňovská, L.; Tomášková, E.: Drivers for Smart Servitization in Manufacturing Companies. In: Agris online Papers in Economics and Informatics 10 (2018) 3, S. 57 – 68.

[26] Binckebanck, L.: Grundlagen zum strategischen Vertriebsmanagement. In: Führung von Vertriebsorganisationen. Publ.: L. Binckebanck; A.-K. Hölter; A. Tiffert. Edition Sales Excellence. Springer Fachmedien Wiesbaden, Wiesbaden 2020b, S. 3 – 34.

[27] Belz, C.; Weibel, M.: Vertriebsdifferenzierung im Industriegütergeschäft. In: Handbuch Business-to-Business-Marketing. Publ.: K. Backhaus; M. Voeth. Springer Fachmedien Wiesbaden, Wiesbaden 2015, S. 437-460.

[28] Storbacka, K.; Polsa, P.; Sääksjärvi, M.: Management Practices in Solution Sales: A Multilevel and Cross-Functional Framework. In: Journal of Personal Selling & Sales Management 31 (2011) 1, S. 35-54.

[29] Ansorge, B.: Ordnungsrahmen für die Positionierung industrieller Dienstleister. 1. Aufl. Apprimus-Verl. Schriftenreihe Rationalisierung; Bd. 129, Aachen 2014.

[30] Haberfellner, R.; Weck, O.; Fricke, E.; Vössner, S.: Systems Thinking. In: Systems engineering. Fundamentals and applications. Publ.: R. Haberfellner; O. L. de Weck; E. Fricke; S. Vössner. Birkhäuser, Cham 2019, S. 3-26.

[31] Bogner, A.; Littig, B.; Menz, W.: Interviews mit Experten. Eine praxisorientierte Einführung. Springer VS, Wiesbaden 2014.

[32] Welter, M.: Die Forschungsmethode der Typisierung. In: WiSt-Wirtschaftswissenschaftliches Studium 35 (2006) 2, S. 113-116.

[33] Belz, C.: Neue Formen der Zusammenarbeit mit Kunden in der Industrie: Wann lohnt sich eine intensive Zusammenarbeit mit Kunden? In: Business Innovation: Das St. Galler Modell. Publ.: C. P. Hoffmann; S. Lennerts; C. Schmitz; W. Stölzle; F. Uebernickel. Springer Fachmedien Wiesbaden, Wiesbaden 2016, p. 105-121.

[34] Kolz, D.: Komponenten industrieller, datenbasierter Dienstleistungen. 1. Auflage. Apprimus-Verl. Schriftenreihe Rationalisierung; Bd. 167, Aachen 2019.

[35] Schuh, G.; Hoffart, C.; Gudergan, G.; Siegers, J.: Kundensysteme. In: Management industrieller Dienstleistungen. Publ.: G. Schuh; G. Gudergan; A. Kampker. Springer Berlin Heidelberg, Berlin, Heidelberg 2016, p. 141-168.

[36] Paul, J.: Praxisorientierte Einführung in die Allgemeine Betriebswirtschaftslehre. Mit Beispielen und Fallstudien. 3., aktualisierte Auflage. Springer Fachmedien Wiesbaden, Wiesbaden 2015.

[37] Belz, C.: Mit Sales Development den Verkauf professionalisieren. In: Sales Management Review 26 (2017) 1, p. 74-82.

[38] Salonen, A.; Terho, H.: Salesforce Transformation to Solution Selling. In: The Palgrave Handbook of Servitization. Publ.: M. Kohtamäki; T. Baines; R. Rabetino; A. Z. Bigdeli; C. Kowalkowski; R. Oliva; V. Parida. Springer International Publishing, Cham 2021, p. 343-354.

[39] Pufahl, M.: Vertriebscontrolling. So steuern Sie Absatz, Umsatz und Gewinn. 6., überarbeitete Auflage. Springer Fachmedien Wiesbaden. Edition Sales Excellence, Wiesbaden 2019.

[40] West, S.; Zou, W.; Rodel, E.; Stoll, O.: Value Co-creation in Digitally-Enabled Product-Service Systems. In: The Palgrave Handbook of Servitization. Publ.: M. Kohtamäki; T. Baines; R. Rabetino; A. Z. Bigdeli; C. Kowalkowski; R. Oliva; V. Parida. Springer International Publishing, Cham 2021, p. 403-417.

[41] Frank, J.: Reifegradbasierte Gestaltung der Unternehmenskultur am Beispiel der Instandhaltung. 1. Auflage. Schriftenreihe Rationalisierung; Bd. 176 2020.

[42] Haas, A.: Potenziale und Herausforderungen erfolgreicher Vertriebsführung. In: Führung von Vertriebsorganisationen. Publ.: L. Binckebanck; A.-K. Hölter; A. Tiffert. Edition Sales Excellence. Springer Fachmedien Wiesbaden, Wiesbaden 2020, p. 455-470.

[43] Quandt, C. O.; Castilho, M. F.: Relationship between collaboration and innovativeness: a case study in an innovative organisation. In: International Journal of Innovation and Learning 21 (2017) 3, p. 257–257.

[44] Gebauer, H.; Kowalkowski, C.: Customer-focused and service-focused orientation in organizational structures. In: Journal of Business & Industrial Marketing 27 (2012) 7, p. 527-537.

[45] Scheed, B.; Scherer, P.: Organisation – Strategische Organisationsanalyse und -planung. In: Strategisches Vertriebsmanagement. B2B-Vertrieb im digitalen Zeitalter. Publ.: B. Scheed; P. Scherer. Springer Fachmedien Wiesbaden, Wiesbaden 2019a, p. 203-231.

Biography

Günther Schuh holds the Chair of Production Systems at the Machine Tool Laboratory (WZL), is a member of the Board of Directors at the Fraunhofer Institute for Production Technology (IPT), Director of the Institute for Industrial Management (FIR) at the RWTH Aachen University and head of the Production Technology Cluster.

Wolfgang Boos has been head of the Institute for Industrial Management (FIR) at RWTH Aachen University since 2023. Wolfgang Boos studied mechanical engineering with a specialization in production engineering at RWTH Aachen University and is responsible for the WBA Tooling Academy at RWTH Aachen Campus as a managing director.

Lennard Holst has been head of the department Service Management at the Institute for Industrial Management (FIR) at RWTH Aachen University since 2021. Lennard Holst leads several research and industrial projects in the fields of subscription management, digital business model transformation as well as industrial service management.

Benedikt Moser studied industrial engineering at RWTH Aachen University and did his doctoral studies at the Institute for Industrial Management (FIR) at RWTH Aachen University, where he was deputy head of the Service Management department. In the meantime, he has co-founded a start-up in the field of online platforms for industrial spare parts and works there as Head of Vendor Management.

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Potentials and Implementation Strategies For Flexible Battery Cell Production

Achim Kampker[1], Heiner Heimes[1], Benjamin Dorn[1], Henning Clever[1], Artur Scheibe[1]

[1]*Production Engineering of E-Mobility Components (PEM), RWTH Aachen University, Aachen, Germany*

Abstract

The effects of a fossil fuel-based economy are becoming increasingly apparent. The storage and use of renewable energy sources are a key strategy to reduce overall greenhouse gas emissions. In this context, the demand for batteries as a suitable medium for energy storage is increasing rapidly. Lithium-ion batteries pioneered in consumer electronics are nowadays used in ever more applications, with the e-mobility sector being one of the most prominent. From a production perspective, the process chain for manufacturing of such lithium-ion batteries can be divided into three main sections: electrode production, cell assembly and cell finishing. However, actual implementation of the process chain differs substantially, depending on the selected cell format (pouch, cylindric, prismatic) and design, manifesting in cell-specific processes (e.g. stacking vs. winding), supplementary and/or omitted process steps and manufacturing technologies (e.g. pouch foil heat sealing vs. hard case laser welding). Currently there is no strictly preferred cell format, as each format has its advantages and disadvantages, depending on its intended application and system integration. Production of different battery cell types thus is spread across various international – mostly Asian – manufacturers, most of which have large scale mass production lines dedicated to a single specific format. Only a few manufacturers have a portfolio of formats (e.g. round and prismatic) in large quantities. Against this background, the following paper provides an overview of the product variety of lithium-ion batteries available on the market, following up with a discussion of potentials and implementation strategies for flexible battery cell production. First, applications and business areas for lithium-ion batteries are analysed and general flexibility areas regarding the battery cell design are derived. Subsequently, the impacts of the different flexibility areas on the production processes are analysed. In a final step, different implementation strategies and approaches for increased flexibility in battery cell production are elaborated.

Keywords: Battery Cell Production; Production Planning; Flexibility; Implementation Strategies

1. Introduction

The storage and use of renewable energy sources are a key factor in becoming independent of fossil fuels and minimizing greenhouse gas emissions. As a result, the demand for batteries as a suitable medium for energy storage is increasing rapidly. [1] Lithium-ion batteries (LIB) originated in consumer electronics are now being used in more and more domains, currently mostly prominently in various e-mobility applications. Main reasons for their market dominance are their long cycle life, high power density and continuously improving energy density. Considering the constant demand for energy sources for transport and environmental concerns about conventional fuels, the demand for lithium-ion batteries has been rising steadily for years. [2] For this reason, and due to the rapid increase in electrification of the mobility sector, global demand for LIBs is expected to exceed 4 TWh in 2030. [3] New battery concepts and new battery

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chemistries are being researched and developed to support this transformation. However, at the same time the battery industry is facing short product life cycles, a growing number of variants and a wide range of applications leading to a high level of technological and market uncertainty. This poses major challenges not only for the product development of new battery cells but also for their production and manufacturing process. [4] .

Current battery cell production plants are designed to manufacture predefined battery cells with a high level of automation, at highest quality, and with minimal deviations in end product characteristics. Production lines focused on high production volumes are trimmed for maximum efficiency and yield, thus relying on a highly streamlined process flow. Once ramped up, these factories are kept at their optimal operating point with the clear objective on standardizing production runs. Once operations and production are fine-tuned, leading battery cell manufacturers try to maintain the optimum operating window for as long as possible with as few changes necessary and deviations as possible. Form this point of view, flexible production of varying customer-specific battery variants in quickly adjustable quantities poses a major challenge for existing factories. Therefore, this paper assesses prerequisites, potentials and implications of product and process flexibility in the battery cell production context and elaborates on different strategies for practical implementation.

2. Fundamentals

2.1 Flexibility in manufacturing systems

Great volatility in customer behaviour and supply chains as well as a fast-moving market pose a great challenge for companies manufacturing lithium-ion batteries. They are forced to adapt to frequent and rapid changes induced by the changing market environment and growing regulatory pressure. [5]

Organizational forms of manufacturing companies can be divided into different categories as shown in Figure 1. Depending on whether the focus is on a high product variety or on a high production volume, the orientation and production system setup leans either towards flexibility or productivity. While most high-volume production lines are typically designed for dedicated cell formats and variants in order to achieve the required outputs at minimum possible cost, pilot-scale production lines primarily serve R&D activities. In this production environment material testing, process validation and integration as well as scale-up of new technologies and innovations are prioritized.

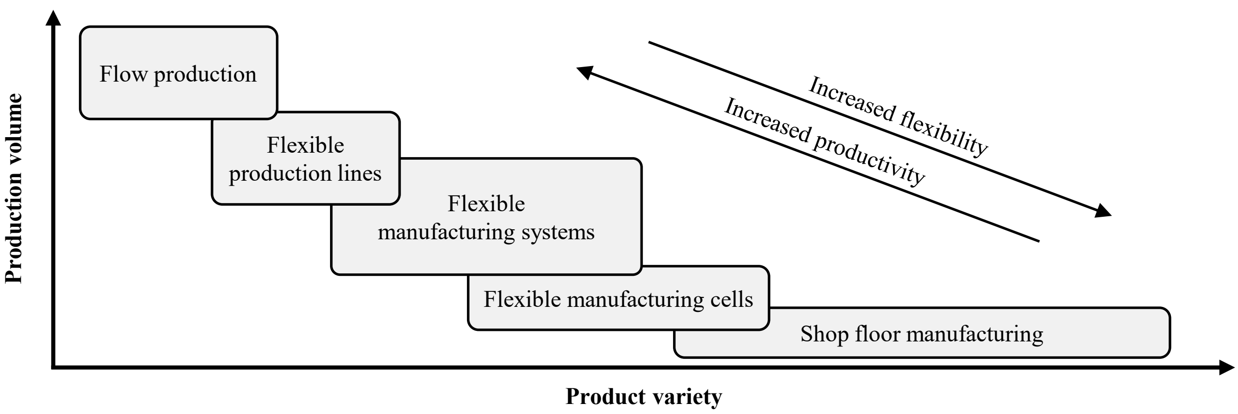

Figure 1: Overview of organizational forms in manufacturing [6]

Product diversity at the cell level is closely related to the diversity of battery-powered applications in the industrial landscape. However, market segments such as electromobility, aerospace, wearables, etc. have inherently different requirements for batteries in terms of performance, lifetime and basic product characteristics such as size and format. In order to redesign a production system into one that bridges the gap between mass production and customised manufacturing, relevant flexibility potentials of the production system need to be well distinguished and addressed accordingly. [4] Following classifications for flexibility in manufacturing are commonly distinguished in scientific literature: [5–9]

- Machine flexibility: Ability to execute the changes needed to produce a given mix of products
- Material flexibility: Ability to handle variations in composition and dimension of parts
- Operation flexibility: Ability to change the sequence of operations and the performing machines
- Volume flexibility: Ability to manufacture economically with different production quantities
- Expansion flexibility: Ability to expand the production apparatus component by component
- Routing flexibility: Ability to change the routes of the parts in case of machine failure
- Process flexibility: Ability produce different parts with different requirements in different ways
- Product flexibility: Ability to perform a changeover to the production of new products

2.2 Current status in lithium-ion battery cell production

Currently, the lithium-ion battery is the most advanced energy storage technology and a key component, specifically in the field of electric mobility. Further developments are intended to improve the performance, cost-effectiveness, environmental friendliness and safety of existing LIB systems. In addition to cell technology, research is also being conducted in the fields of materials technology, process technology and battery cell production.

2.2.1 Structure of lithium-ion batteries

The basic structure of a lithium-ion battery cell consists of two electrodes (anode and cathode) composed of active materials coated on current collectors, a separator, liquid electrolyte and a housing. [10]

The predominant active material for anodes is graphite, because of its low price and reasonable storage capacity of lithium-ions. Silicon is also considered as an upcoming anode material. In theory it has a much larger capacity to store lithium so that the specific electric capacity of the cell can be significantly increased. [11] The cathode can consist of a variety of different materials. Currently most prevalent cathode chemistries are lithium-nickel-manganese-cobalt-oxides (NMC) followed by lithium-iron-phosphate (LFP) and lithium-nickel-cobalt-aluminium-oxides (NCA). [12] The active materials for the electrodes are applied in the form of a slurry on thin metal foils (current collectors). The active material is dried into a porous structure and becomes completely immersed in liquid electrolyte. The electrolyte ensures ionic charge exchange between the electrodes and is composed of conducting salts dissolved in high-purity organic and anhydrous solvents. The microporous separator serves as an insulator between the electrodes, preventing short circuits and allowing the ionic current to pass through at the same time. [13,10]

Depending on the cell design (pouch, prismatic or cylindrical), the anodes and cathodes are stacked or wound into an electrode-separator composite (ESC), with the separator alternating between the anode and cathode. The separate layers of the current collectors are welded together and contacted by tabs. Afterwards the cell stack or roll is placed and enclosed in an impermeable housing (either hardcase or pouch foil). [13]

2.2.2 Process chain in battery cell production

Generally, the production processes for lithium-ion batteries can be divided into three main sections: Electrode production, cell assembly and cell finalization (Figure 2). [14]

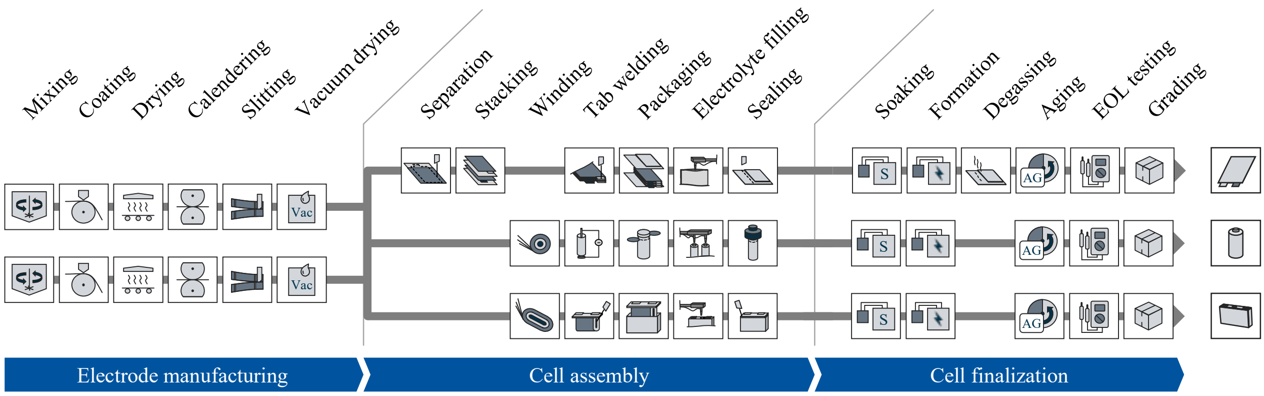

Figure 2: Generic process chain in battery cell production (top-down: pouch, cylindric, prismatic)

Electrode production begins with weighing and mixing the active materials with various additives and solvents to form a slurry. The slurry is then coated onto a thin metal foil in a roll-to-roll process and immediately dried in a convection oven, where the solvent is removed again. The electrodes are then calendered, i.e. pressed for a specific porosity. Depending on the dimensions of the battery cell, the large mother coils are cut into smaller daughter coils. Finally, vacuum drying takes place to remove any residual moisture from the material. Typically, a battery cell production has two separate production lines for anode and cathode to avoid material contamination.

In cell assembly, the electrodes are assembled into a cell. This involves alternately assembling the anode, separator and cathode to form the electrode-separator composite. After that, current collectors are welded and contacted with tabs to form the battery cell's terminals. The electrode-separator-composite is then placed in the housing, which is filled with electrolyte and ultimately sealed hermetically. However, actual implementation of the process chain differs substantially, depending on the selected cell format (pouch, cylindric, prismatic) and design, manifesting in cell-specific processes (e.g. stacking vs. winding), supplementary and/or omitted process steps and manufacturing technologies (e.g. pouch foil heat sealing vs hard case laser welding). Thus, cell-specific assembly lines are mainly being considered for high-volume production in the Gigafactory scale.

In cell finalization, the assembled battery cell is electrochemically activated for the first time. At the beginning, wetting takes place, where it is ensured that the electrolyte is completely and sufficiently distributed within the entire cell. Only then can formation continue, in which the battery cell is charged and discharged under controlled conditions to form the solid electrolyte interface (SEI). During this process, gases are released which have to be extracted from within the cell. Afterwards, the battery cell undergoes an aging phase, where it is monitored and controlled for any anomalies such as for example low capacity retention and performance losses. At the end, the EOL testing and grading of the battery cell is performed based on the performance parameters recorded throughout the cell finalization. [15,14,13]

3. Approach

The main objective of implementation strategies of different flexibility types in production is a demand-driven manufacturing of product variants, while ensuring an optimal capacity utilization with high economic efficiency at the same time. Therefore, a high reactivity and adaptability of the production is required in order to realize an adjustment to different changes in the market. [16] The objective of this paper is to investigate and evaluate the potential of flexibility in battery cell production to enable an increase in customer and market orientation while maintaining economic and demand-driven production of customized lithium-ion batteries. Figure 3 shows the underlying approach for this paper.

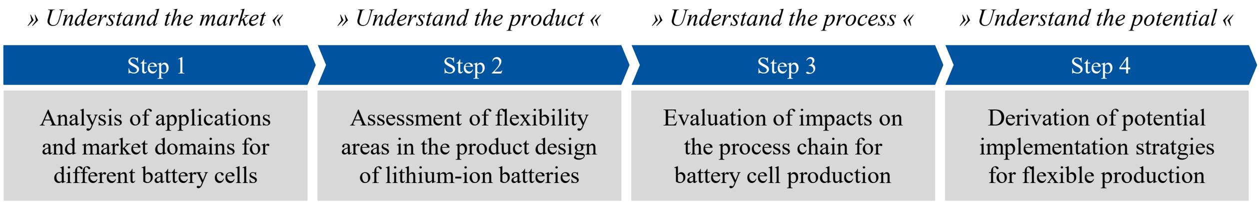

Figure 3: Approach for deriving implementation strategies for a flexible battery cell production

4. Results

While previous approaches [4,17,18] on agile battery cell production have focused primarily on the aspect of functional units for the process steps based on a prototype facility, the following analysis will look in particular at scaled implementation strategies aiming for flexibility in battery cell production within an industrial relevant scale.

4.1 Potential market demand for flexibility in battery cell production

A high number of applications and business opportunities for batteries have been established over the last three decades. Figure 4 shows the key findings of a meta-study conducted by PEM, which divides the total battery market into several core domains, outlining their battery demand, market value and anticipated development.

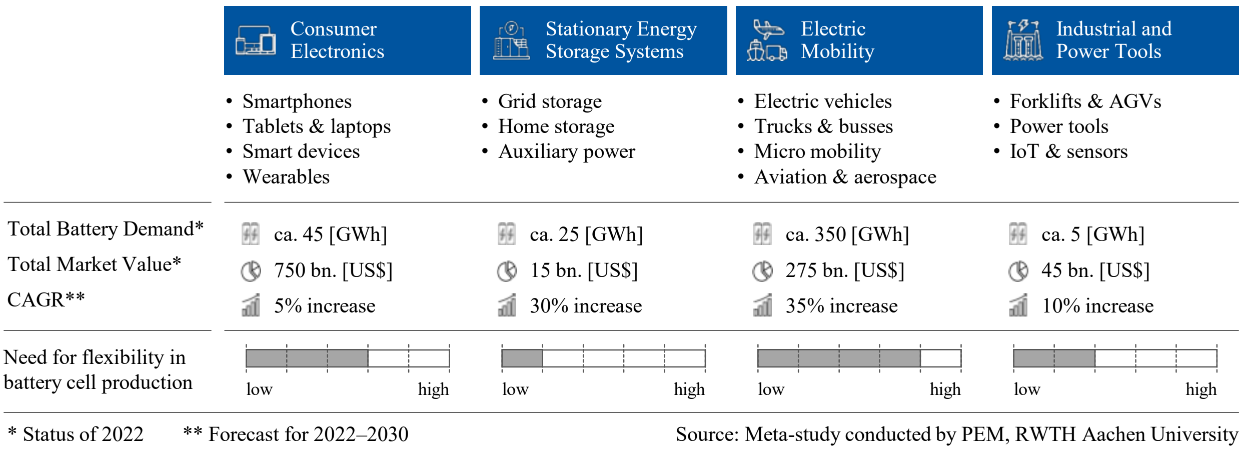

Figure 4: Market overview for established and emerging markets for lithium-ion batteries

A further breakdown of these core domains (consumer electronics, stationary storage, e-mobility, industrial and power tools) reveals several individual segments that are constantly bringing along new innovations. Due to the rapid technological development, various battery powered products such as for example wearables, smart devices and other niche gadgets can be seen adding to the market. Beyond this, a multitude of new and emerging markets are driving the battery industry. Most prominent domains cover electric transport and aviation, which include various forms of electrified transport on paved roads and in the air. Besides, stationary energy storage systems, as well as industrial and power tools for various types of industrial equipment and applications, are growing in total produced quantities. Together, these emerging markets account for a significant share of today's total battery demand, reflected in about 380 GWh of already deployed capacity in 2022.

Applications in the emerging markets (especially in the premium segments) thereby are more likely to show noticeable demand for custom battery solutions and thus flexible battery cell production. Examples include the fast-growing electric aviation market and the market for sports and hyper cars. They are characterized by constraints in space and weight as well as high performance requirements, motivating optimally integrable battery solutions

4.2 Flexibility potentials in the design of lithium-ion batteries

As previously outlined, the rapid development and optimization of battery cell technology in various industries is accompanied by a large number of product variants. These can differ significantly in terms of format, chemistry and other product properties depending on the market and application requirements. A stage-gate process for the generalized development of lithium-ion battery cells is shown in Figure 5.

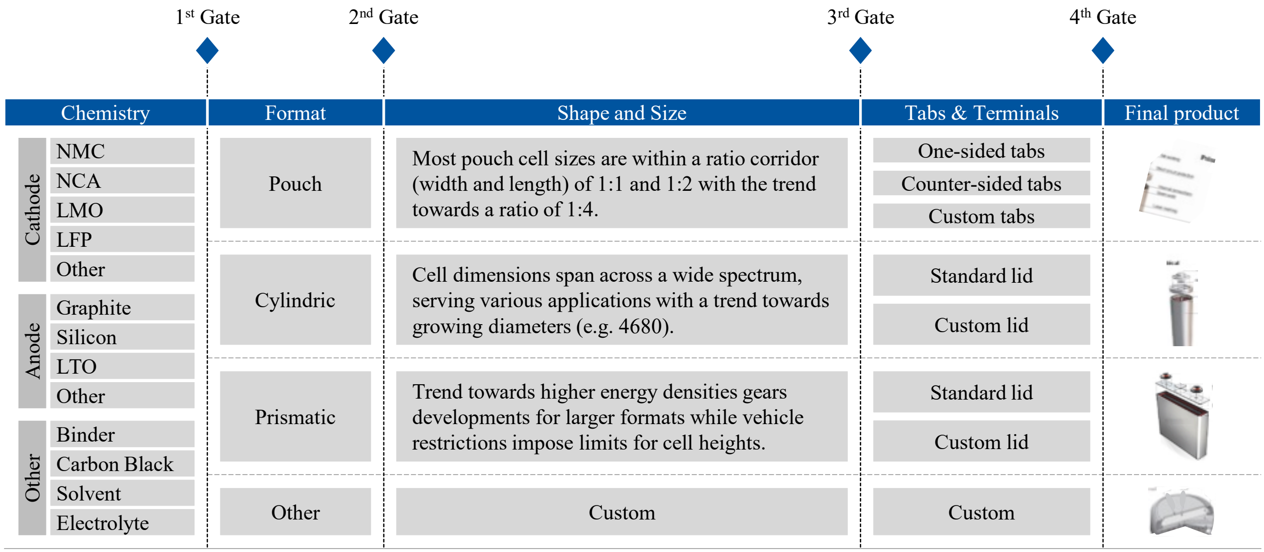

Figure 5: Stage-gate process for the development of different lithium-ion battery cells

In general, these design stages, accounting for a variety of specifications can be summarized and classified as cell chemistry, cell format, shape and size, as well as contacts, with latter referring to tabs and terminals that provide the electrical contacting at the module level. These four aspects are responsible for the majority of different cell variants observable in the grand battery landscape. With the selection of the active materials, the formation of the cell core (electrode-separator composite), and the interfaces for electrical contacts they represent clear distinguishing features of a lithium-ion battery, eventually determining final product properties and performance characteristics. For sake of completeness it should be mentioned, that there are additional cell components, that are subject to only minor changes so that they can be seen as standardized items (e.g. current collector foils, centre pins).

4.3 Flexibility potentials in the process chain of battery cell production

As previously described, the generic process chain for lithium-ion batteries is divided into the three main areas of electrode production, cell assembly and cell finishing, each of which applies to all common cell formats. Figure 6 highlights the process sensitivity within battery cell production regarding the different product changes for lithium-ion batteries.

In direct comparison, electrode production has the highest flexibility with regard to the individual cell formats, as they are all based on a current collector foil coated with active material. Anode and cathode production are therefore largely uniform, apart from process-related differences in coating patterns, widths and thicknesses. Different cell chemistries such as NMC, LFP or NCA can be processed with great flexibility. The effort required to adapt to new product variants is relatively low, as it mostly involves adjustments to the process parameters (e.g. mixing times and speeds) without the need for further changes to the equipment. However, changeovers may be necessary e.g. in case of the slot die for processing rheological significantly different slurry mixtures or applying particularly thin layers.

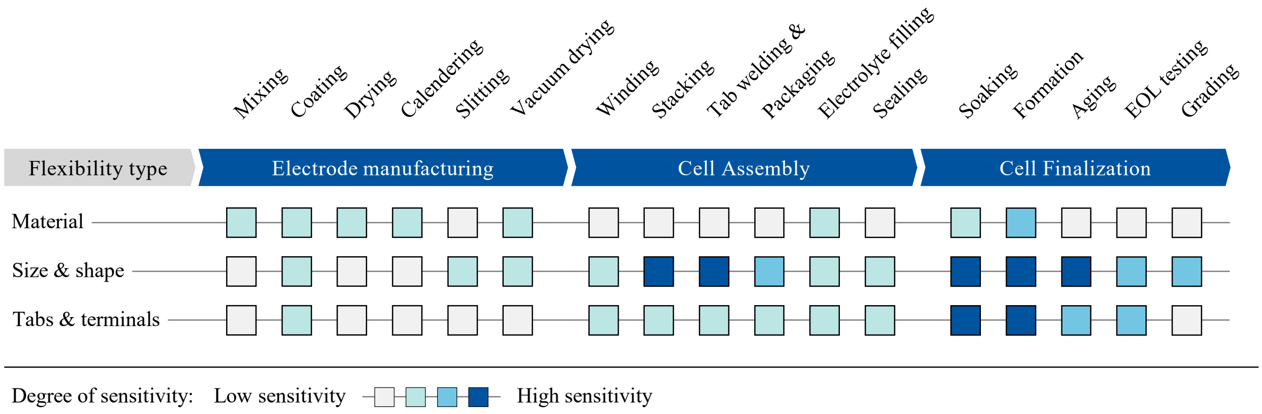

Figure 6: Process sensitivity regarding the different design aspects for lithium-ion batteries

The main implications on the process chain are particularly noticeable in cell assembly. All three cell formats are based on different assembly and production steps, which require different manufacturing technologies, handling processes and quality inspections. As within this section of the cell production, a large number of cell-specific components is assembled, even slight product changes are reflected in severe propagation effects, extending on several downstream process steps. An illustrative example can be given by alternated tab positions for the pouch cell, where not only the cutting and notching processes require tool changes, but also, welding, sealing and the whole set of process accompanying measures such as handling, tool alignment etc. While some minor variations in cell design can be accommodated by the flexibility of current off-the-shelf equipment, limits are quickly reached due to tools, manufacturing technologies and automation specifically adjusted to the produced battery cell.

Cell finalization remains largely similar across all cell formats, whereas only the pouch cell deviates more due to the need for active degassing and subsequent resealing. The equipment used for the electrochemical activation of the battery cell is currently precisely matched to the format of the battery cell. The same applies to the aging process, during which the cells are controlled and monitored in their properties. While the current systems are characterized by a high level of product orientation and specialization, especially with regard to cell contacting the modular setup of formation and aging chambers and the use of intelligent and adjustable carriers or trays indicates existing and further exploitable flexibility potentials.

4.4 Implementation strategies for different types of flexibility

The spectrum of flexibility opportunities between a streamlined, ramped-up battery production line for a specific cell format and a fully flexible battery cell production offering highly customized solutions is vast. Already in early stages of factory and process planning as well as conceptualization of logistics and warehouses this becomes very apparent. In each case different degrees of flexibility can be considered and realized accordingly. However, ensuring flexibility has its price that needs be taken into consideration. Thus, the general question arises as to how flexibility can be addressed so that initial efforts and investments ultimately pay off. The transformation of currently known LIB factories in a way that end-of-line products are variable and able to incorporate customer-specific requirements becomes the grand challenge. To set up a production system in this intersection of process optimization and flexible production, several approaches are feasible. Driven by the market demand, different flexibility areas can be addressed selectively or collectively by prioritizing different aspects of the product flexibility (Figure 7).

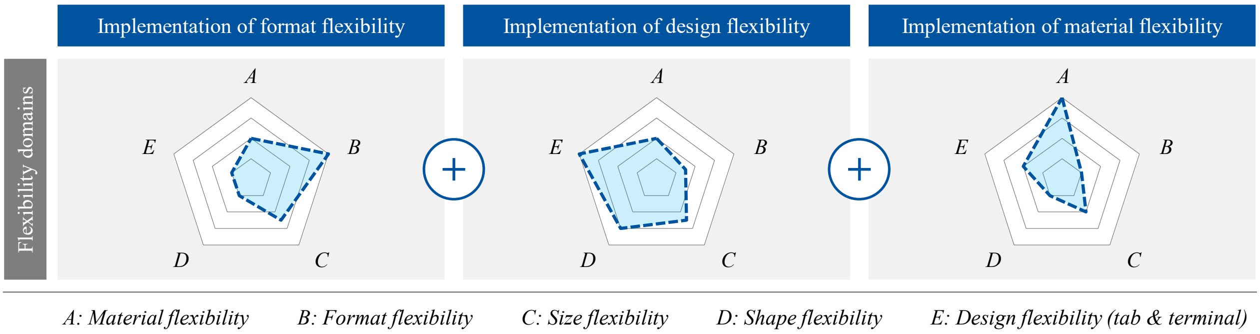

Figure 7: Overview of potential flexibility domains for implementation into battery cell production

A factory designed according to these flexibility areas differs from conventional configurations in several aspects, most notably in an even greater equipment complexity. The desired flexibility thus becomes the challenge of optimal coordination of individual equipment units within the production system, further extended to logistics and personnel, up to the underlying supply chains.

5. Conclusion

The demand for additional battery systems is primarily driven by automotive applications, but other new and promising segments such as aviation, wearables etc. are also increasingly emerging. Overall growth is driven by improved and application-specific battery cell technology. Flexibility areas in the battery cell design and their impact on process chain are critical to establishing a flexible production system capable of meeting the needs of multiple customers. Different implementation strategies can be pursued and practically implemented into a production system in order to leverage the potential of flexibility.

Flexibility potential can be tapped by focusing on selected formats, a defined design corridor and the ability to process a certain range of materials. The path to flexible battery cell production then can be paved by selecting or combining several of those flexibility areas. Other remaining challenges of supplying specific variants and changing market requirements can be overcome by adaptive electrode production and by expanding the equipment infrastructure within cell assembly and finalization as required. This not only enables on-demand production of different cell variants within one factory, but even parallel processing of individual production orders running in campaigns. Such flexible production systems hold the potential to handle multiple customer orders and reduce project-specific investment costs.

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References

[1] Lazkano, I., Nøstbakken, L., Pelli, M., 2017. From fossil fuels to renewables: The role of electricity storage. European economic review.

[2] Zeng, X., Li, M., Abd El-Hady, D., Alshitari, W., Al-Bogami, A.S., Lu, J., Amine, K., 2019. Commercialization of Lithium Battery Technologies for Electric Vehicles. Adv. Energy Mater. 9 (27), 1900161.

[3] Usai, L., Lamb, J.J., Hertwich, E., Burheim, O.S., Strømman, A.H., 2022. Analysis of the Li-ion battery industry in light of the global transition to electric passenger light duty vehicles until 2050. Environ. Res.: Infrastruct. Sustain. 2 (1), 11002.

[4] Fleischer, J., Fraider, F., Kößler, F., Mayer, D., Wirth, F., 2022. Agile Production Systems for Electric Mobility. Procedia CIRP 107, 1251–1256.

[5] Beach, R., Muhlemann, A.P., Price, D.H.R., Paterson, A., Sharp, J.A., 2000. A review of manufacturing flexibility. European Journal of Operational Research 122 (1), 41–57.

[6] Bossert, B., 1999. Einlastungsplanung flexibler Fertigungssysteme. Deutscher Universitätsverlag, Wiesbaden.

[7] Jacob, H., Dankert, U., 1995. Planung des Designs flexibler Fertigungssysteme. Gabler Verlag, Wiesbaden.

[8] Schmenner, R.W., Tatikonda, M.V., 2005. Manufacturing process flexibility revisited. International Journal of Operations & Production Management 25 (12), 1183–1189.

[9] Shivanand, H.K., 2006. Flexible Manufacturing System, 1st ed. ed. New Age International, Daryaganj, 165 pp.

[10] Vuorilehto, K., 2013. Materialien und Funktion, in: Korthauer, R. (Ed.), Handbuch Lithium-Ionen-Batterien, vol. 414. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 21–29.

[11] Chae, S., Choi, S.-H., Kim, N., Sung, J., Cho, J., 2020. Integration of Graphite and Silicon Anodes for the Commercialization of High-Energy Lithium-Ion Batteries. Angewandte Chemie (International ed. in English) 59 (1), 110–135.

[12] Or, T., Gourley, S.W.D., Kaliyappan, K., Yu, A., Chen, Z., 2020. Recycling of mixed cathode lithium-ion batteries for electric vehicles: Current status and future outlook. Carbon Energy 2 (1), 6–43.

[13] Kwade, A., Haselrieder, W., Leithoff, R., Modlinger, A., Dietrich, F., Droeder, K., 2018. Current status and challenges for automotive battery production technologies. Nat Energy 3 (4), 290–300.

[14] Heimes, H.H., Kampker, A., Lienemann, C., Locke, M., Offermanns, C., Michaelis, S., Rahimzei, E., 2018. Lithium-ion battery cell production process. PEM der RWTH Aachen University; DVMA, Aachen, Frankfurt am Main.

[15] Brodd, R.J., Helou, C., 2013. Cost comparison of producing high-performance Li-ion batteries in the U.S. and in China. Journal of Power Sources 231, 293–300.

[16] Krüger, A., 2004. Planung und Kapazitätsabstimmung stückzahlflexibler Montagesysteme. Zugl.: München, Techn. Univ., Diss., 2004. Utz, München, 189 pp.

[17] Fleischer, J., Kößler, F., Sawodny, J., Storz, T., Gönnheimer, P., Hofmann, J., 2021. Flexible Produktionsysteme/Agile Battery Cell Manufacturing as Response for Volatile Markets and Technologies. wt 111 (07-08), 486–489.

[18] Kößler, F., Mayer, D., Fleischer, J., 2022. Agile Produktionssysteme in der Batteriezellfertigung/Plant Concept for Highly Automated and Agile Calendering of Battery Electrodes. wt 112 (07-08), 492–495.

Biography

Artur Scheibe (*1996) is research associate at the Chair of Production Engineering of E-Mobility Components (PEM) at the RWTH Aachen University since 2021. He graduated business administration and mechanical engineering specializing in the fields of automotive engineering and corporate development strategy at the RWTH Aachen University.

Henning Clever (*1992) is research associate at the Chair of Production Engineering of E-Mobility Components (PEM) at the RWTH Aachen University since 2019 and group lead for the research group Battery Production Management since 2021. He studied mechanical engineering specializing in production engineering at the RWTH Aachen University. In his research, he focuses on factory design and flexible manufacturing in battery cell production.

Benjamin Dorn (*1990) studied industrial engineering with a focus on mechanical engineering at RWTH Aachen University. He worked as a research assistant from 2017 and as a group leader from 2020 at the PEM of RWTH Aachen in the Electric Drive Production group. Since 2021, he has been part of the institute's management as chief engineer of the Production Technologies and Organization division.

Dr.-Ing. Heiner Hans Heimes (*1983) is executive chief engineer of the Chair of Production Engineering of E-Mobility Components (PEM) at the RWTH Aachen University since 2019. He studied mechanical engineering with a focus on production engineering at RWTH Aachen University. From 2015 to 2019, he was head of the Electromobility Laboratory (eLab) of RWTH Aachen University and chief engineer of the newly established Chair of Production Engineering of E-Mobility Components (PEM).

Prof. Dr.-Ing. Achim Kampker (*1976) is head of the Chair of Production Engineering of E-Mobility Components (PEM) at the RWTH Aachen University and known for his co-development of the 'StreetScooter' electric vehicle. Prof. Dr.-Ing. Achim Kampker also acts as member of the executive board of the "Fraunhofer Research Institution for Battery Cell Production FFB" in Münster and is part of various national and international advisory boards.

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Digitalisation And Its Impact On Leadership Competences In Production Work

Bernd Dworschak[1], Alexander Karapidis[1]
[1]Fraunhofer Institute for Industrial Engineering IAO, Stuttgart, Germany

Abstract

This contribution tackles the effects of digitalisation on leadership in production work. Based on the assumption that production work in the future will be characterised as more flexible, networked and digitalised, the digital transformation will lead to changes in business models, organisations and work design. Accordingly, changed and new competences are needed by executives. There is a new generation of executives who have to view business differently and use different sets of competences to lead employees. In this paper, an overview will be given about digital trends and their impact on leadership. Secondly, definitions of terms about leadership and the difference between traditional management and digital leadership will be illustrated. Furthermore, competence sets for leadership in digital transformation in production work will be outlined. These competence sets can be described both by several competences subsumed under the term "interactional competences" and by competences needed to establish a work design conducive to learning, facilitating and enabling competence development of employees. We think that these two competence bunches depict the core of future competences of executives in production.

Keywords

Digitalisation; Leadership; Competence management; Digital transformation; Interactional competences; Work design for learning

1. Digital trends and their impact on leadership

Nowadays, everything gets more dynamic, more volatile and changes at an enormous pace. The driving force of change for organisations can be found in three topics: globalization, society and digital transformation [1, 2].

Within the digital transformation as one of the major megatrends we are facing numerous technological and organisational challenges aligned with topics like data analytics, blockchain, virtual/augmented reality or artificial intelligence [3, 4, 5]. According to Barley [6], this will lead to fundamental changes in business models, organisations and work design. Today, many entrepreneurs still think digital transformation means switching to new information technologies or even just adopting social media to the business. However, digital transformation is much more far-reaching: what began in the 1970s with computers and emails now includes self-driving cars, smart refrigerators, human-machine interaction at the workplace and 3D printers that even print cars. Digitalisation impacts on all company functions: from research and development to production and marketing, human resources and administration. Impacts are thus created for the entire company, functions and projects as well as for each individual employee [7]. More and more companies are

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establishing new structures and processes, new roles and responsibilities, new forms of cooperation, new leadership and motivation systems [8].

Accordingly, completely new demands are placed on leaders. The new requirements for leaders within the context of digitalisation fill long lists. Most importantly, they should be more agile, innovative and creative, think disruptively and tolerate mistakes, reduce their ego and instead take a moderating role for their employees [2, 4, 9, 10, 11, 12]. All in all, the new requirements are extensive, and they intervene deeply in the personality. This leads to the assumption, that digitalisation requires a new way of leading which comprises a broad range of requirements for executives - both in terms of breadth of skills required and depth.

Unfortunately, in the context of digital transformation and considering the role of leadership there is a huge need for solutions giving answers about how to enable leaders in organisations to cope with all these new demands. Furthermore, research on these topics is still low [13]. In the past, some research activities can be found in the following areas concentrating on different aspects: Impact on leadership of home office and teleworking concepts [14], leadership in virtual teams [15] as well as digital technologies and the potential to substitute employees and leaders [16]. Schwarzmüller et al. [17] concluded, that the research topics mentioned (amongst others) have a strong impact on leadership principles. So, the research on competences required for leaders in new digitalised work environments is of greater concern for many organisations [18, [19].

2. Evolution of digital leadership

Digitalisation, which is characterized by technologies that transform the analogue physical world into digital applications, is not just a technological challenge [11, 20]. It is currently initiating a cultural revolution that turns the classical understanding of leadership on its head. The new version is called digital leadership [4, 11, 21]). When talking about digital leadership, there are other synonymous terms in other countries, e.g. leadership 4.0 in Germany, referring to the term Industrie 4.0 [22, 23]. Besides that, digital leadership is also used to describe companies holding a lead position in the field of digitalisation, e.g. Google LLC. Digital leadership in the context of this paper refers to the leadership style needed to manage an increasingly digitalised world. It does not only mean to use digital media for communication and cooperation as a leader, but also to adapt the leadership behaviour to the demands of the new digital reality.

But what distinguishes digital leadership from traditional management and leadership and what are its unique features? The different concepts describe specific prototypes of executives' roles which arose in the context of different historical eras as a result of adapting to new challenges emerging from revolutionary changes in economy. Figure 1 shows their evolutionary development along the different eras, their main tasks and characteristics (own supplemented and modified representation according to [24]).

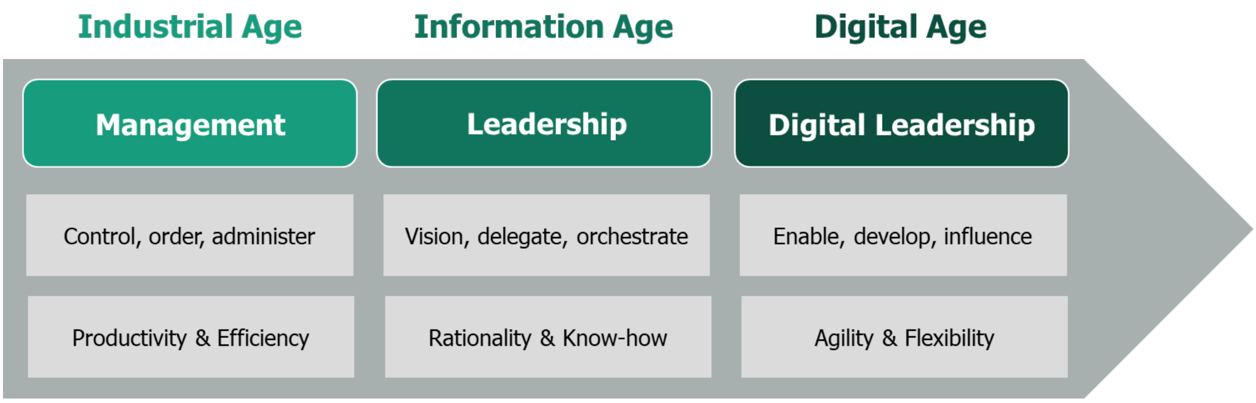

Figure 1: Evolution of digital leadership

Traditional management concepts mark the beginning and started to evolve during the industrial age characterised by mass customization. The critical factors to remain competitive within this context are productivity and efficiency. Decisions are made based on strict guidelines and processes (efficient decision making). Therefore, management tasks focus on controlling, ordering and administering promoting stability and continuity [2, 24, 25].

As a next evolutionary step, leadership concepts started to develop sparked by the new challenges that came along with the information age. This era was induced by the introduction of computer technology, followed by other information technologies such as internet connectivity. Easy access to information and directly sharing it with others was made possible enabling a more decentralized decision-making and autonomously working employees. Thus, in this context, the critical factor for competitiveness is the knowledge gained from analysing information. Consequently, leadership tasks focus on visioning, delegating and orchestrating aiming to create a working environment that offers more latitude to the employees in performing their actions, since guidance is provided by the accessible information, a shared vision and culture [2, 24, 25].

The digital age is, where we stand right now, and the evolution of digital leadership has just started [22]. As a reaction to the challenges of high levels of unpredictability and complexity when making decisions due to a fast-changing dynamic work environment shaped by digital transformation leadership has differentiated itself significantly from traditional management tasks. Basing decisions on knowledge and insights gained from data analysis is not enough anymore. Digital leaders need an agile mindset enabling them to adapt quickly to new requirements, to make decisions intuitively and by using their creativity, if this is required by the circumstances, but also to support their employees and the organisation to cope with changing requirements [9, 10, 24]. Therefore, the following tasks and corresponding competences are central for leaders to act successfully in a digitalised work environment:

- Enable digital change: Not only competences to use digital methods or social media are requested but also competences to be the driving force in change processes to cope with challenges caused by digitalisation (e.g. new business models and processes) [2, 10, 11, 25].
- Develop employees: Competences are needed to give employees a kind of corridor to develop a specific training and to speed up their individual development in coordination with the organisational targets. For these issues, a digital leader could be a coach, a „good practice", and again, an enabler [2, 11, 22, 25]. Furthermore, competences are needed to early recognize if employees tend to get health problems by working (especially psychological problems) and to find options to overcome them or avoid them [2, 4, 26].
- Influence: Competences to inspire employees and encourage them to cope with challenges in work are important. This includes, that errors are a part of the development process and to inspire employees to learn for the benefit of their own employability as well as the organisational success [2, 27, 28].

3. Interactional competence

At the centre of the project "ella4.0 - Sociodigital transformation towards excellent leadership and labour" funded by the German Federal Ministry of Education and Research is the topic of interaction and the competence-related requirements that managers face in order to establish "good work" with employees via new channels, in a digital setting of processes and procedures and under constantly changing conditions.

The socio-technical system within organisations is increasingly becoming a socio-digital system. The entire interaction structure (People (M)-technology (T)-organisation (O)) is subjected to continuous, accelerating change. With the influence of digitalisation and the associated changes in the technical infrastructure in the company, the working methods are also changing, they are becoming more digital. At the latest when the global corona pandemic broke out, many companies increasingly used video and web conferencing tools overnight [29]. The networked production systems in industry also enable remote maintenance from the computer at home and create a new form of long-distance collaboration that requires the development of competences on the part of managers. The effects impact the individual employees, teamwork and the managers in the company, who shall continue to pull the strings in a controlling and orchestrating manner.

Interaction denotes a reciprocal and related action between two or more people. Interactional competence is thus to be understood as the ability to express oneself appropriately and constructively in social relationships and situations, to act and to speak. Interactional competence aims at a behaviour-influencing design of the entire company-related (digitally supported) interaction space (MTO) in normative, strategic and operational terms. With the result informational, qualificational, motivational and infrastructural conditions should be created. In the exchange with various companies, this definition has turned out to be particularly appropriate for defining interaction competence and also for describing it from a practical or operational point of view.

Thomson et al. [30] show that the environment in companies and their requirements are changing. They evaluated the promotion criteria of employees in the company in a meta-study in their project report. These should be sorted by importance. Unsurprisingly, from the point of view of the followers, professional competence is in first place, but closely followed by personal competences, which are of similar importance. This indicates the change in the understanding of leadership, from professional experts to inspiring leadership.

The question of whether there is a change in the leadership role in the course of the digital transformation is also confirmed by almost 80 percent of respondents in the study by Hofmann et al. [31]. This does not mean, however, that the new management approaches are also reflected in the organisational structure of the company with regard to organisational charts, cooperation, incentive or evaluation systems. The field of tension between the old and the new comes to light again, in which the executives have to move and find their way.

Great importance is attached to one's own attitude towards change. As an absolute top issue, “openness to change” is confirmed as a currently very important competence of managers [32]. If personal responsibility for the current situation is still the same, the ability to change clearly dominates the list of additional questions about what will become increasingly important in the future, with over 90 percent agreement.

Although the importance of personal competences is slowly increasing, companies seem to be paying little attention to the targeted development of digital competences. Surprisingly, competences for the digitised workplace, which are important for “collaboration in virtual teams”, “communication via digital media” or “handling data”, are found in the lower ranks and will continue to be of little importance in the future allocated [32]. This picture can also be seen in Hofmann & Wienken [33], where it is still accompanied by a decline in the importance of area-specific expertise.

These digital competences have either not yet arrived in their importance for the future development of the company or do not (yet) play a role. In many companies, the topic of internal digital forms of cooperation has so far received little attention (Beyer 2015). Moreover, it is remarkable that research has not yet provided any significant findings here either, although internal cooperation between managers and employees is very important for the success of digitisation strategies. The mechanisms of action of the digital cooperation between managers and employees to be taken into account in this design field are still largely unknown.

One area of competence is “digital and media competences”, which particularly emphasizes the important topic of communication in the digital setting.

“Analytical and planning competences” will also be important in order to be able to recognise, analyse and implement as a manager, for example, the needs of employees with regard to future development - here again the topic of basic digital competences for everyone. This can only succeed if, at the same time, “economic competences” are developed to such an extent that managers are able to recognize the potential and threats from their environment for their company (in good time) and to initiate measures that will contribute in the long term to put the processes, working methods and the business model on a sustainable footing.

With the change in the leadership role, the changed need for leadership, which, as discussed above, is supplemented or replaced, new competence requirements located in the area of "leadership competences" are defined for executives. These competences as well have to be developed.

The last two points form the closely related personal competences of the manager, which are ultimately decisive for the managerial success, as well as the professional competence of the manager.

It thus becomes clear that interactional competence is not a specific, single competence, but rather consists of several specific competence bundles:

1. Digital & media competences

2. Analytical and planning competences

3. Economic competences

4. Leadership competences

5. Personal competences

6. Professional competences

The clustering of competences was based on the analysis of the above-mentioned literature. Furthermore, in the first year of the project, qualitative surveys on the topic of "Effects of digitalisation on leadership" were conducted with 19 participants, including entrepreneurs, consultants and experts from science. The results of the interviews were then analysed and evaluated using a uniform code book with the software MAXQDA.

From the results of the interviews the mentioned competence bundles can be presented in more detail as follows:

Digital and media competences	▪ Communicate effectively, also across distances ▪ Digital competences ▪ Technological know-how/acquisition of new knowledge ▪ Understanding of data, privacy and processes ▪ Creative thinking ▪ Media literacy
Analytical and planning competences	▪ Good comprehension to fully comprehend/understand the situation at hand ▪ Problem-solving skills ▪ Further development of technologies in professional and activity fields ▪ Coordination
Economic competences	▪ Strategic thinking ▪ Strategic competence with regard to changes in the working world ▪ Dealing with data and the question of what potential is associated with the data for the organisation
Leadership competences	▪ Employees expect a counterpart at eye level ▪ Develop a framework in which people can display their strengths ▪ Health-promoting leadership ▪ Dealing with people, developing them, recognising their potential and dealing with the differences between employees (e.g. attitudes, skills). ▪ Coaching; respond to the potential, lead individually and take time ▪ Sensitivity of the manager and the ability to lead in a situational manner ▪ Decision-making skills and knowing how to enforce them
Professional competences	▪ Basic understanding of process knowledge / professional knowledge ▪ Experiential knowledge about the respective processes, problems, framework conditions

Personal competences	▪ Personal development of leadership style
	▪ Leadership at a distance
	▪ Ability to reflect (reflect on oneself critically and then make decisions)
	▪ Communication:
	    ▪ Communication skills – and strength
	    ▪ Appreciating people, encouraging communication
	    ▪ Introduce and establish new, changed forms of communication
	    ▪ Constitute an understanding of communication and explanation, the comparison of expectations and the conveying of strategies
	    ▪ Ability to listen and understand the other person
	▪ Political skills (ability to place and enforce one's own needs in the right place)
	▪ Emotional Intelligence/Competence
	▪ Conflict resolution:
	    ▪ Conflict Resolution Skills
	    ▪ Ability to resolve conflicts
	▪ Motivation:
	    ▪ Motivation and coordination of employees
	    ▪ Methods for motivating employees
	    ▪ Able to give constructive criticism as well as praise and appreciation
	▪ Being able to endure uncertainty (VUCA) Socio-emotional self-competence
	▪ Collaboration skills
	▪ Attitude between laissez faire and collaborative (relaxed and at eye level)
	▪ Willingness to change (flat hierarchies, etc.), also with regard to the innovative design of leadership
	▪ Collaboration across subject and organizational boundaries / networking / exchange
	▪ Support in the change process / navigation, provide more leadership in the sense of orientation
	▪ Confidence to go in a certain direction and having the necessary openness to do so
	▪ Willingness and ability to learn
	▪ Personal maturity
	▪ Reverse monitoring, accept leading of younger people
	▪ Systemic thinking

Figure 2: Competences derived from the interviews, summarised as a model in areas of competence

From the point of view of company actors of our project, some competences from the above-mentioned bundle of competences are of particular importance. In the case of "digital and media competences", for example, dealing with which medium is best suited for which specific situation turns out to be an essential competence. There is usually a large selection of different tools available, and it is important to keep track of them. A good grasp of situations quickly and as completely as possible is emphasized by the companies with respect to “analytical and planning competences”. When it comes to “leadership competences”, it is dealing with people. Employees must be viewed as individuals whose potential must first be recognised so that they can then develop accordingly. With regard to “professional competences”, the professional knowledge and basic understanding of processes are particularly relevant. In terms of “personal competences”, companies identify several specific competences as particularly relevant, such as the personal development of leadership style, the ability to bear uncertainty, the socio-emotional self-competence and the willingness and ability to learn as a manager.

At first glance, the bare number of different “personal competences” that need to be developed seems surprising. Along with the change caused by digitalisation, the procedures, processes and tasks are changing at the structural level in the company. Project work is finding its way and is thus also changing the way in which people work together. If you look at leadership as interactional work, this development cannot remain without an impact on the way in which leadership is carried out, since leaders and those being led are in exchange:

Leadership is not replaced by digitalisation. This is also reflected in what is by far the most frequently mentioned ability of a manager to shape communication as an information hub and also to be the central point of contact in the team. At the organisational level, working in networks and projects that follow different rules, processes and methods is becoming more and more common. The ambidextrous structures lead to a “communication explosion”. All the more important in this context is and remains the manager with the task of ensuring cohesion, direction and connection within the team and at the internal and external interfaces.

4. Competences for learning-friendly work design

According to the VDI/VDE Standard 7100 “Learning-friendly work design. Goals, benefits, terms and definitions” [34] the design options for learning-friendly work in general can be broken down in eight fields of action: Leadership, competence development, learning culture, communication, work organisation, work tasks, technical infrastructure and installed learning solutions [35]. These fields of action can in turn be assigned to the MTO model, which with human (M), technology (T) and organisation (O) delineates three fundamentally different but closely interacting perspectives from each other and thus offers a structuring means for the complex world. An integration of the two models offers an identification of different practical fields of action of what can be called learning-friendly work or work conducive to learning. The figure provides an overview of the concept of the standard.

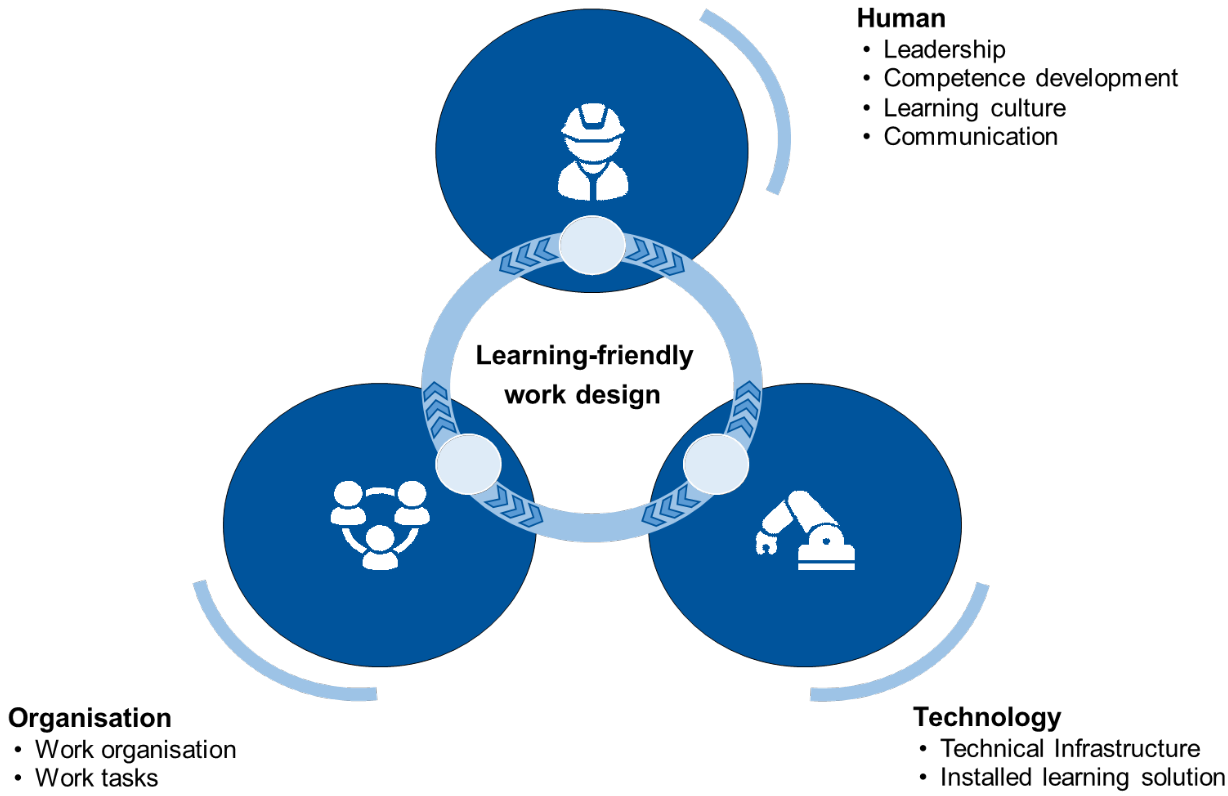

Figure 3: Perspectives on learning-friendly work design
(own illustration according to [36] and [35])

The figure illustrates the holistic orientation of learning-friendly work design. The fields of action of the human perspective are leadership, competence development, learning culture and communcation. Fields of action in the organisational perspective lie work organisation and work tasks. The design of technical infrastructure and installed learning solutions are the focus of the technology perspective in terms of fields of action promoting learning. The standard takes a closer look at these different perspectives and takes into account interactions and inferfaces. Since it is not only the isolated design of the individual perspectives but it is the design of the relationships between people and technology, technology and organisation as well as organisation and people which enables the full potential of a learning-friendly work design to be realized.

And this is where the link to leadership competences comes into play. Since the three perspectives are all interrelated between each other and leadership is a central field of action in the human perspective, leadership itself is interrelated to all other fields of action as well and, furthermore, can interpreted in a competence-oriented way: In this sense, leadership needs to foster and develop learning-friendly work and it is a leadership competence to design such kind of work systems, in particular, of production work. Leadership competences then include competences to develop competences of employees, to establish fostering conditions for an appropriate learning culture as well as to communicate with the employees and within the organization appropriately. Furthermore, leadership competences include discuss and decide on the technical infrastructure of the work systems and the learning solutions to be installed. Leadership competences for learning-friendly work finally include an understanding of work organisation and work tasks. How do digital technologies impact work organization and work tasks in production work and what does that mean for leadership, which competences are needed in this respect?

5. Conclusion

As a first step, this contribution described the evolution of digital leadership highlighting the unique features of digital leadership against traditional management. In the next step, the major challenges of leadership arising in the context of digital transformation were discussed. The interviews carried out in the course of the project ella4.0 and the project work itself led to the conclusion that interactional competences and interactional work are the core of leadership work in digital transformation. Furthermore, leadership of the future needs also competences for a work design conducive for learning. Obviously, these two competence bunches depict the core future competences of managers and executives in production.

References

[1] Beyer, K., 2015. DGFP-Studie Megatrends 2015, Deutsche Gesellschaft für Personalführung e.V. (Ed.), DGFP-Praxispapiere, Düsseldorf.

[2] Franken, S., 2016. Führen in der Arbeitswelt der Zukunft. Wiesbaden: Springer Gabler.

[3] Colbert, A., Yee, N., & George, G., 2016. The digital workforce and the workplace of the future. Academy of Management Journal, 59, 731-739.

[4] Creusen, U. et al., 2017. Digital Leadership – Führung in Zeiten des digitalen Wandels. Wiesbaden: Springer Gabler.

[5] Pohl, V. et al., 2017. Zukunftsstudie 2027. Wie aktuelle Technologien und Entwicklungen unsere Lebenswelten verändern. Stuttgart: Fraunhofer-Institut für Arbeitswirtschaft und Organisation IAO.

[6] Barley, S. R., 2015. Why the internet makes buying a car less loathsome: How technologies change role relations. Academy of Management Discoveries, 1, 5-35.

[7] Avogaro, M., 2019. The Highest Skilled Workers of Industry 4.0: New Forms of Work Organization for New Professions. A Comparative Study. E-Journal of International and Comperative Labour Studies, Volume 1, January 2019.

[8] Parida, V. et al., 2019. Reviewing Literature on Digitalization, Business Model Innovation, and Sustainable Industry: Past Achievements and Future Promises. Sustainability Volume 11, Issue 2, 391.

[9] Summa, L., 2016a. (Un)Bequeme Denkimpulse für Veränderung zugunsten einer digitalen Welt, in Summa, L. (Ed.), Digitale Führungsintelligenz: „Adapt to win“, Wiesbaden: Springer Gabler, 13-150.

[10] Summa, L., 2016b. Digitale Führungsintelligenz, in Summa, L. (Ed.), Digitale Führungsintelligenz: „Adapt to win“, Wiesbaden: Springer Gabler, 151-170.

[11] Wagner, G., 2017. Digital Leadership – die Führungskraft im Zeitalter von Industrie 4.0, in Andelfinger, V. P. and Hänisch, T. (Ed.), Industrie 4.0 – Wie cyber-physische Systeme die Arbeitswelt verändern, Wiesbaden: Springer Gabler, 165-214.

[12] Zeichhardt, R., 2018. E-Leader, CDOs & Digital Fools – eine Führungstypologie für den digitalen Wandel, in Keuper, F. et al. (Ed.), Disruption und Transformation Management, Wiesbaden: Springer Gabler, 3-22.

[13] Cascio, W. F., Montealegre, R., 2016. How technology is changing work and organizations. Annual Review of Organizational Psychology and Organizational Behavior, 3, 349-375.

[14] Leslie, L. M. et al., 2012. Flexible work practices: A source of career premiums or penalties? Academy of Management Journal, 55, 1407-1428.

[15] Hoch, J. E., Kozlowski, S. W., 2014. Leading virtual teams: Hierarchical leadership, structural supports, and shared team leadership. Journal of Applied Psychology, 99, 390-403.

[16] Campion, M. C. et al., 2016. Initial investigation into computer scoring of candidate essays for personnel selection, Journal of Applied Psychology, 101, 958-975.

[17] Schwarzmüller, T. et al., 2018. How does the digital transformation affect organizations? Key themes of change in work design and leadership, Management Revue, 29(2), 114-138.

[18] Frey, C. B., Osborne, M. A., 2017. The future of employment: How susceptible are jobs to computerization? Technological Forecasting and Social Change, 114, 254-280.

[19] Van Knippenberg, D. et al., 2015. Information, attention, and decision making. Academy of Management Journal, 58, 649-657.

[20] Heuermann, R. et al., 2018. Digitalisierung: Begriff, Ziele und Steuerung, in Heuermann, R. et al. (Ed.), Digitalisierung in Bund, Ländern und Gemeinden, Berlin: Springer Gabler, 9-50.

[21] Keuper, F. et al. (Ed.), 2018. Disruption und Transformation Management. Wiesbaden: Springer Gabler.

[22] Eggers, B., Hollmann, S., 2018. Digital Leadership – Anforderungen, Aufgaben und Skills von Führungskräften in der „Arbeitswelt 4.0", in Keuper, F. et al. (Ed.), Disruption und Transformation Management. Wiesbaden: Springer Gabler, 43-68.

[23] Schwarzmüller, T. et al., 2017. Führung 4.0 – Wie die Digitalisierung Führung verändert, in Hildebrandt, A., Landhäußer, W. (Ed.), CSR und Digitalisierung, Berlin: Springer, 617-628.

[24] Birkinshaw, J., Ridderstrale, J., 2017. Fast/Forward. Make your company fit for the future. Stanford: Stanford University Press.

[25] Crummenerl, C., Kemmer, K., 2015. Digital Leadership – Führungskräfteentwicklung im digitalen Zeitalter, retrieved from https://www.capgemini.com/consulting-de/wp-content/uploads/sites/32/2017/08/14-10-16_digital_leadership_v11_web_17102016.pdf, accessed 02-20-2019.

[26] Feldhaus, C., 2017. Gesundheit als Führungsaufgabe – Gesundes Führen am Beispiel eines Großkonzerns, in Spieß, B., Fabisch, N. (Ed.), CSR und neue Arbeitswelten, Berlin: Springer Gabler, 415-429.

[27] Deloitte, 2016. Decoding digital leadership, retrieved from https://www2.deloitte.com/content/dam/Deloitte/uk/Documents/public-sector/deloitte-uk-decoding-digital-leadership.pdf, accessed 02-20-2019.

[28] Teichmann, S., Hüning, C., 2018. Digital Leadership – Führung neu gedacht: Was bleibt, was geht?, in Keuper, F. et al. (Ed,), Disruption und Transformation Management. Wiesbaden: Springer Gabler, 23-42.

[29] Hofmann, J.; Piele, A.; Piele, C., 2020a: Arbeiten in der Corona-Pandemie – auf dem Weg zum New Normal, urn:nbn:de:0011-n-5934454, http://publica.fraunhofer.de/dokumente/N-593445.html, accessed 02-14-2023.

[30] Thomson, B., Steidelmüller, C., Schröder, T., Wittmers, A., Pundt, F., Weber, C., 2020: Der Zusammenhang organisationaler Rahmenbedingungen und Gesundheit bei Führungskräften und Beschäftigten, ASU Zeitschrift für medizinische Prävention, Sonderheft Führungsforschung, Ausgabe Mai 2020.

[31] Hofmann, J., Ricci, C., Schwarz, R., Wienken, V., 2020b. Erfolgskriterien betrieblicher Digitalisierung. Gütersloh, Bertelsmann Stiftung.

[32] Hofmann, J., Wienken, V., 2020. Führung in der digitalen Transformation. Ein Realitätscheck für mittelständische Industrieunternehmen. Stuttgart: Fraunhofer IAO.

[33] Hofmann, J., Wienken, V., 2018. Digital Leadership. Führung in der digitalen Transformation. urn:nbn:de:0011-n-5040742, http://publica.fraunhofer.de/dokumente/N-504074.html, accessed 02-14-2023.

[34] Dworschak, B., Altepost, A., Bau, M., Berger, C., Brandt, P., Gerst, D., Jeske, T., Kötter, W., Mühlbradt, T., Senderek, R., Schweppe, K., Ullrich, C., Wischmann, S., Ziegler, J., 2021. Die VDI/VDE-Richtlinie 7100 „Lernförderliche Arbeitsgestaltung": ein Beitrag zum humanorientierten Management der Digitalen Transformation, in: Arbeit HUMAINE gestalten: 67. Kongress der Gesellschaft für Arbeitswissenschaft, Dortmund: GfA-Press.

[35] Senderek, R., 2016. A model for learning-enhancing work design in a digitized world. 16th IEEE International Conference on Advanced Learning Technologies (ICALT2016). 25.-28.07.2016. Austin IEEE Computer Society.

[36] Strohm, O., Ulich, E., 1997. Unternehmen arbeitspsychologisch bewerten – Ein Mehr-Ebenen-Ansatz unter besonderer Berücksichtigung von Mensch, Technik, Organisation, Zürich: vdf Hochschulverlag AG an der ETH Zürich.

Biography

Bernd Dworschak (*1971) has been head of the team Competence Management at the Fraunhofer Institute for Industrial Engineering, Stuttgart, Germany, since 2016. His research interests include topics such as the early identification of skill needs as well as concepts for competence management and development in integrated industry and advanced manufacturing. Currently, he focuses on the impact of digitisation and industry 4.0 on work, competences, competence development and leadership.

Alexander Karapidis (*1967) is Senior Researcher in the team Competence Management at the Fraunhofer Institute for Industrial Engineering, Stuttgart, Germany. His research interests focus on competence management and competence development both in service industries and advanced manufacturing. Currently, he focuses on the impact of digitisation on work, competences, competence development and leadership in services and production work.

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Evaluation Of A Capacity-oriented, Agent-based Order Release For Matrix-structured Assembly Systems

Peter Burggräf[1,2], Tobias Adlon[1], Esben Schukat[1], Nina Katharina Weber[1]
[1] *Laboratory for Machine Tools and Production Engineering (WZL) of RWTH Aachen University, Aachen, Germany*
[2] *Chair of International Production Engineering and Management (IPEM), University of Siegen, Siegen, Germany*

Abstract

To address growing challenges in automotive assembly with ever shorter innovation cycles, increasing variant diversity and uncertain market development, innovative concepts for assembly systems are needed. As a response, the concept of matrix-structured assembly system was introduced. Matrix-structured assembly systems break up with the rigid line structure of assembly stations and replace the cycle time-bound and product-specific station assignment of line assembly. A major challenge in the design of matrix-structured assembly systems is the assembly control. While certain approaches, mostly decentral and agent-based, are already capable to assign orders to assembly stations based on the availability of production resources, order release as part of the assembly control has been largely neglected. This is because routing and sequence flexibility lead to temporal uncertainty in the prediction of station-specific capacity utilization. Accordingly, the authors' previous work includes a conceptual methodology for capacity-oriented order release in matrix-structured assembly systems. After implementing the previously introduced methodology, the actual benefit needs to be determined. For this purpose, the present paper suggests and applies a testing strategy based on the fundamentals of successful testing in software development domain. The testing aims to demonstrate the basic functionality of the implemented methodology as well as to compare it with other order release procedures that have been used for simulations in the context of matrix-structured assembly systems so far. It can be shown that the methodology for capacity-oriented order release in matrix-structured assembly systems achieves better adherence to delivery dates and lead times by anticipating bottlenecks compared to ConWIP control with a random order release. The knowledge gained from the testing strategy contributes to the improvement of order release in matrix-structured assembly systems.

Keywords

Matrix-structured assembly system; order release; multi-agent system; assembly control; factory planning

1. Introduction

Conventional assembly lines in automotive final assembly have been in place for 100 years. In recent decades, customized products, short innovation cycles and new vehicle concepts, resulting in high line balancing efforts and declining utilization of assembly stations, have challenged assembly lines [1–3]. Future assembly systems need to address these trends by being more flexible as well as adaptable, allowing economical production of smaller quantities and shorter ramp-up times [4]. As a potential solution, matrix structured assembly systems (MSAS) gained more and more attention in research [5]. MSAS break up with the rigid line structure of assembly stations [1,2,6]. Assembly stations are arranged in matrix form, allowing a cycle-time-independent and an order-specific flow of assembly objects [7]. By this, MSAS are supposed to reduce manufacturing costs in multi-variant production as well as to increase flexibility and efficiency in assembly [2]. An essential prerequisite for the operation of MSAS is an advanced assembly control that takes

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into account the increased degrees of freedom of assembly processes. The assembly control is responsible for the reactive and situational assignment of assembly operations and orders to multifunctional assembly stations [1,7–9]. In preliminary work on assembly control, order release as a sub-task of assembly control has been neglected so far. Corresponding simulation show randomly, alternating, or time-based order release, ignoring capacity constraints. Consequently, the authors developed and published a methodology for capacity-oriented, agent-based order release in MSAS [5].

The previously conceptual methodology for order release in MSAS has been recently implemented. Therefore, a qualified testing strategy is needed to scientifically validate the functionality and the actual benefit of the methodology for capacity-oriented, agent-based order release in MSAS. This includes a comparison to random order release. Accordingly, this paper presents a summary of essential properties for order release in MSAS as well as the aforementioned methodology. Afterwards, the evaluation environment used for testing and simulation is described. Based on that, a testing strategy specifying the development, planning and specification of test processes in the field of software development is applied. Subsequently, the testing strategy with its defined test cases are executed and results evaluated. Finally, the testing strategy is critically reviewed and an outlook for future research is given.

2. Order release in matrix-structured assembly systems

2.1 Properties to order release

The authors' previous work [5] specifies six requirements for order release in matrix-structured assembly systems. The **first property** is to perform a capacity analysis on operation and system level. In some cases, assembly stations can perform different kind of operations, so a capacity analysis at the operation and overall system level is necessary. The **second property** deals with the consideration of all possible sequences of operations and related capacity demands of an order when released and processed in MSAS. For this, orders that have not yet been released and orders that have already been released must be evaluated. The latter also includes a monitoring of the current processing progress. To meet the flexibility of MSAS, the **third property** asks for an event-oriented release logic. Order release should take place after defined events such as the completion of an operation. This reduces the frequency of calculations while latest information from MSAS is processed. The **fourth property** deals with the ability to set individual production targets. Possible production targets include minimizing lead times, reducing waiting times or compensating for fluctuations in the capacity situation of the individual assembly stations. The **fifth property** ensures the recognition of order-specific characteristics such as due dates or margins. These characteristics might be included in the release decision through weightings, allowing similar products of different relevance being released in the correct order. For this reason, orders should not be bundled as batches or lots. The last and **sixth property** for order release in MSAS refers to practicability. Order release should be scalable and feasible in reasonable computation time.[5] Scalability describes the ability of a system or process to easily handle extension as the number of elements and objects increases [10]. Reasonable computation time should always be significantly shorter than the shortest operation time so that order release can include the current capacity situation in its evaluation at any time [5].

2.2 Methodology for capacity-oriented, agent-based order release

To address these properties, a methodology for capacity-oriented, agent-based order release in MSAS has been developed. While a detailed description can be found in the authors' previous work [5], Figure 1 and the following explanations provide a summary of the developed methodology.

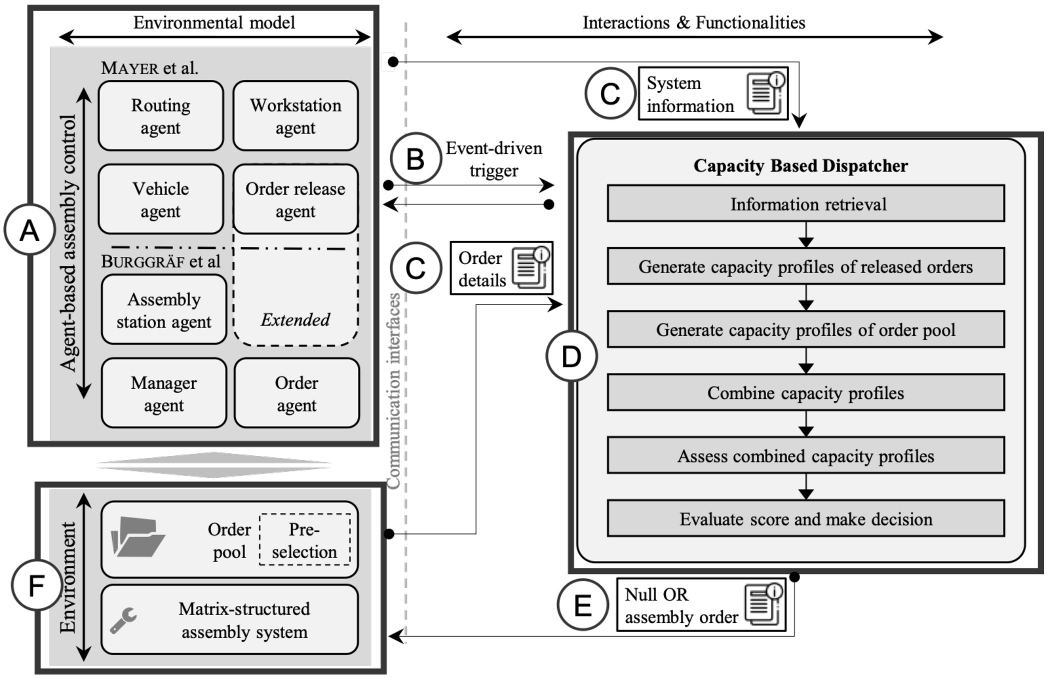

Figure 1: Methodology for order release in MSAS adapted from [5]

As shown in Section A, the methodology is embedded in a separate order release agent and can be part of an existing agent-based assembly control system as proposed by BURGGRÄF et al. [7] or MAYER et al [9]. In this methodology, the order release agent is referred to as Capacity Based Dispatcher (CBD). Section B shows that the CBD is triggered by a defined event, such as an order release or the completion of an operation. The CBD subsequently receives information from the agent-based assembly control system and order-specific details from the order pool, as presented in Section C.

Section D describes the functionality and procedure of the CBD. After the received information has been processed, next, to evaluate the capacity situation of the assembly system and takes release decisions, the CBD creates capacity profiles for each order already released and for each possible release candidate. A capacity profile describes the time-specific demand for assembly operations of an order. These are represented as a matrix, where each column represents a time step and each row represents the demand for an assembly operation as a binary variable. The number of columns covers the entire time horizon until the completion of an order. The sequence of assembly operations is based on the assembly precedence graph. A widely branched precedence graph offers more possibilities for different assembly sequences resulting in a higher number of capacity profiles per order. Thus, one capacity profile is generated for every valid sequence of assembly operations for each order. Capacity profiles also present the current state of the job. Accordingly, orders with completed assembly operations have fewer capacity profiles than unprocessed orders while also having fever number of filled columns representing as the time horizon until completion is shorter. In order to keep calculations between matrices possible, the size of every capacity profile is stretched to the longest possible sequence in the system and filled with zeroes in time steps that exceed the actual demand for assembly operations. Each capacity profile thus reflects a possible load of the assembly system by an order. Since all assembly sequences and thus all capacity profiles can occur in reactive assembly control, all capacity profiles are still considered. In order to map the current capacity load of the assembly system, all combinations of the capacity profiles of the orders currently being processed are added up. This results in an operation- and time-specific prediction of the system load. All these combinations are then extended by capacity profiles of unprocessed orders. Those matched capacity profiles must be compared with the available processing capacity of the assembly system. The available processing capacity is also described in a matrix. For this purpose, each assembly station receives a matrix in which the columns also show the time horizon and the entries in the rows show the ability to process a specific assembly operation. The overall available processing capacity can be determined by summing up the matrices of each workstation. Now, for each time unit, the overall available processing capacity can be compared column by column with the previously combined capacity profiles. If the demand for a certain operation exceeds the available processing capacity, the combined capacity profiles is rejected. Nevertheless, a different combined capacity profile of the same order may be accepted. The non-rejected profiles or rather their unprocessed orders are then evaluated in terms of best capacity fit. For this purpose, these orders are initially distinguished exclusively by the assembly operations they contain. Identical assembly operations of an order are interpreted as identical products and these orders are correspondingly equated at first. The capacity fit is the sum the free capacity of the system for all operations, calculated by subtracting the combined capacity profile from the available processing capacity over all time steps. The product which utilizes the system the most is then selected for further evaluation on order specific level.

In Section E, a score-based decision considering due dates or expected profit are considered to select a specific job for release is made. When no order was selected due to the overload constraint, then no order is dispatched and the agent goes into standby. Information about the order release decision is also passed back to the matrix-structured assembly system and order pool, which are shown in Section F.[5]

2.3 Evaluation Environment

To evaluate the implementation of the methodology in the CBD, an evaluation environment is required. In general, an evaluation environment is defined as a technology platform that serves the purpose of validation methodologies, models and theories developed in innovation projects. By integrating those into a common environment, the acceptance of new approaches can be increased. An evaluation environment allows multiple stakeholders to gain a common understanding of the program and the evaluation process [11,12]. In the present context, an evaluation environment must include an agent-based assembly control for MSAS, have an order pool, simulate the processes in MSAS and also record all results while making them available for output. Such an evaluation environment was developed accordingly. The used logic for assembly control is based on the preliminary work of the authors and includes the agents mentioned in Figure 1 [7]. The evaluation environment enables simulation of an MSAS, allowing users to enter their own assembly system configurations, products and production scenarios quickly and easily. The graphical user interface of the evaluation environment is shown in Figure 2.

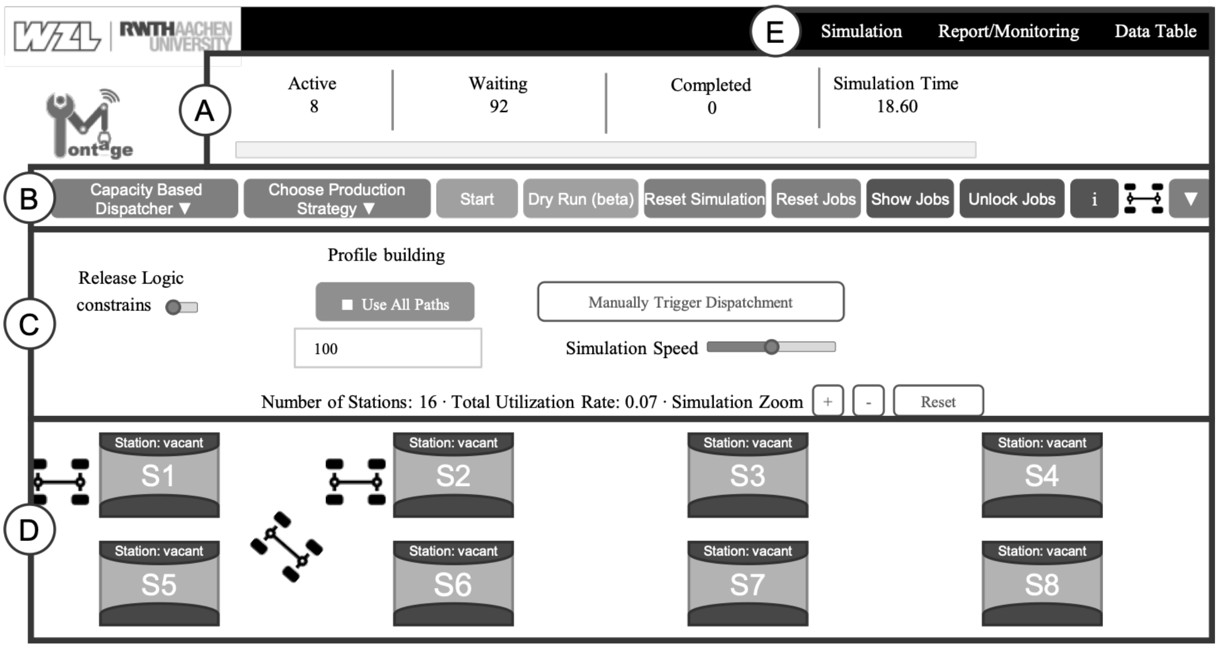

Figure 2: Dashboard of Evaluation Environment [13]

Section A shows a status display of the simulated assembly. The status display visualizes active, waiting and completed orders as well as the current time stamp since a simulation has been started. Buttons to control the simulation and set parameters for assembly control can be found in in **Section B**. This includes options such as start, reset or also an option to enter order-specific due dates. Furthermore, different order release agent types such as the Capacity Based Dispatcher (CBD), which includes the Methodology for capacity-oriented, agent-based order release in MSAS, can be selected. Alternatively, order release agent types for push- or pull-based order releases are possible. In this work, a Random Pull Dispatcher (RPD) is relevant in addition to the CBD. It releases orders randomly using a ConWIP control. **Section C** gives options to set order release parameters. These options differ between the order release agent types. The CBD allows to limit the number of capacity profiles considered for order release. This reduces the number of calculations this type of order release agent is performing when triggered. **Section D** shows a visualization of the entered layout with its assembly stations and orders. Different icons can be selected to visualize orders. **Section E** offers access to the Report and Monitoring as well as the Data Table of the evaluation environment. Report and Monitoring gives a detailed analysis of the system and tracking of individual orders can be done. Here, all information on orders and assembly stations such as station histories, operation histories or lead times can be seen and exported. Moreover, utilization rates of the assembly stations and the number of active orders is mapped. The Data Table includes information regarding products, assembly stations and their arrangement.

3. Testing strategy

3.1 Conception

Literature mostly evaluates the effectiveness of order release procedures simulation-based analysing key performance indicators (KPIs). Typical KPIs are lead times, adherence to delivery dates or capacity utilization [14–16]. The implementation of those in the evaluation environment build the fundament to test the implemented CBD. Before running any tests, a testing strategy to systemically validate the degree of fulfilment of mentioned properties is defined. A testing strategy answers the questions, which test cases should be used, which goals are pursued and which expectation the software application should fulfill [17]. To conceptually design the testing strategy, existing approaches in software development in accordance with WITTE, GRIMME and the standard published of the Institute Of Electrical and Electronics Engineers are combined. The characteristics of test organization, infrastructure and execution specified in the standard are made applicable in WITTE by a theoretical basis to the practical approach [17,18]. GRIMME gives additions to test procedures and environments [19]. This results in five phases and 11 steps, shown in Figure 3.

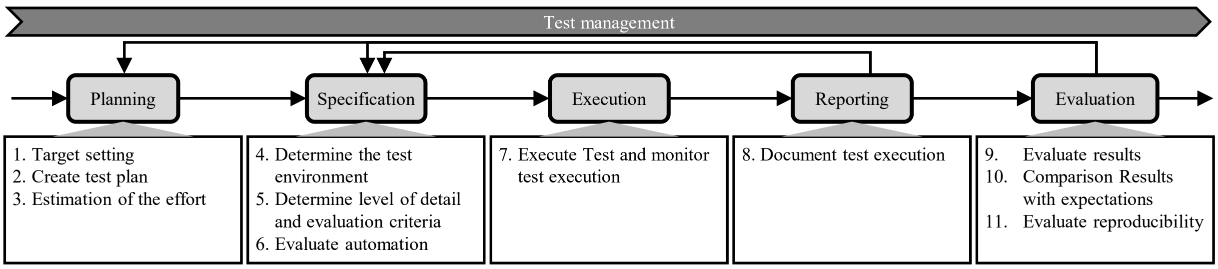

Figure 3: Testing strategy based on [17–19]

The eleven steps of the testing strategy are assigned to the phases of planning, specification, execution and reporting. The individual phases are not to be processed strictly one after the other and partly overlap in time. A continuous test management supports the phases. The planning includes the **target definition**, creation of the **test plan** and the **estimation of the effort**. Test effort and benefit should be plannable and predictable. The relationship between effort and benefit should be constantly optimized from the point of view of economic efficiency. In the specification, the **test environment** is described. When defining the test environment, the hardware, middleware and software used are specified, as well as properties of the organization, test data used, simulation, operational components and various configurations. These properties should be mapped under conditions close to production. A realistic environment, detailed documentation and the use of appropriate test tools improve test results. Next, the **level of detail as well as the evaluation criteria** are determined and **test automation** is evaluated. This is followed by the test **execution including monitoring**. The test is **documented** in the reporting. Finally, the evaluation takes place. In the evaluation, the **results are analysed** and **compared with expectations**. When comparing results to expectations, two questions will be answered. First, whether the objectives were achieved and second, what deviations occurred and how they can be explained. The **reproducibility** of the results for evaluating the suitability of the testing strategy is also examined. It allows conclusions about quality of the test strategy. The results should not be collected randomly or under unknown boundary conditions. The aim is to identify deviations in the results, explain their significance and make a final assessment.[17–19]

3.2 Specification for capacity-based order release in MSAS

The **target** of the test is to validate the functionality of the methodology for capacity-oriented, agent-based order release in MSAS. It shall be shown whether the methodology fulfils the underlying six requirements for order release in MSAS. Furthermore, the added value of the methodology compared to a random order release in MSAS shall be shown. The **test plan** includes the definition of six different test cases to validate each of the requirements for the methodology. The six test cases are executed sequentially. During the execution, data is collected on the production characteristics and, depending on the test case, the lead time, the waiting and transport time or the utilization of the assembly stations are considered and compared. Data is processed and presented in diagrams. To do justice to **effort** in comparison to benefit, the black-box testing method is used in this testing strategy. Black-box testing is a simple and widely used method. It tests the essential functionality of the application without going into the implementation level details [19]. The goal is to determine if the user's original requirements are met and to identify faulty functionality.

For the design of the **test environment** in a matrix-structured system, the number of assembly stations is described in advance. These determine the assembly layout. It should also be specified how many orders will be fed into the system and how many product types will be produced. Variations in these characteristics should be considered during testing. The **level of detail and the evaluation criteria** are set up in form of six test cases. The evaluation is based on KPIs. Depending on the test case process times or the capacity utilization of the assembly stations is analysed. The **execution** of the individual test case**s** is performed in the evaluation environment. This is done automatically. However, data analysis and evaluation are performed manually. A complete implementation for **test automation** in this use case would significantly exceed the effort compared to the benefit. Consequently, automation is not required here. The test cases are implemented in the evaluation environment to perform multiple simulations. The evaluation environment is also used for Monitoring and provides the required productivity metrics for data evaluation. The **test documentation** is ensured by a structured data export of KIPs generated during simulation via the agents representing orders and assembly stations. Simulation aborts or misbehaviour are manually logged. The data export is used to **evaluate the results**. The results are **compared with the expectations** defined in advance and the deviations are examined. It is expected that the developed order release methodology can meet the properties for order release in MSAS which have been stated before. By using the agent-based, capacity-oriented approach different sequences of assembly operations should be anticipated, bottlenecks should be avoided and different weighting factors for order release should be considered. The **reproducibility** is verified by the applicability in the evaluation environment. Nevertheless, the tests are performed three times to support the significance of the data generated during simulation.

4. Application and results

4.1 Test cases

For each property, one specific is defined. The **first test case** examines capacity analysis at the operation and system levels. For this purpose, the various process times of the average lead time, processing time, transport time and waiting time of all orders are examined as a first step. The obtained data is compared with the different types of order release agents as CBD and RPD during simulation execution. For RPD, there are consistently 16 orders in system according to the number of assembly stations to model a ConWIP control. Second, this test case examines the workloads of the assembly stations and the overall workload for overloads. The **second test case** examines the extent to which the order release methodology considers different paths an order takes through the assembly system by evaluating the corresponding sequences of assembly operations. Therefore, the number of sequences and capacity profiles calculated and considered by the CBD are analysed. To validate the requirement of the event-based release logic, test environment is adapted to create a bottleneck at an assembly station for the **third test case**. In addition, there is a disorder in the system. Here, the responsiveness of the agent is evaluated. The **fourth test case** is to validate the adjustability of individual manufacturing goals. As an individual manufacturing goal, for example, the focus can be set on a certain operation to prioritize the processing of this operation. To validate this feature, weighting shall be shifted to a specific operation and an analysis of the utilization of the assembly stations shall be performed. Individual properties are also considered in the order release methodology. The properties can be the weighting of a delivery date, a margin, or a product. The **fifth test case** is used to test the property that an urgent delivery date of an order leads to an earlier order release due to the higher weighting. Margins or product weightings are neglected here at first. Release times and delivery dates of the orders are compared for evaluation. The practicability of the order release methodology in MSAS is evaluated using an acceptance test for the **sixth test case**. The acceptance test verifies the scalability of the CBD. Therefore, one parameter of each test case is incrementally increased during the execution, presenting larger problem instances. Secondly, the sixth test case evaluates the added value of the CBD. Similar to the first test case, KPIs are accessed after certain simulation runs using CBD and RPD. The added value is highlighted by comparing the process times.

To run the test cases, a notional use case is chosen. The individual precedence graphs of each product are presented in Figure 4.

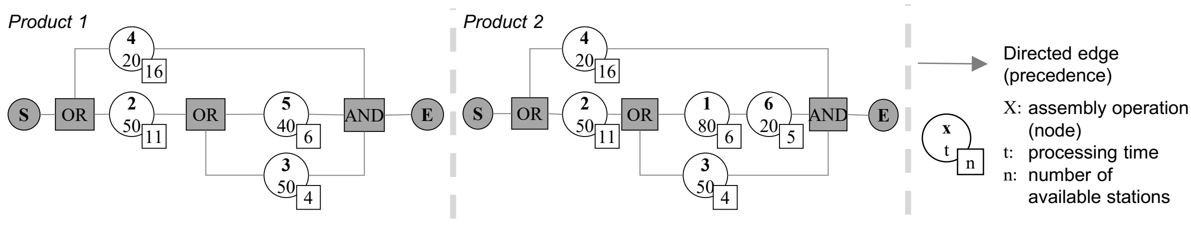

Figure 4: Assembly precedence graphs of Product 1 and Product 2

The use case contains two fictional product types. For assembly, six different operations are performed. Based on possible sequences for assembly, eight sequences can be derived for Product 1 and 15 possible sequences for Product 2. The layout contains 16 assembly stations (see Figure 5).

Each station has specific capabilities, resulting in multiple assembly operations that can be conducted. The numbers shown in each assembly station represent the possible operations. The total simulation time is determined by the processing time of a set 50 orders of each product type. The number of capacity profiles to be considered was limited to a number of 100. This is to circumvent the known NP-hardness of the CBD that is caused by the consideration of all assembly sequences an order can take leading to an exponential growth of the number of capacity profiles and corresponding calculations. The limitation ensures a stable test environment. If promising results are obtained despite this limitation, functionality and added value can still be demonstrated.

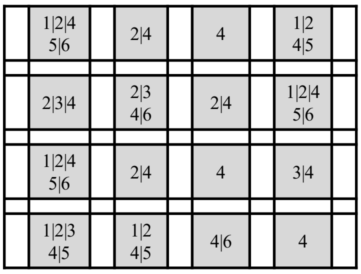

Figure 5: Assembly station layout and possible operations

4.2 Results

Functionality of the Capacity Based Dispatcher can be fully validated in almost all aspects. The **first test case** has shown that, as expected, no bottlenecks occur in the assembly system when performing a capacity analysis at operation and system level. The stations are utilized according to available capacity. In the **second test case**, it was found that the order release methodology considers different assembly sequences according and includes 100 capacity profiles in the evaluation. In addition, the CBD responds in real time to different situations in the system. For example, in the **third test case**, a corrected disruption in the assembly system and the resulting increase in available capacity leads to an additional order release. The **fourth test case** was also able to meet almost all expectations. Depending on how utilized the assembly system already is, certain assembly stations can be utilized to a greater extent by weighting individual operations. In addition, the **fifth test case** confirms the realization of early release of orders with more urgent delivery dates. Only in terms of scalability the expectations could not be met to the full extent in the **sixth test case**. Increasing certain parameters leads to memory leaks and deadlocks in simulation. As a possible improvement of this deficit in application of CBD, use of higher computing power could be mentioned. Moreover, reproducibility of the results is fully achieved for all test cases. There are no significant deviations in the generated data of the individual test runs. By meeting these requirements, the use of the CBD already provides added value in this assembly system. In addition, better process times can be achieved by using the CBD instead of the RPD (see Figure 6).

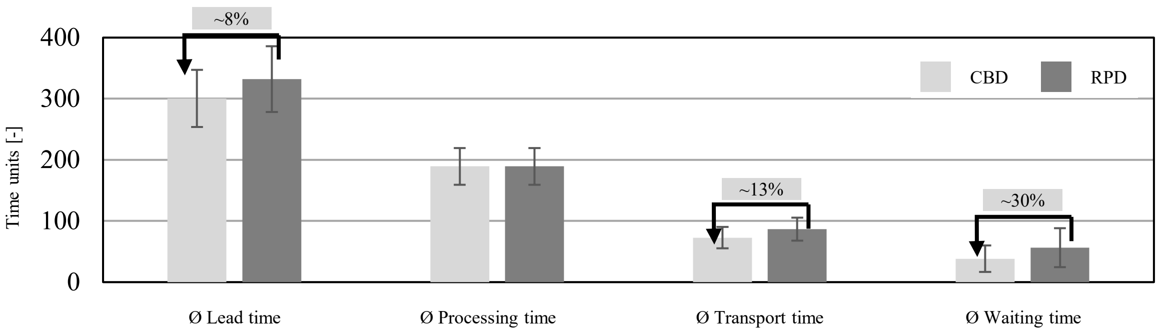

Figure 6: Process time distribution

Using CBD, an average decrease of 13% in transport times and 30% in waiting times can be achieved. This results in an 8% lower value for the total lead time. Since the CBD allows orders to be released only if they can be processed by the system in terms of capacity, shorter waiting times result. In addition, weighting is carried out according to transport routes. All simulation runs were performed three times with an Intel® Core™ i7-2620M CPU@2.70 GHz and 4 GB of RAM. No interruptions, deadlocks or errors were detected.

5. Discussion

The individual test cases were executed without any interruptions. In almost all cases, the results reflect the expectations defined in advance. Nevertheless, it should be critically considered that only one notional use case is used for execution so far. It should be investigated if other use cases e.g., with different arrangements of assembly stations or a higher variety of products lead to a significant different behaviour. Furthermore, the number of capacity profiles considered by the CBD was limited. Although results are promising, the correlation between obtained benefits and the considered capacity profiles can be further investigated. This, however, requires an improvement of the algorithms used for capacity profile generation and evaluation. A renewed execution with higher computing power should also be considered to examine if better results can be archived.

To sum up, the goal of this work was achieved. After developing and applying a testing strategy can validate the methodology for capacity-oriented, agent-based order release in MSAS, results deliver evidence for functionality and added value.

6. Summary and Outlook

Assembly control and its subtask order release is a major challenge in matrix-structured assembly systems. To address this, the authors presented a methodology for order release in a previous work. The suggested methodology performs a capacity analysis at operation and system level specifically. By this, different sequences resulting from sequence and routing flexibility can be considered in capacity analysis. The methodology suggests an event-oriented release logic. In addition, individual production targets as well as individual orders can be set. After implementing the former conceptual approach in an order release agent, this paper aimed to validate its functionality and added value. Thus, this paper introduced a testing strategy based on the fundamentals of successful testing in the field of software development. The testing strategy includes 11 steps that were applied to six test cases. It can be shown that all properties to successfully run a capacity-orientated order release for matrix-structured assembly systems can be widely fulfilled. Especially in comparison to random order release, also used by many researchers in the context of MSAS, the capacity-orientated order release improves lead times.

Further research should repeat the testing with larger problem instances and high-performance computing power. In addition, the implemented methodology is currently limited by the efficiency of its algorithms when calculating all possible sequences and matched capacity profiles to evaluate the capacity constraints, resulting in NP-hardness. Thus, the considered sequences and capacity profiles were limited for this work. Consequently, new solutions need to be found to ease this limitation.

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References

[1] Greschke, P., 2020. Matrix-Produktion: Konzept einer taktunabhängigen Fließfertigung, Norderstedt.

[2] Bebersdorf, P., Huchzermeier, A., 2021. Variabler Takt. Springer Berlin Heidelberg, 275 pp.

[3] Kern, W., 2021. Modulare Produktion. Dissertation.

[4] Kampker, A., Kreisköther, K., Burggräf, P., Dannapfel, M., Bertram, S., Wagner, J., Fischer, A., Knau, J., Grams, J., Bartl M., 2017. Agile Low-Cost Montage.

[5] Schukat, E., Rachner, J., Göppert, A., Adlon, T., Burggräf, P., Schmitt, R.H., 2022. Agent-based Order Release In Matrix Structured Assembly Systems. publish-Ing.

[6] Schönemann, M., Herrmann, C., Greschke, P., Thiede, S., 2015. Simulation of matrix-structured manufacturing systems. Journal of Manufacturing Systems 37, 104–112.

[7] Burggräf, P., Dannapfel, M., Adlon, T., Kahmann, H., Schukat, E., Holtwiesche, L., 2020. Multiagentensysteme in der Agilen Montage.

[8] Kern, W., Rusitschkab, F., Kopytynskib, W., Keckla, S., Bauernhansl, T., 2015. Alternatives to assembly line production in the automotive industry.

[9] Mayer, S., Arnet, C., Gankin, D., Endisch, C., 2019. Standardized Framework for Evaluating Centralized and Decentralized Control Systems in Modular Assembly Systems.

[10] Bondi, A.B., 2000. Characteristics of scalability and their impact on performance, 195–203.

[11] Koch, R., 2011. Systemarchitektur zur Ein- und Ausbruchserkennung in verschlüsselten Umgebungen. Zugl.: München, Univ. der Bundeswehr, Diss., 2011. Books on Demand, Norderstedt, 490 pp.

[12] Fynn, J.F., Hardeman, W., Milton, K., Jones, A.P., 2020. A scoping review of evaluation frameworks and their applicability to real-world physical activity and dietary change programme evaluation. BMC public health 20 (1), 1000.

[13] Werkzeugmaschinenlabor WZL der RWTH Aachen. Agile Assembly. https://www.produktionssysteme.rwth-aachen.de/agile-montage/.

[14] Corsten, H., Sartor, C., 2005. Simulationsuntersuchungen zur Auftragsfreigabe bei Werkstattproduktion. Zeitschrift für Planung & Unternehmenssteuerung 16 (1), 27–52.

[15] Fernandes, N., Thürer, M., Pinho, T., Torres, P., Carmo-Silva, S., 2020. Workload control and optimised order release: an assessment by simulation. International Journal of Production Research, 3180–3193.

[16] Hendry, L., Wong, S., 1994. Alternative order release mechanisms: a comparison by simulation. International Journal of Production Research 32 (12), 2827–2842.

[17] Witte, F., 2016. Testmanagement und Softwaretest. Springer Fachmedien Wiesbaden, 274 pp.

[18] Institute of Electrical and Electronics Engineers. IEEE Standard for Software and System Test Documentation, Piscataway, NJ, USA, 132 pp.

[19] Grimme, C., 2011. Strategien für den Aufbau und Betrieb von Testumgebungen.

Biography

Prof. Dr.-Ing. Peter Burggräf (*1980) is scientific head of the Department of Factory Planning at the Laboratory of Machine Tools and Production Engineering WZL of RWTH Aachen University and has been head of the Institute of International Production Engineering and Management at the University of Siegen since 2017.

Tobias Adlon (*1989) has been head of department of Factory Planning at Laboratory of Machine Tools and Production Engineering WZL of RWTH Aachen University since 2020.

Esben Schukat (*1993) has been research associate in the Department of Factory Planning at Laboratory of Machine Tools and Production Engineering WZL of RWTH Aachen University since 2019. In 2022 he took over the group lead of the research group 'Assembly Planning' while continuing his research activities on matrix-structured assembly systems.

Nina Katharina Weber (*1999) has been student research assistant at the Laboratory of Machine Tools and Production Engineering WZL of RWTH Aachen University since 2022.

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A Systematic Literature Review Of Blockchain-Based Traceability Solutions

Fabian Dietrich[1,2], Louis Louw[2], Daniel Palm[1,3]

[1]*ESB Business School, Reutlingen University, Alteburgstr. 150, 72762 Reutlingen, Germany*
[2]*Department of Industrial Engineering, Stellenbosch University, 145 Banghoek Rd., 7600, Stellenbosch, South Africa*
[3]*Fraunhofer Institute for Manufacturing Engineering and Automation, Alteburgstr. 150, 72762 Reutlingen, Germany*

Abstract

Blockchain technology shows great potential in providing object-related end-to-end traceability in complex multitiered supply networks. However, the first systematic literature reviews indicate the immaturity of current blockchain-based solutions and highlight difficulties in assessing their object traceability capabilities. Therefore, this paper provides a systematic literature review of blockchain-based traceability solutions and analyses their object-related mapping capabilities. As the systematic literature reveals, the vast majority of the identified traceability solutions deal with low-complexity architectures without the ability to map objects' compositional changes. Here, food and medical supply chains represent the most dominant domains. Supply chains in the automotive and manufacturing domain place the highest requirements for mapping object-related supply chain events. In this context, solutions incorporating the tokenisation of objects show the most advanced object-related mapping capabilities. However, the identified advanced solutions show limitations regarding their ability to map object deletions, aggregations, and disaggregations. Furthermore, current blockchain-based traceability solutions provide only limited validations based on industrial case studies.

Keywords

Blockchain; Traceability; Supply Chain; Object Mapping; Supply Chain Event Mapping

1. Introduction

In 2016, Abeyratne and Monfared published the first concept adopting an emerging technology – the blockchain technology – in manufacturing supply chains as a potential solution for solving their end-to-end traceability problems [1]. Blockchain technology, which Satoshi Nakamoto first introduced in 2008 [2], "is a multi-party system in which all participants or an agreed fraction of participants reach a consensus over shared transaction data summarised in linked data blocks and their validity, resulting in a linear and immutable chain of data blocks without requiring a central coordinator" [3]. In particular, blockchain technology's capabilities of providing a superordinate system without requiring a trusted third party, while still ensuring a secure, transparent, and immutable environment with globally unique 'digital profiles', brought it onto the map as a potential solution to the problem of achieving end-to-end traceability in complex multitiered supply networks [1,4,5]. Nowadays, such 'digital profiles' are referred to as blockchain tokens, which, generally, are "blockchain-based abstractions that can be owned and that represent assets, currency, or access rights" [6].

As a review and bibliometric analysis conducted by Fang, Fang, Hu, and Wan [7] reveals, over the years, technology-wise, the term 'blockchain' has become the most frequently used keyword related to supply

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chain management in recent publications. Accordingly, various blockchain-based traceability solutions have arisen, making blockchain technology arguably the "most promising technology for providing traceability-related services in supply chain [abbreviation deleted] networks" [8]. Olsen and Borit define traceability "as the ability to access any or all information relating to that which is under consideration, throughout its entire life cycle, by means of recorded identifications" [9]. Interconnected traceability systems map objects through their object-related supply chain events [10] – also referred to as object-related 'visibility events' [11]. The international standard IEC 62507 distinguishes between physical and abstract objects in a traceability context. In contrast, an object-related supply chain event "is the record of the completion of a specific business process step acting upon one or more objects" [11]. Here, the Electronic Product Code Information Services (EPCIS) standard – which represents the most frequently applied standard in industrial traceability systems [12] – defines the following core supply chain events: Object creation and deletion, object aggregation and disaggregation, object transformation, and object transaction [11].

2. Rational and methodology of the paper

A systematic literature review by Chang and Chen [13] reviewed potential blockchain applications and their development status in the supply chain management domain to identify future trends. As a result, the authors identify that the vast majority of blockchain-based publications address traceability and transparency issues in supply chains. A further literature review conducted by Dasaklis et al. [8] specifically focuses on the implementation state of blockchain-enabled traceability solutions. As a result, the authors point out that even though blockchain-enabled traceability implementations encompass various supply chain domains, they currently lack advanced and functional interfaces and validations in industrial settings, making it difficult to assess the quality of the proposed solutions. Dasaklis et al. [8] state the hypothesis that each traceability problem may require a different blockchain platform since the design of most architectures aims to solve a specific problem in a particular supply chain domain without showing general-purpose capabilities.

Building on the results of previously conducted systematic literature reviews, the systematic literature review provided in this publication intends to identify existing blockchain-based traceability solutions to evaluate their state regarding their mapping capabilities and to identify future trends. In addition, this review intends to point out the development of solutions in comparison to an past review and analysis from 2020 [14]. For the systematic literature review, this publication follows the guideline by Xiao and Watson [15], which consists of three different phases. **Figure 1** shows the process flow of the systematic literature review.

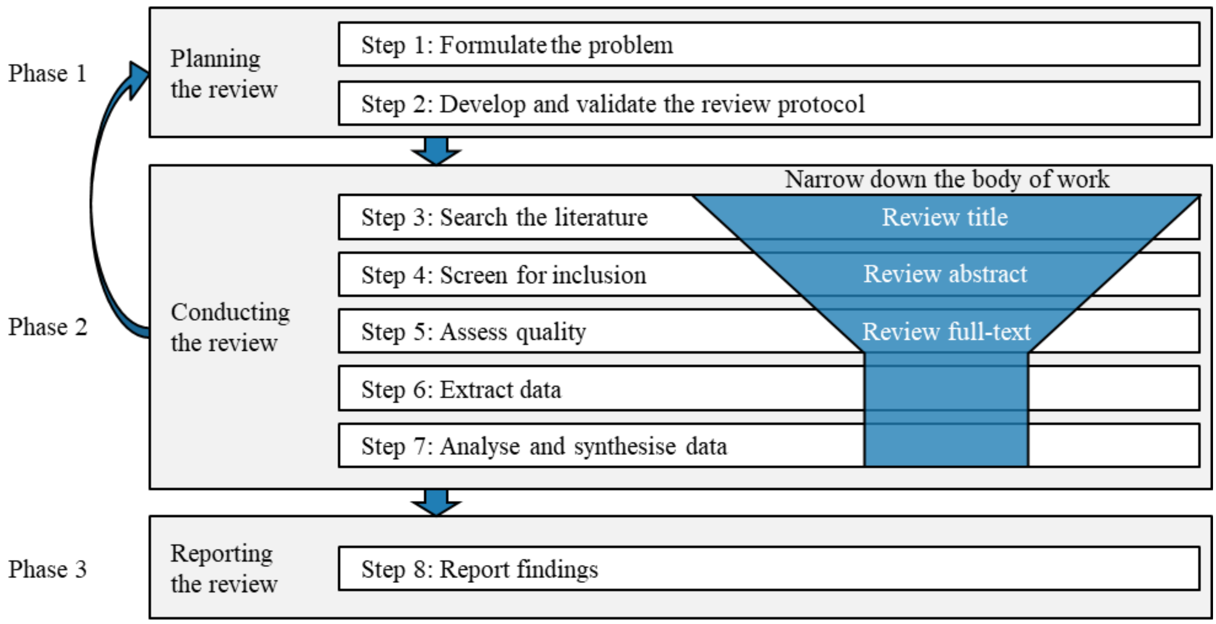

Figure 1: Process flow of the systematic literature review (based on [15])

Phase 1 guides the systematic literature review by defining a research question. The research question aims to investigate the mapping capabilities of blockchain-based traceability solutions described in the literature.

Research question: What are the object-related mapping capabilities of blockchain-based traceability solutions described in the literature?

In addition to the research question, a purposive review protocol defines the literature selection process. It represents the research design for the systematic literature review specifying methods, boundary conditions, and quality measures [16]. This also involves an explicit description of the inclusion and exclusion criteria to limit selection bias on the reviewer's part [17]. For the selection of literature databases, the review of this publication takes into account the results of previously conducted systematic literature reviews in the blockchain and supply chain management domain by Chang and Chen [13] and Dasaklis et al. [8]. These reviews show that, in particular, the literature databases IEEE Xplore and MDPI contain a significant part of blockchain publications in supply chain management. In addition to these literature databases, this publication's systematic literature review supplements these two databases with Scopus and the Google Scholar search engine for the initial search. Furthermore, this publication extends the systematic literature review methodology of Xiao and Watson [15] with the 'snowballing' procedure proposed by Wohlin [18] to ensure a complete overview of all relevant publications – also beyond the initially listed literature databases. This procedure iterates until it no longer leads to additional publications.

The publication by Abeyratne and Monfared [1] represents one of the first rough concepts described in literature connecting blockchain technology and supply chain management. Based on this scientific starting point, the systematic literature review considers publications published in the time span from January 2016 to March 2022. This review includes only peer-reviewed publications describing advanced architectures, concepts, and frameworks written in English. Here, the term 'advanced' refers to publications that provide at least a proof of concept, such as initial experiments, which explicitly excludes rough concepts without any hints of theoretical or practical feasibility. For the initial search, the systematic literature review searches for the following predefined set of terms within publication titles, abstracts, and keywords: 'Supply Chain' OR 'Supply Chain Management' AND 'Blockchain' OR 'Blockchain Technology' AND 'Traceability'.

3. Data extraction

The data extraction consists of two iterations. The first iteration extracts methodology, industry/domain, project objective, and object complexity from all included studies. Here, object complexity refers to the ability of the proposed solution to map objects' changes in terms of their modular composition. While 'single' indicates that the architecture only maps single objects, complex refers to the ability to map objects' compositional changes. Subsequently, the second iteration further classifies all publications dealing with complex objects regarding their general completeness in terms of mapping the object-related core supply chain events defined by the EPCIS standard [11].

When applying the research protocol, the search results in 57 publications included for data extraction. **Table 1** lists the identified literature, sorted by year of publication and alphabetically within the same publication year and extracts the research methodology, industry/domain, project objective, and the object complexity.

Table 1: Publications included for data extraction

No.	Source	Year	Methodology	Industry/domain	Project objective	Object complexity
1	[19]	2017	Architecture, pilot project	Medical supplies	Traceability, automation	Single
2	[20]	2017	Architecture, prototype	Retail	Traceability	Single
3	[21]	2018	Architecture, experiment	Food	Traceability, automation	Single
4	[22]	2018	Architecture, prototype	Wood	Traceability	Single
5	[23]	2018	Architecture, Prototype	E-commerce	Traceability, automation, payments	Single
6	[24]	2018	Architecture, prototype	Transport	Automation, payments	Single
7	[25]	2018	Concept, experiment	Food	Traceability	Single
8	[26]	2018	Architecture, pilot project	Food	Traceability	Single
9	[27]	2018	Architecture, experiment	Food	Quality assurance, disintermediation	Single
10	[28]	2018	Architecture, prototype	Food	Traceability	Complex
11	[29]	2018	Architecture, experiment	Transport	Traceability	Single
13	[30]	2018	Architecture, experiment	Food	Traceability	Single
12	[31]	2019	Framework, prototype	Food	Traceability	Single
14	[32]	2019	Architecture, experiment	Food	Traceability, disintermediation	Single
15	[33]	2019	Concept, experiment	Food	Traceability	Single
16	[34]	2019	Architecture, industrialisation	Transport	Traceability, automation, disintermediation	Single
17	[35]	2019	Architecture, experiment	Transport	Automation, payments, disintermediation	Single
18	[36]	2019	Architecture, experiment	Food	Traceability	Complex
19	[37]	2019	Architecture, prototype	Automotive	Traceability	Complex
20	[38]	2019	Architecture, prototype	Food	Automation, payments	Single
21	[39]	2019	Architecture, prototype	Automotive	Traceability	Complex
22	[40]	2019	Architecture, experiment	Food	Traceability, quality assurance	Single
23	[41]	2019	Architecture, experiment	Medical supplies	Traceability	Single
24	[42]	2019	Architecture, prototype	Automotive	Traceability	Complex
25	[43]	2019	Architecture, prototype	Food	Traceability, disintermediation	Single
26	[44]	2019	Architecture, prototype	Medical supplies	Traceability	Single
27	[45]	2019	Architecture, experiment	Food	Traceability	Single
28	[46]	2019	Architecture, experiment	Transport	Traceability, payments	Single
29	[47]	2019	Architecture, prototype, case study	Food	Traceability	Single
30	[48]	2019	Architecture, prototype	Food	Traceability	Complex
31	[49]	2019	Architecture, prototype	Manufacturing	Traceability	Complex
32	[50]	2020	Architecture, prototype	Manufacturing	Traceability, disintermediation	Single
33	[51]	2020	Architecture, prototype,	Food	Traceability, payments	Single
34	[52]	2020	Architecture, experiment	Medical supplies	Automation, payments, disintermediation	Single
35	[53]	2020	Architecture, case study	Retail	Automation, payments, disintermediation	Single
36	[54]	2020	Architecture, prototype	Manufacturing	Traceability	Single
37	[55]	2020	Architecture, prototype	Medical supplies	Traceability	Single
38	[56]	2020	Architecture, prototype	Food	Traceability	Single
39	[57]	2020	Architecture, prototype	Medical supplies	Traceability	Single
40	[58]	2020	Architecture, prototype	Food	Traceability	Single
41	[59]	2020	Architecture, prototype	Food	Traceability	Single
42	[60]	2020	Architecture, prototype, case study	Medical supplies	Traceability	Single
43	[61]	2020	Architecture, prototype	Food	Traceability, automation, payments	Single
44	[62]	2020	Architecture, experiment	Transport	Traceability	Single
45	[63]	2020	Architecture, prototype	Manufacturing	Traceability	Complex
46	[64]	2020	Architecture, prototype	Food	Traceability	Single
47	[65]	2020	Architecture, prototype	Medical supplies	Traceability, disintermediation	Single
48	[66]	2021	Architecture, prototype	E-commerce	Traceability, disintermediation	Single
49	[67]	2021	Architecture, prototype, case study	Manufacturing	Traceability	Complex
50	[68]	2021	Architecture, prototype	Medical supplies	Traceability, disintermediation	Single
51	[69]	2021	Architecture, prototype	Medical supplies	Traceability	Single
52	[70]	2021	Framework, prototype	Food	Traceability, disintermediation	Single
53	[71]	2021	Architecture, prototype	Food	Traceability	Single
54	[72]	2021	Architecture, prototype	Food	Traceability	Single
55	[73]	2022	Architecture, prototype	Food	Traceability	Single
56	[74]	2022	Architecture, prototype	Medical supplies	Traceability	Single
57	[75]	2022	Architecture, prototype	Food	Traceability	Single

The second iteration aims at further classifying all solutions dealing with complex objects. Accordingly, **Table 2** lists all publications with the ability to map complex objects and classifies them regarding their object-related mapping capabilities according to the supply chain events defined by EPCIS [11].

Table 2: Data extraction of publications dealing with the mapping of complex objects

No.	Source	Object event		Aggregation event		Transformation	Transaction
		Create	Delete	Aggregate	Disaggregate		
10	[28]	x		x			x
18	[36]	x				x	x
19	[37]	x				x	x
21	[39]	x				x	x
24	[42]	x				x	x
30	[48]	x		x			x
31	[49]	x		x		x	x
45	[63]	x		x		x	x
49	[67]	x		x		x	x

4. Data analysis and synthesis

The extraction of the first iteration results in a total number of 57 publications describing architectures (53), concepts (2), and frameworks (2). Most publications validate the solution based on prototypes (38), followed by experiments (15), case studies (4), pilot projects (2), and industrialisation (1), whereas some publications combine a prototypical validation with case studies. Experiments differ from prototypes in terms of completeness. While prototypes implement all required components, experiments prove the feasibility based on implementing only certain key elements. Solutions for food supply chains (27) represent the most dominant industry/domain among the identified publications, followed by medical supplies (11), transport (6), manufacturing (5), automotive (3), e-commerce (2), retail (2), and wood (1). In total, 51 publications aim to improve the traceability of objects, representing the identified solutions' major objective. Since solutions can have several objectives, 12 publications mention disintermediation as an objective, 10 automation, 8 payments, and 2 ensuring quality. Furthermore, a vast majority of the publications only present solutions with the ability to map single objects (48), while only 9 publications include solutions with the ability to map complex objects. **Figure 2** illustrates these findings and their distribution among the identified publications.

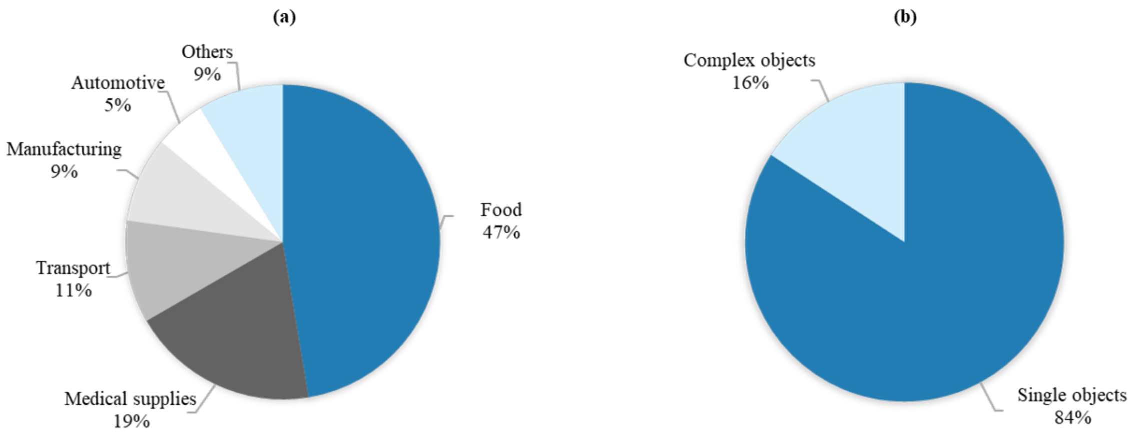

Figure 2: (a) Industry/domain distribution; (b) Mapping complexity distribution

All publications with the ability to map complex objects show incompleteness regarding the capabilities to map the supply chain events defined by EPCIS [11]. Nevertheless, the three solutions by Westerkamp et al. [63], Watanabe et al. [49], and Kuhn et al. [67] – all adopting the tokenisation of objects – represent the most advanced solutions in this comparison. However, the analysis of their object-related mapping capabilities reveals the following limitations:

Token deletion. The advanced solutions do not describe the possibility of an explicit token deletion. For example, the traceability architectures by Westerkamp et al. [63] and Watanabe et al. [49] provide logic for 'consuming' tokens. Here, consumed tokens receive a mark indicating their state to avoid the reusability of consumed tokens in further token recipes. Kuhn et al. [67] describe a similar logic, but referring to the consumption of tokens as the 'burning' of tokens. Even though the logic to consume or burn tokens intentionally serves as functionality to avoid the reusability of tokens, for example, after assembling processes, this logic also allows the creation of a token recipe to remove tokens from the supply chain. Although all three architectures do not further specify this procedure, a recipe that consumes or burns its input tokens supposedly results in a new, albeit useless, 'waste token'. Therefore, strictly speaking, this logic does not allow the deletion of tokens in the sense of EPCIS [11].

Token aggregation. Kuhn et al. [67] point out the ill-suited capabilities of the applied token standard by Westerkamp et al. when mapping objects with great variety and assembly complexity. As a solution, Kuhn et al. [67] adopt a new token standard, which, however, only shows advantages when applying it to batches of fungible assemblies of various fungible components, such as incorporated by the electrical and electronic system case study of Kuhn et al. [67]. However, when mapping multiple non-fungible assemblies of the same type with non-fungible inputs of the same type, the solution by Kuhn et al. [67] reaches the same limitations as the solution by Westerkamp et al. [63].

Token disaggregation. Among the advanced solutions, only the architecture by Watanabe et al. [49] describes a mechanism for token 'forking'. The architecture of Westerkamp et al. [63] and Kuhn et al. [67] solely includes a logic for 'splitting' token batches, which describes distributing a share of a token batch to different owners. Westerkamp et al. [63] even state the missing ability for token disaggregations as a limitation of their architecture and refer to a possible example of packaging processes, which require the extraction of the original good when unpacking [63]. Even though the 'forking' described by Watanabe et al. [49] forks a token into two tokens, these forked tokens receive new identifiers and new smart contract addresses, which does not 'restore' the previously aggregated tokens and therefore does not solve the limitation mentioned by Westerkamp et al. [63] and represent a disaggregation according to EPCIS [11].

Case study validation. Among the advanced architectures, only the architecture of Kuhn et al. [67] provides – besides the prototyping-based validation – a validation with an industrial case study. Even though the authors claim general-purpose mapping capabilities transferable to a large number of manufacturing scenarios, the case study includes mapping several fungible assembly batches, which may not be common in other manufacturing supply chains. Particularly since Westerkamp et al. [63] state that mapping of delivery processes is a limitation of their token-based traceability solution, a general-purpose architecture requires further evaluation based on a case study from a logistics management perspective.

5. Key findings

This chapter summarises the key findings in accordance with the initially stated research question.

> *Research question: What are the object-related mapping capabilities of blockchain-based traceability solutions described in the literature?*

As the publication's systematic literature reveals, 84% of the identified traceability solutions deal with low-complexity solutions allowing the traceability of single objects without the ability to map objects' compositional changes. Domain-specific, this applies to 89% of the solutions in food and 100% in medical supply chains. This represents 27 (food supply chains) and 11 (medical supply chains) publications, the most dominant industries/domains among the 57 publications identified in this review. Besides the traceability's importance in these strongly represented domains, these results imply, on the one hand, the low complexity traceability requirements of food and medical supply chains. On the other hand, the strong propagation of these supply chains can result from the currently available low-complexity solutions that are sufficient for meeting their requirements.

This publication identifies three advanced blockchain-based traceability solutions – all of which apply the concept of object tokenisation – that show certain general-purpose capabilities among the nine identified architectures with the ability to map compositional changes. However, as the architecture analysis reveals, these architectures show limitations in their ability to map object-related supply chain events. This is necessary for ensuring end-to-end traceability in complex supply chains that involve dynamic sequences of object flows, such as in manufacturing or delivery supply chains. On a system level, this particularly applies to objects' deletion, aggregation, and disaggregation.

6. Conclusion

Blockchain technology shows great potential in providing object-related end-to-end traceability in contemporary supply chain networks. However, the majority of currently available blockchain-based traceability solutions incorporate low-complexity architectures without the ability to map objects' compositional changes – which is sufficient for some industries and domains such as food supply chains and medical supplies. Three advanced blockchain-based traceability solutions show certain general-purpose capabilities that can map compositional changes – all of which incorporate the concept of tokenisation of objects. However, the applied architectural means by the advanced solutions show limitations regarding their ability to map all object-related supply chain events and validations based on case studies from operations and logistics management perspectives. Therefore, in order to provide general-purpose blockchain-based traceability solutions for industries and domains with complex objects, such as the automotive industry and general manufacturing, further research is necessary to develop traceability architectures that show completeness regarding their ability to map object-related supply chain events as well as to validate their capabilities based on industrial case studies in various domains.

References

[1] S.A. Abeyratne, R.P. Monfared, Blockchain ready manufacturing supply chain using distributed ledger, International Journal of Research in Engineering and Technology 05 (2016) 1–10.

[2] S. Nakamoto, Bitcoin: A Peer-to-Peer Electronic Cash System, 2008, https://bitcoin.org/bitcoin.pdf, accessed 5 September 2022.

[3] F. Dietrich, L. Louw, D. Palm, Blockchain-Based Traceability Architecture for Mapping Object-Related Supply Chain Events, Sensors (Basel, Switzerland) 23 (2023).

[4] Y. Liu, Q. Lu, X. Xu, L. Zhu, H. Yao, Applying Design Patterns in Smart Contracts: A Case Study on a Blockchain-Based Traceability Application, Lecture Notes in Computer Science (2018) 92–106.

[5] R. Cole, M. Stevenson, J. Aitken, Blockchain technology: implications for operations and supply chain management, SCM 24 (2019) 469–483.

[6] A.M. Antonopoulos, G.A. Wood, Mastering Ethereum - Building smart contracts and DApps, O'Reilly Media, Tokyo, 2019.

[7] H. Fang, F. Fang, Q. Hu, Y. Wan, Supply Chain Management: A Review and Bibliometric Analysis, Processes 10 (2022) 1681.

[8] T.K. Dasaklis, T.G. Voutsinas, G.T. Tsoulfas, F. Casino, A Systematic Literature Review of Blockchain-Enabled Supply Chain Traceability Implementations, MDPI - Sustainability 14 (2022).

[9] P. Olsen, M. Borit, How to define traceability, Trends in Food Science & Technology 29 (2013) 142–150.

[10] GS1 Global Traceability Standard, GS1's framework for the design of interoperable traceability systems for supply chains, GS1, 2017.

[11] EPCIS, EPC Information Services (EPCIS) Standard, 2016, https://www.gs1.org/sites/default/files/docs/epc/EPCIS-Standard-1.2-r-2016-09-29.pdf, accessed 5 September 2022.

[12] I. Konovalenko, A. Ludwig, Event processing in supply chain management – The status quo and research outlook, Computers in Industry 105 (2019) 229–249.

[13] S. Chang, Y. Chen, When Blockchain Meets Supply Chain: A Systematic Literature Review on Current Development and Potential Applications, IEEE Access 8 (2020) 62478–62494.

[14] F. Dietrich, Y. Ge, A. Turgut, L. Louw, D. Palm, Review and analysis of blockchain projects in supply chain management, Procedia Computer Science 180 (2021) 724–733.

[15] Y. Xiao, M. Watson, Guidance on Conducting a Systematic Literature Review, Journal of Planning Education and Research 39 (2019) 93–112.

[16] P. Brereton, B.A. Kitchenham, D. Budgen, M. Turner, M. Khalil, Lessons from applying the systematic literature review process within the software engineering domain, Journal of Systems and Software 80 (2007) 571–583.

[17] A. Armitage, D. Keeble-Allen, Undertaking a Structured Literature Review or Structuring a Literature Review: Tales from the Field, The Electronic Journal of Business Research Methods 6 (2008) 103–114.

[18] C. Wohlin, Guidelines for snowballing in systematic literature studies and a replication in software engineering, International Conference on Evaluation and Assessment in Software Engineering 18 (2014) 1–10.

[19] T. Bocek, B. Rodrigues, T. Strasser, B. Stiller, Blockchains everywhere - a use-case of blockchains in the pharma supply-chain, IFIP/IEEE Symposium on Integrated Network and Service Management (IM) (2017) 772–777.

[20] K. Toyoda, P.T. Mathiopoulos, I. Sasase, T. Ohtsuki, A Novel Blockchain-Based Product Ownership Management System (POMS) for Anti-Counterfeits in the Post Supply Chain, IEEE Access 5 (2017) 17465–17477.

[21] M.P. Caro, M.S. Ali, M. Vecchio, R. Giaffreda, Blockchain-based traceability in Agri-Food supply chain management: A practical implementation, IoT Vertical and Topical Summit on Agriculture - Tuscany (IOT Tuscany) (2018) 1–4.

[22] S. Figorilli, F. Antonucci, C. Costa, F. Pallottino, L. Raso, M. Castiglione, E. Pinci, D. Del Vecchio, G. Colle, A.R. Proto, G. Sperandio, P. Menesatti, A Blockchain Implementation Prototype for the Electronic Open Source Traceability of Wood along the Whole Supply Chain, Sensors (Basel, Switzerland) 18 (2018).

[23] H.R. Hasan, K. Salah, Blockchain-Based Proof of Delivery of Physical Assets With Single and Multiple Transporters, IEEE Access 6 (2018) 46781–46793.

[24] J. Hinckeldeyn, K. Jochen, Developing a Smart Storage Container for a Blockchain-Based Supply Chain Application, Crypto Valley Conference (2018) 97–100.

[25] J. Hua, X. Wang, M. Kang, H. Wang, F.-Y. Wang, Blockchain Based Provenance for Agricultural Products: A Distributed Platform with Duplicated and shared Bookkeeping, IEEE Intelligent Vehicles Symposium 4 (2018).

[26] R. Kamath, Food Traceability on Blockchain: Walmart's Pork and Mango Pilots with IBM, The JBBA 1 (2018)

[27] P. Lucena, A. Binotto, F. Da Silva Momo, H. Kim, A Case Study for Grain Quality Assurance Tracking basedon a Blockchain Business Network, Symposium on Foundations and Applications of Blockchain (2018).

[28] S. Malik, S.S. Kanhere, R. Jurdak, ProductChain: Scalable Blockchain Framework to Support Provenance in Supply Chains, International Symposium on Network Computing and Applications (NCA) 17 (2018) 1–10.

[29] S. Ngamsuriyaroj, T. Likitttheerameth, A. Kahutson, T. Pathummasut, Package Delivery System Based on Blockchain Infrastructure, ICT International Student Project Conference (ICT-ISPC) 7 (2018).

[30] G. Baralla, S. Ibba, M. Marchesi, R. Tonelli, S. Missineo, A Blockchain Based System to Ensure Transparency and Reliability in Food Supply Chain, Lecture Notes in Computer Science 11339 (2018) 379–391.

[31] A. Arena, A. Bianchini, P. Perazzo, C. Vallati, G. Dini, BRUSCHETTA: An IoT Blockchain-Based Framework for Certifying Extra Virgin Olive Oil Supply Chain, IEEE International Conference on Smart Computing (SMARTCOMP) 7 (2019) 173–179.

[32] F.M. Bencic, P. Skocir, I.P. Zarko, DL-Tags: DLT and Smart Tags for Decentralized, Privacy-Preserving, and Verifiable Supply Chain Management, IEEE Access 7 (2019) 46198–46209.

[33] H. Huang, X. Zhou, J. Liu, Food Supply Chain Traceability Scheme Based on Blockchain and EPC Technology, in: M. Qiu (Ed.), Smart Blockchain, Springer International Publishing, Cham, 2019, pp. 32–42.

[34] T. Jensen, J. Hedman, S. Henningsson, How TradeLens Delivers Business Value With Blockchain Technology, MISQE 18 (2019) 221–243.

[35] R. Koirala, K. Dahal, S. Matalonga, R. Rijal, A Supply Chain Model with Blockchain-Enabled Reverse Auction Bidding Process for Transparency and Efficiency, International Conference on Software, Knowledge, Information Management and Applications (SKIMA) 13 (2019).

[36] Q. Lin, H. Wang, X. Pei, J. Wang, Food Safety Traceability System Based on Blockchain and EPCIS, IEEE Access 7 (2019) 20698–20707.

[37] D. Lu, P. Moreno-Sanchez, A. Zeryihun, S. Bajpayi, S. Yin, K. Feldman, J. Kosofsky, P. Mitra, A. Kate, Reducing Automotive Counterfeiting Using Blockchain: Benefits and Challenges, IEEE International Conference on Decentralized Applications and Infrastructures (DAPPCON) (2019) 39–48.

[38] D. Mao, Z. Hao, F. Wang, H. Li, Novel Automatic Food Trading System Using Consortium Blockchain, Arab J Sci Eng 44 (2019) 3439–3455.

[39] D. Miehle, D. Henze, A. Seitz, A. Luckow, B. Bruegge, PartChain: A Decentralized Traceability Application for Multi-Tier Supply Chain Networks in the Automotive Industry, International Conference on Decentralized Applications and Infrastructures (DAPPCON) (2019) 140–145.

[40] S. Mondal, K.P. Wijewardena, S. Karuppuswami, N. Kriti, D. Kumar, P. Chahal, Blockchain Inspired RFID-Based Information Architecture for Food Supply Chain, IEEE Internet Things J. 6 (2019) 5803–5813.

[41] H.L. Pham, T.H. Tran, Y. Nakashima, Practical Anti-Counterfeit Medicine Management System Based on Blockchain Technology, Technology Innovation Management and Engineering Science International Conference (TIMES-iCON) 4 (2019) 1–5.

[42] T. Reimers, F. Leber, U. Lechner, Integration of Blockchain and Internet of Things in a Car Supply Chain, IEEE International Conference on Decentralized Applications and Infrastructures (2019) 146–151.

[43] K. Salah, N. Nizamuddin, R. Jayaraman, M. Omar, Blockchain-Based Soybean Traceability in Agricultural Supply Chain, IEEE Access 7 (2019) 73295–73305.

[44] J. Shi, D. Yi, J. Kuang, Pharmaceutical Supply Chain Management System with Integration of IoT and Blockchain Technology, in: M. Qiu (Ed.), Smart Blockchain, Springer International Publishing, Cham, 2019, pp. 97–108.

[45] W. Sun, X. Zhu, T. Zhou, Y. Su, B. Mo, Application of Blockchain and RFID in Anti-counterfeiting Traceability of Liquor, IEEE International Conference on Computer and Communications 5 (2019).

[46] C. Toma, B. Talpiga, C. Boja, M. Popa, B. Iancu, M. Zurini, Secure IoT Supply Chain Management Solution Using Blockchain and Smart Contracts Technology, Innovative Security Solutions for Information Technology and Communication 11359 (2019) 288–299.

[47] Y.P. Tsang, K.L. Choy, C.H. Wu, G.T.S. Ho, H.Y. Lam, Blockchain-Driven IoT for Food Traceability With an Integrated Consensus Mechanism, IEEE Access 7 (2019) 129000–129017.

[48] S. Wang, D. Li, Y. Zhang, J. Chen, Smart Contract-Based Product Traceability System in the Supply Chain Scenario, IEEE Access 7 (2019) 115122–115133.

[49] H. Watanabe, T. Ishida, S. Ohashi, S. Fujimura, A. Nakadaira, K. Hidaka, J. Kishigami, Enhancing Blockchain Traceability with DAG-Based Tokens, International Conference on Blockchain (Blockchain) (2019) 220–227.

[50] Alkhader, Alkaabi, Salah, Jayaraman, Arshad, Omar, Blockchain-Based Traceability and Management for Additive Manufacturing, IEEE Access 8 (2020) 188363–188377.

[51] K. Gao, Y. Liu, H. Xu, T. Han, Hyper-FTT: A Food Supply-Chain Trading and Traceability System Based on Hyperledger Fabric, Communications in Computer and Information Science (2020) 648–661.

[52] T. Guggenberger, A. Schweizer, N. Urbach, Improving Interorganizational Information Sharing for Vendor Managed Inventory: Toward a Decentralized Information Hub Using Blockchain Technology, IEEE Trans. Eng. Manage. (2020) 1–12.

[53] M. Habib, M. Sardar, S. Jabbar, C. Faisal, N. Mahmood, M. Ahmad, Blockchain-based Supply Chain for the Automation of Transaction Process: Case Study based Validation, International Conference on Engineering and Emerging Technologies (ICEET) (2020).

[54] H.R. Hasan, K. Salah, R. Jayaraman, R.W. Ahmad, I. Yaqoob, M. Omar, Blockchain-Based Solution for the Traceability of Spare Parts in Manufacturing, IEEE Access 8 (2020).

[55] S. Kim, J. Kim, D. Kim, Implementation of a Blood Cold Chain System Using Blockchain Technology, Applied Sciences 10 (2020) 3330.

[56] F. Miatton, L. Amado, Fairness, Transparency and Traceability in the Coffee Value Chain through Blockchain Innovation, International Conference on Technology and Entrepreneurship - Virtual (ICTE-V) (2020).

[57] P. Pandey, R. Litoriya, Securing E-health Networks from Counterfeit Medicine Penetration Using Blockchain, Wireless Pers Commun (2020).

[58] I. Pradana, T. Djatna, I. Hermadi, Blockchain Modeling for Traceability Information System in Supply Chain of Coffee Agroindustry, International Conference on Advanced Computer Science and Information Systems (ICACSIS) (2020) 217–224.

[59] D. Prashar, N. Jha, S. Jha, Y. Lee, G.P. Joshi, Blockchain-Based Traceability and Visibility for Agricultural Products: A Decentralized Way of Ensuring Food Safety in India, Sustainability 12 (2020) 3497.

[60] N. Saxena, I. Thomas, P. Gope, P. Burnap, N. Kumar, PharmaCrypt: Blockchain for Critical Pharmaceutical Industry to Counterfeit Drugs, IEEE Computer 53 (2020) 29–44.

[61] A. Shahid, A. Almogren, N. Javaid, F.A. Al-Zahrani, M. Zuair, M. Alam, Blockchain-Based Agri-Food Supply Chain: A Complete Solution, IEEE Access 8 (2020) 69230–69243.

[62] Y. Wei, Blockchain-based Data Traceability Platform Architecture for Supply Chain Management, IEEE International Conference on Big Data Security on Cloud (BigDataSecurity), IEEE International Conference on High Performance and Smart Computing, (HPSC) and IEEE International Conference on Intelligent Data and Security (IDS) 6 (2020) 77–85.

[63] M. Westerkamp, V. Friedhelm, A. Kuepper, Tracing manufacturing processes using blockchain-based token compositions, Digital Communications and Networks 6 (2020) 167–176.

[64] X. Zhang, P. Sun, J. Xu, X. Wang, J. Yu, Z. Zhao, Y. Dong, Blockchain-Based Safety Management System for the Grain Supply Chain, IEEE Access 8 (2020) 36398–36410.

[65] P. Zhu, J. Hu, Y. Zhang, X. Li, A Blockchain Based Solution for Medication Anti-Counterfeiting and Traceability, IEEE Access 8 (2020) 184256–184272.

[66] C.-L. Chen, X. Shang, W.-J. Tsaur, W. Weng, Y.-Y. Deng, C.-M. Wu, J. Cui, An Anti-Counterfeit and Traceable Management System for Brand Clothing with Hyperledger Fabric Framework, Symmetry 13 (2021)

[67] M. Kuhn, F. Funk, G. Zhang, J. Franke, Blockchain-based application for the traceability of complex assembly structures, Journal of Manufacturing Systems 59 (2021) 617–630.

[68] A. Musamih, K. Salah, R. Jayaraman, J. Arshad, M. Debe, Y. Al-Hammadi, S. Ellahham, A Blockchain-Based Approach for Drug Traceability in Healthcare Supply Chain, IEEE Access 9 (2021) 9728–9743.

[69] S. Sadri, A. Shahzad, K. Zhang, Blockchain Traceability in Healthcare: Blood Donation Supply Chain, IEEE International Conference on Advanced Communication Technology (ICACT) 23 (2021) 119–126.

[70] L. Wang, L. Xu, Z. Zheng, S. Liu, X. Li, L. Cao, J. Li, C. Sun, Smart Contract-Based Agricultural Food Supply Chain Traceability, IEEE Access 9 (2021) 9296–9307.

[71] X. Wang, G. Yu, R.P. Liu, J. Zhang, Q. Wu, S. Su, Y. He, Z. Zhang, L. Yu, T. Liu, W. Zhang, P. Loneragan, E. Dutkiewicz, E. Poole, N. Paton, Blockchain-Enabled Fish Provenance and Quality Tracking System, IEEE Internet of Things Journal (2021).

[72] X. Yang, M. Li, H. Yu, M. Wang, D. Xu, C. Sun, A Trusted Blockchain-Based Traceability System for Fruit and Vegetable Agricultural Products, IEEE Access 9 (2021) 36282–36293.

[73] G. Varavallo, G. Caragnano, F. Bertone, L. Vernetti-Prot, O. Terzo, Traceability Platform Based on Green Blockchain: An Application Case Study in Dairy Supply Chain, Sustainability 14 (2022) 3321.

[74] H.T. Le, T.T.L. Nguyen, T.A. Nguyen, X.S. Ha, N. Duong-Trung, BloodChain: A Blood Donation Network Managed by Blockchain Technologies, Network 2 (2022) 21–35.

[75] L. Wang, Y. He, Z. Wu, Design of a Blockchain-Enabled Traceability System Framework for Food Supply Chains, Foods (Basel, Switzerland) 11 (2022).

Biography

Fabian Dietrich (*1993) has a Ph.D. in Industrial Engineering from Stellenbosch University and works as Research Project Coordinator at the ESB Business School. His research focuses on blockchain technology, supply chain management, and wireless communication technologies.

Louis Louw (*1974) has been an associate professor at Stellenbosch University since 2018. Previously Prof. Dr. Louis Louw spent twelve years in industry as a business consultant and senior manager, before joining the university in 2014. His research interests are in the field of Digital Operations & Supply Chain Management, and he is a member of the International Association of Learning Factories.

Daniel Palm (*1967) is a Professor of Supply Chain Management at the ESB Business School. Univ.Lektor Prof. Dr.techn. Dipl.-Ing. Daniel Palm is head of the teaching and research centre for Value-Added and Logistics Systems at Reutlingen University and the Reutlingen Center Industry 4.0, RZI 4.0 – a cooperation of the Fraunhofer Institutes IPA and IAO as well as Reutlingen University.

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Derivation Of MTM-UAS® Analyses From Virtual Reality Tools Using MTMmotion®

Martin Benter[1]

[1]*MTM-Institute/ MTM ASSOCIATION e. V., Zeuthen, Germany*
[2]*Institute/ Organisation, City, Country*

Abstract

Designing human work in a productive way plays a vital role in maintaining competitiveness of industrial companies. In order to fulfil this task, practitioners can use different methods to describe, analyse and design work processes. One widely used method is the process building block system MTM-UAS®. Analysing the work processes manually (with MTM-UAS® or other methods) requires manual effort for data collection and interpretation of the method user. Due to this fact, not every industrial company has the capacities to design work productively.

One possibility to reduce this effort is the automatic interpretation of digitized human motion data. Motion data describes human movements and includes, for example, distances covered, joint positions or object interactions. The technology virtual reality is capable to generate this movement data. Thanks to the advances in the technology in recent years, it can be used in a large number of workplaces.

This article presents an approach how one can use the motion data of virtual reality tools to derive an automated MTM-UAS® analysis. The technology thus reduces the analysis effort significantly and offers the possibility of expanding the areas of application. First, the article explains the process building block system MTM-UAS®. It then explains the virtual reality data that is needed to automatically generate MTM-UAS® analyses and that can be generated by the virtual reality tool. It then shows how the data is translated into a valid MTM-UAS® analysis. The Steps are explained using an exemplary workplace that was modelled using a virtual reality tool.

The article concludes with an outlook on how this approach can be transferred to other technologies like human simulation. With such a transfer it is conceivable to design a higher number of workplaces in a productive way and thus to maintain the competitiveness of industrial companies.

Keywords

digital human motion data; human work design; automated process analysis; MTM-UAS®; MTMmotion®

1. Introduction

One key factor for being competitive as an industrial company in international markets is the cost of production. One relevant portion of these costs are labour costs, especially for productions with a high share of manual processes. Thus, describing, analysing, and designing manual work processes in a systematic way is an important task in every Industrial Engineering department. By designing productive and healthy workplaces, companies can reduce the cost of production and make sure that the time of their employees is used for meaningful activities.

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There are multiple methods to describe and analyse work processes (i.e. REFA [1], MTM [2, 3, 4] or Work Factor [5]). One established method, especially in the automotive sector, is the process building block system MTM-UAS® [2, 6].

2. The process building block system MTM-UAS®

The process language MTM and its different process block building systems like MTM-UAS® are characterized by its own syntax and semantics. This provides the vocabulary as well as the grammar to describe work processes in an understandable and standardized way [2, 3, 4, 7].

The notation of each MTM process building block is characterized by multiple language elements [2, 3, 4, 7]. The code is the “name” or designation of a building block. For example, the code *KA* in MTM-UAS® describes the time relevant movement of the trunk. It is then characterized by a defined beginning, description and ending. The building block *KA*, for example, starts when the trunk begins to move and ends when the target location has been reached. Another language element are the influencing variables that further describe each building block [6].

In addition to these descriptive language elements, each building block has an evaluated standard time value. For the building block, that standard time is 25 TMU (Time Measurement Units, 25TMU equal approximately 0.9 seconds). These standard times are globally standardized and widely accepted in multiple industries (i. e. automotive or white goods). By describing a whole work process with the corresponding building blocks, the entire required time for that process can be calculated [6].

Motion Length in **cm**	≤ 20	> 20 to ≤ 50	> 50 to ≤ 80
Distance Class	**1**	**2**	**3**

Get and Place			**Code**	**1**	**2**	**3**
				TMU		
	Case of Get	Case of Place				
≤1 kg	easy	approx.	**AA**	20	35	50
		loose	**AB**	30	45	60
		tight	**AC**	40	55	70
	difficult	approx.	**AD**	20	45	60
		loose	**AE**	30	55	70
		tight	**AF**	40	65	80
	handful	approx.	**AG**	40	65	80
> 1 kg to ≤ 8 kg		approx.	**AH**	25	45	55
		loose	**AJ**	40	65	75
		tight	**AK**	50	75	85
> 8 kg to ≤ 22 kg		approx.	**AL**	80	105	115
		loose	**AM**	95	120	130
		tight	**AN**	120	145	160

Place	**Code**	**1**	**2**	**3**
		TMU		
approx.	**PA**	10	20	25
loose	**PB**	20	30	35
tight	**PC**	30	40	45

Motion Length in **cm**	≤ 20	> 20 to ≤ 50	> 50 to ≤ 80
Distance Class	**1**	**2**	**3**

Handle Tool	**Code**	**1**	**2**	**3**
		TMU		
approximate	**HA**	25	45	65
loose	**HB**	40	60	75
tight	**HC**	50	70	85

Operate	**Code**	**1**	**2**	**3**
single	**BA**	10	25	40
compound	**BB**	30	45	60

Motion Cycles	**Code**	**1**	**2**	**3**
one motion	**ZA**	5	15	20
motion sequence	**ZB**	10	30	40
re-position and one motion	**ZC**	30	45	55
tighten or loosen	**ZD**	20		

Body Motions	**Code**	**TMU**
Walk / m	**KA**	25
Bend, Stoop, Kneel (incl. arise)	**KB**	60
Sit and Stand	**KC**	110

Visual Control	**VA**	15

Figure 1 MTM-UAS®-Data Card Basic Operations

Figure 1 shows all the process building blocks (here: basic operations) for MTM-UAS®. They are divided into *Get and Place, Place, Handle Tool, Operate, Motion Cycles, Body Motions and Visual Control*. The Figure also shows the central influencing factors for these motions like the *Distance Class* or the *Case of Place*.

3. Exemplary workplace

To demonstrate the interface data as well as the results of the translation algorithm, an exemplary workplace will be used. In this case, the worker preassembles a module for a dish washing machine, which consists of a component carrier, two pumps, several hoses, screws, and other small parts. The complete process has a duration of about 2 minutes, but this article focuses on the last step of the process, which is fastening the pumps with screws.

The process was modelled in a virtual reality (VR) tool developed by the company LIVINGSOLIDS [8]. This VR solution uses a VR headset and handheld controllers. To allow for tracking the body motions it also uses marker-based motion capture cameras. With that VR setup, a worker assembled the product in the virtual reality application.

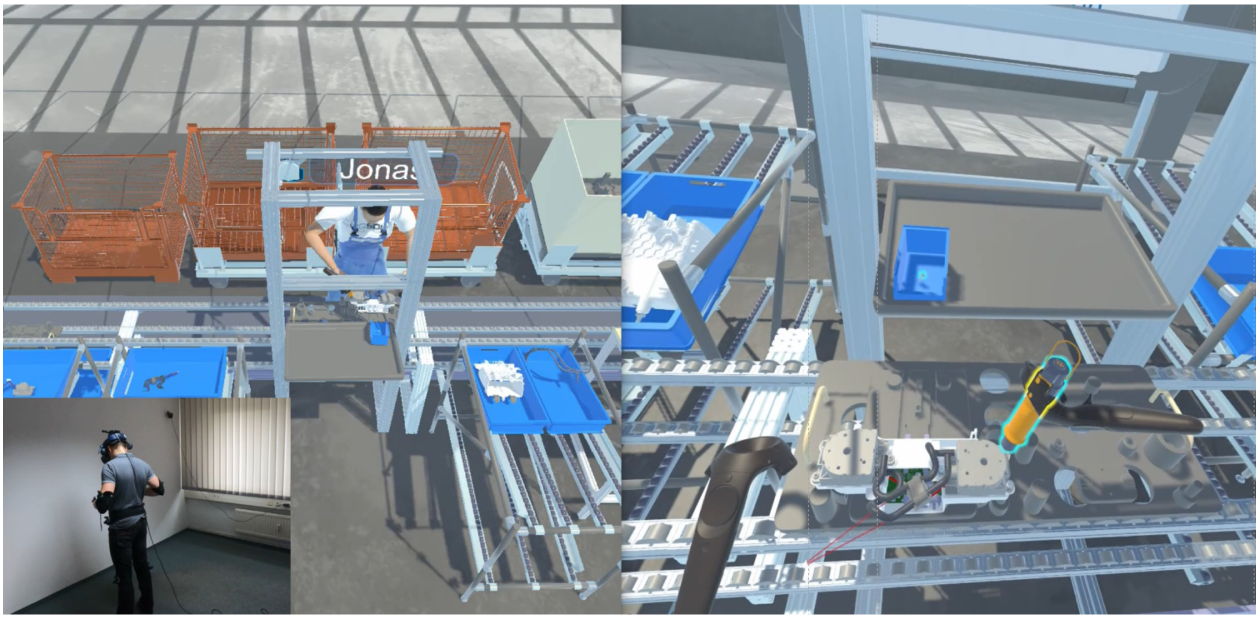

Figure 2 views of the LIVINGSOLIDS virtual reality tool

Figure 2 shows several images of the usage of the software during the recording. On the lower left, one can see the worker wearing the VR components. Above this is the view of the software on the main computer, while the right side shows the view of the worker. In the shown moment, the worker is assembling a screw using an electric screwdriver.

4. Translation of virtual reality motion data using the MTMmotion® interface.

To realize the translation from the recorded data in the shown example to valid MTM-UAS®-analyses, the developed approach utilizes a uniform interface for motion data. The principle is depicted in Figure 3. Central element is the interface. It describes digital motion data in a way that allows digital tools like the VR solution by LIVINGSOLIDS to deduce it from their own inherit data structure. Furthermore, the data consists of all the necessary information to derive valid MTM-UAS® analyses. The data is described in chapter 4.1.

The next part of the approach is the mentioned deduction of the interface data from the VR software. In the shown case, LIVINGSOLIDS developed those algorithms and tested them in cooperation with the MTM ASSOCIATION. The last part is the derivation of a valid MTM-UAS®-analysis from the interface data. This process is described in chapter 4.2.

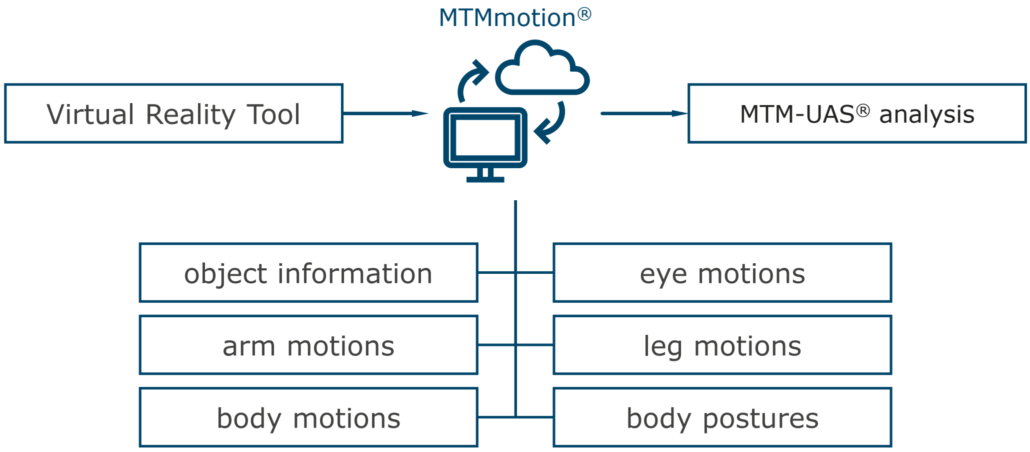

Figure 3 Derivation of MTM-UAS®-analyses form VR tools using MTMmotion®

4.1 MTMmotion® interface data

The interface contains all relevant data needed to describe the relevant movements and postures performed by an employee when executing a work task as well as the objects with which he/she interacts. It contains an object list and six motion channels that describe human work processes:

1. Object List
2. Channel Body Motions
3. Channel Arm Motions
4. Channel Leg Motions
5. Channel Eye Motions
6. Channel Body Posture
7. Channel Arm Posture

The Object List describes the objects being handled by the worker and their relevant values such as weight or measurements for a more specific description of the object. The Motion Channels (Body, Arm, Leg and Eye) describe the movements that are performed by the worker. The following channels depict the posture of the worker during his work task. Following, only the object list and the arm motions are shown for the example workplace. They contain the most relevant information for manual work tasks.

Table 1 MTMmotion® data – object list

object id	object type	weight [kg]	dimensions [mm]	flexible
1	screw	0.02	5x12x12	no
2	screwdriver	1.2	150x50x80	no
3	hose	0.2	10x10x100	yes

Various object information is required to derive MTM-analyses (see Table 1). *Weight, Height, Width,* and *Length* describe the physical properties of the object. In general, the larger or heavier an object is, the more difficult it is to handle and thus, the MTM standard time is higher. *Flexible* is another further physical property that can make the handling of the object more difficult.

In the exemplary workplace several objects are described in the object list. For the presented steps of our process, three objects are used. Screws and a corresponding screwdriver to assemble the screws and the hoses.

Table 2 MTMmotion® data – arm motions

time start	time end	object ID	side	arm motion	supply	usage type
51.0	51.5	2	right	ObtainObject	separated	-
51.5	52.5	2	right	MoveObjectTo OtherPosition	-	-
52.5	56.8	2	right	HoldObject	-	-
52.6	53.6	1	left	ObtainObject	clustered	-
53.6	54.4	1	left	MoveObjectTo PointOfUse	-	-
54.4	56.8	1	left	UseObject	-	place
56.8	57.8	2	right	MoveObjectTo PointOfUse	-	-
57.8	61.7	2	right	UseObject	-	screw in

Table 2 shows the necessary information for the channel arm motions. To describe the arm movements, it is important to know what type of movement (*motion*) is performed by the employee. The motions are differentiated according to whether an object is obtained, moved, used or held. The *Usage Type* differentiates the motion type *UseObject* further, because for most objects there are different ways to use the object. A screw could – at its point of use – be screwed in or inserted or just placed on a screwdriver tip. Additionally, object usages generally follow motion trajectories dictated by the object, while the other motion types can usually follow any trajectories chosen by the employee. As an example, the screwdriver can be brought to its place of use via multiple valid movement paths, but the insertion of the screw with the screwdriver and the following screwing process are predetermined by the component's geometry.

For each motion, various additional influencing variables are important to describe the individual movement. For example, it is relevant which arm (*side*) performs the movement. In addition, the *start* and *end time* of the movement are necessary to determine if it takes place at the same time as the movements of other body parts. There is also motion specific information like the *supply* for the motion type *ObtainObject*. It describes if the object is picked up from a box with several object (*clustered*) or if it is *separated*.

In the example workplace the worker firstly obtains the screwdriver, which hangs separated, with his right hand and moves it into the core working area. He then holds the screwdriver in position while he picks up a screw out of box full of screws with his left hand. He brings the screw to the screwdriver (point of use) and places the screw on the screwdriver. Lastly, he moves the screwdriver (with screw) to its point of use (the pump) and screws in the screw.

4.2 Derivation of MTM-UAS analyses®

The translation of the interface data into MTM analyses is the last step of the approach. This process consists of several steps:

1. Input data validation: Firstly, the algorithm checks if the input data is meaningful. This means that it checks if the handling of objects follows a meaningful order. For example, the algorithm would detect an error if objects were moved that were not obtained before.
2. Input data completion: In the next step the algorithm also checks whether the input data is complete. Although the interface contains all the information that is needed for a complete MTM-UAS® analysis, it is not necessary to put in every non-essential information. If this kind of information is

missing the algorithm fills it with standard data. For example, the algorithm would add an average screw weight if it wasn't given by the VR tool.

3. Translation into building blocks: One central step in the algorithm is the translation of the various motions into building blocks. In the case of MTM-UAS®, it combines the motions into basic operations. Here, it would combine all motions in Table 2 that relate to the screw into one *Get and Place*.
4. Combination of different body parts: The last step of the algorithm matches each motion channel with the other motion channels to check if there are parallel motions. If that is the case, the MTM rules are applied to check if they can be performed simultaneously in industrial workplaces. For example, the algorithm would check if the screw can be obtained and placed, while the other hand holds an object. In that case, it does not result in a conflict.

The result is of these four steps is a valid MTM-UAS® analysis that matches the interface data supplied by the VR tool. Table 3 shows the result for the example workplace. The analysis describes the assembly of the first two screws for the described work process. The result is a total standard time of 275 TMU (approx. 10 seconds).

To compare the results, an experienced MTM practitioner conducted a manual analysis using the video and the relevant object data as well as estimated distances. The automatically generated analysis from the VR input data matches the analysis without any differences.

Table 3 Automatically generated MTM-UAS® analysis

Description	Code	Q x F	TMU
Screwdriver into workspace	HA2	1 x 1	45
Place screw	AE2	1 x 1	55
Place screwdriver	PC1	1 x 1	30
Process time screwdriver	PTTMU	1 x 30	30
Place screw	AE2	1 x 1	55
Place screwdriver	PC1	1 x 1	30
Process time screwdriver	PTTMU	1 x 30	30
Sum	**-**	**-**	**275**

5 Conclusion and Outlook

5.1 Critical Discussion

The presented approach has shown good results for the first cases for VR technologies. However, there are some aspects that need to be discussed critically.

1. Completeness of VR data: Since the process relies on the shown data being transferred from the VR tool to the data interface, it is necessary that firstly, the tool can model said data in a VR simulation, and secondly, that the data is input correctly by the VR user. One example is the object data. If the simulation does not include object types or weights, the data cannot be translated, or the standard values provided by the algorithm are translated, which might not be correct for all cases.

2. Quality of the motion capture algorithm in the VR tool: To derive the correct process building blocks, the motions must be recorded properly by the VR tool. In the shown example case, all relevant motions were captured. The quality in a wide use must be checked in future cases.

3. Translation of motion data 'as provided': The approach translates the motion data without checking if it would make sense for the real product in a real production. That means that if the process is modelled wrong or unnecessarily complicated, the resulting MTM-UAS® analysis describes exactly that process. That's why it will still be necessary that an industrial engineer checks the modelled process and the MTM-UAS® analysis.

When those aspects are properly addressed, the approach can help industrial engineers to plan workplaces in a modern and efficient way. If they use VR technologies, they will need little effort to also get valid MTM analyses. It will be easier for them to model different variants and simultaneously get valid process descriptions and analyses, which helps choosing the best variants or to identify optimizations.

The interface was developed to be accessible for all technologies that record or generate motion data. As different technologies yield different data types as well as qualities while recording or generating motion data the quality of the resulting MTM analyses might differ as well. However, the developed approach was designed to yield analyses matching the input data and thus, the success of the approach is not impacted by the quality of the input technology.

5.3 Outlook

To improve the approach and thus its usability, several developments are possible. Firstly, the approach will be tested on several additional workplaces in industrial companies. Secondly, other VR tools will be enabled to supply the interface data. Thirdly, other MTM process building block systems such as MTM-1® or MTM-MEK® will be implemented. These steps aim to advance the combined use of VR and MTM in industrial companies.

Since the interface data is designed in a way that does not depend on the VR technology, it is possible to transfer the approach to other technologies that use digital motion data such as human simulation tools [i. e.] or motion capture suits [i. e.]. The transfer of this approach to other technologies would also offer starting points to develop interfaces that transfer motion data combined with process data from one technology to another.

References

[1] REFA, 1997. Datenermittlung. Carl Hanser, München.

[2] Bokranz R., Landau K., 2012. Handbuch Industrial Engineering. Produktivitätsmanagement mit MTM, 2., überarb. und erw. Aufl. Schäffer-Poeschel, Stuttgart.

[3] Antis, W., Honeycutt, J. M., Koch, E. N., 1969. Die MTM-Grundbewegungen. Maynard, Düsseldorf.

[4] Maynard, H. B., Stegemerten, G. J., Schwab, J. L., 1948. Methods-Time Measurement. McGraw Hill, New York.

[5] Quick, J. H., 1960. Das Work-Factor-System. Beuth, Berlin.

[6] MTM-UAS, 2019. Manual. MTM ASSOCIATION e. V. Hamburg.

[7] Kuhlang, P., 2018. Produktive und ergonomiegerechte Arbeit – Von Grundsätzlichem zur Prozesssprache MTM über die Ergonomiebewertung zu Human Work Design. In: ifaa, Leistung und Entgelt. Joh. Heider, Düsseldorf.

[8] LIVINGSOLIDS, 2022. www.livingsolids.de.

Martin Benter (*1986) did his doctorate at the Institute for Production Management and Technology at the Technical University of Hamburg in 2018. Since then, he is working for the MTM-Institute at the MTM ASSOCIATION e. V., where he focuses on the translation of digital motion data into MTM-analyses.

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Analysis of Strategic Business Ecosystem Role Models for Service-Oriented Value Creation Systems

Gerrit Hoeborn[1], Agustin Gonzalez[1]

[1]*FIR at RWTH Aachen University, Aachen, Germany*

Abstract

The way companies create service-oriented value is changing as organizational boundaries blur towards value creation in ecosystems. To position themselves strategically, practitioners need to understand the different roles in service-oriented value creation systems (SOVCS). Still, there is no evidence if existing role models can be applied for SOVCS. This paper analyses the adequacy of existing strategic role models for service-oriented business ecosystems. The suitability of the role models is evaluated using central aspects of the Service-Dominant Logic. We demonstrate that the existing central strategic role models cannot be transferred to a SOVCS and outline the research need for an adequate strategic role model. Scholars will find an overview of existing role models and use the conducted evaluation as a foundation for further service science research. Based on the identified inaccessibility, a comprehensive strategic positioning model can be developed.

Keywords

Business ecosystems; value co-creation; service-dominant logic; value creation system; Service ecosystems

1. Introduction

For decades it is known that companies do not create value in complete isolation, but often operate as part of a network or other collaboration form [1]. This interconnection between companies is favored by the increasing technological possibilities, which result in blurry boundaries between organizations and a more distributed value creation process [2,3]. In this interorganizational collaboration context, specially one value creation system (VCS) archetype: the business ecosystem (BE), gained relevance for practitioners and researchers. The servitization of many industries and the growing interest in BE call for interdisciplinary research combining those research streams [4,5]. In this context, the Service-Dominant Logic (SDL) presents a service-oriented framework to explain the creation of value [6,7].

Although through the development of the service ecosystem concept it was possible to combine the concept of SDL with the BE, to date there is no analysis that evaluates to what extent the different existent role constellations, denominated strategic role models, in BE as an archetype of VCS are adequate to model service-oriented value creation systems. This knowledge gap therefore offers an opportunity to advance in the field of service science, as well as an opportunity for practitioners seeking to position themselves in a service-oriented value creation systems to further develop their understanding of service-oriented role models.

To address this challenge, better the understanding of the value creation process according to the SDL and contribute to the strategic positioning for actors, this paper seeks to answer the following question: How adequate are the existing strategic role models for service-oriented value creation systems?

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2. Research Objectives

To answer the research question, our paper assesses the adequacy of the different strategic role models (SRM) by evaluating them based on criteria reflecting the service-oriented value creation process in accordance with the SDL. To achieve this, through a systematic literature review, we first identify groups of roles useful to describe how value creation in BE functions. After presenting the results of the systematic literature review on BE strategic role models, five central aspects derived from the eleven foundational premises from the SDL: a) resource integration, b) the user/customer role, c) service exchange, d) institutions & institutional arrangements and e) service innovation are further analysed. In conclusion, we present the results of the analysis, the insights gained through the evaluation and possible extensions of this paper that could be beneficial to further develop the understanding of SOVCS. As indicated, the focus of this paper is set on BE as a VCS archetype, therefore, from now on when mentioning VCS, reference will be made primarily to BE. Given that the SDL provides a meta-theoretical framework for understanding value creation, the results of the analysis are useful not only for BE, but also for other VCS where complex constellations of actors are present [8].

3. Value creation systems

Using the term "Value creating system" from Parolini (1999) as a reference, this paper introduces the term Value creation system as an overarching term to refer to the models such as cluster, value chain, value network, business ecosystem etc., which, although varying in their approaches, directly or indirectly explain the activities and processes that result in the creation of value [9]. The word system manages to capture the complexity and dynamism of the value creation process, as well as the flow and exchanges between the actors, an aspect that the term network does not manage to encapsulate completely [10]. A Value creation system is therefore a set of actors interacting with each other with different behaviours (cooperation, competition, or coopetition) performing activities with the main goal of creating value, generating monetary profit, and innovating in the process.

In this context, particularly the business ecosystem as an archetype of VCS has grown considerably in recent years; a search for the term ecosystem in the main strategy journals reveals that in the last five years alone, the number of articles has increased sevenfold [11]. Business ecosystems can be defined as an at least partially open structure made up of different interdependent, yet autonomous, actors who coordinate their activities towards a shared purpose to co-create value [12,13]. Unlike other VCS such as clusters or value networks, BE are characterized by the presence of competition and cooperation among the actors, also denominated coopetition, as well as by the co-evolution that takes place thanks to the intensive exchange of information and knowledge among the actors of a business ecosystem [14,15]. In the SDL, SE are seen as self-adjusting, relatively self-contained systems consisting of resource-integrating actors, which are connected through so called shared institutional arrangements as well as mutual value creation through service-exchange [10].

4. Role Models in Business Ecosystems

It is essential to understand that actors in BE adopt roles. These can be described as set of characteristic behaviours and activities carried out by BE actors which serve to specify how they contribute and position themselves in relation to the common created and captured value [8,16].

A thorough comprehension of the different roles, as well as their implications, activities and risks within a BE is necessary for the development of positioning strategies. Doing that, companies are able to identify and achieve a favourable position through the efficient use of resources and capabilities, while simultaneously considering other relevant actors [17].

Since value is co-created among several actors, the individual analysis of roles considering their adequacy to model SOVCS would not be applicable. Therefore, to provide an adequate unit of analysis, the concept of strategic role model (SRM) is introduced as a set or constellation of roles in a VCS, which seeks to explain how value is created, as well as the contribution of each role to the viability and functionality of the system. The need for further research into the different constellations of roles in the value creation process has already been stressed by leading academics in the service science field [18].

4.1 The literature review process

The review of existing relevant literature is fundamental in the academic context and serves as a firm foundation in the advancement of knowledge, closing existing research areas and simultaneously discovering new ones [19]. By integrating different findings and perspectives, the research question is addressed with a higher coverage than individual studies [20]. Considering the need to synthesize relevant literature on SRM, the systematic literature review framework developed by Vom Brocket et al., consisting of five phases (I-V) was used. The framework begins with the (I) definition of the review scope, continues with the (II) conceptualization of topic, which is followed by the (III) literature search, with its contents analysed in the (IV) literature analysis and synthesis phase, to finally develop a (V) research agenda [21].

To delimit the scope of the research, in the initial phase (I) the taxonomy of literature reviews developed by Cooper (1988) was used [22]. In a second phase (II), a coherent structuring of the topic of research was necessary, demanding the adoption of a point of view about the topic, as well as a broad conception of what is known about the topic and potential areas needing knowledge [23].

The third phase (III) according to Vom Brocke et al.´s approach is the literature search, which possesses a funnel form and consists of five stages. Following the recommendations of Antons et al. (2021), Reuters Web of Science and Scopus were used as initial datasets [24]. In addition, IEEE Xplore was used to increase the literary volume of the search. As a result of the search, a total of 2883 publications matching the defined search string were gathered. Since the systematic reviewing process is error prone and time consuming and considering that computational techniques offer to combine human knowledge and judgment with the speed and efficiency of computers, the open-source Tool ASREVIEW was used to accelerate the screening process, thus increasing transparency and efficiency [24–26]. This way, it was possible to reduce the literature to a total of 32 publications. Prior to the final selection, a forward and backward search according to Webster & Watson was conducted [19]. In a final selection stage, the literature was reduced to a total of eleven papers from seven different authors. The decisive factor for the final selection of the literature (n=11) was the presence of a clear differentiation between the roles, as well as the respective role description regarding functions and behavior. Figure 1 shows a summary of the search and selection process.

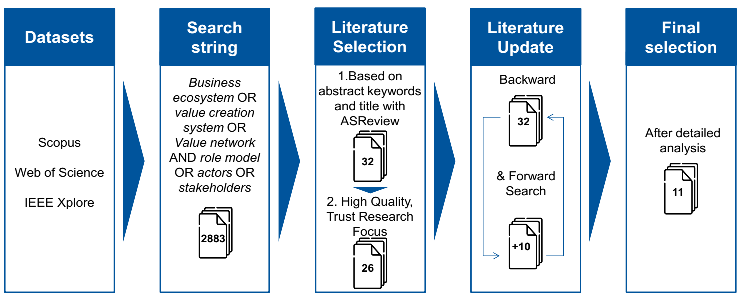

Figure 1-Systematic literature review process

4.2 The literature review results

After having carried out the literature analysis and synthesis (IV) and summarizing seven strategic role models (see Figure 2), recognizing the different roles as well as their functions and characteristics, two relevant conclusions could be drawn (V). The first is, that despite the differing compositions and approaches of the SRM, certain roles are replicated more often and do not distinguish much in terms of activities and contribution to value co-creation. This applies particularly to the leading role of the VCS, which in general orchestrates the rest of the roles to co-create value and guarantee the survival of the BE.

Strategic Role Models	Roles			
Moore (1993,1996)	Leader	Follower	Outsider	Customer
Iansiti & Levien (2004a, 2004b)	Keystone	Niche Player	**Dominator**: Physical / Value	
Adner (2006, 2017)	Leader	Follower	Complementor	Intermediaries
Gawer & Cusumano (2008, 2014)	Platform Leader	Complementor	Platform leader-wannabe	
Kastalli & Neely (2013)	**Architects**	**Solvers**	**Constructors**	**Resources**
	Hub - Influencer	Scales - Niches Innovators	Connectors and integrators Facilitators – representatives-promoters Infrastructure	Talent & Knowledge Capital
Jacobides et al. (2018)	Hub	Complementor	Customer	
Dedehayir et al. (2018)	**Leadership roles**	**Direct Value Creation**	**Value Support**	**Entrepeneurial**
	Ecosystem Leader - Dominator	Supplier - Assembler Complementor - User	Expert - Champion	Entrepreneur - Sponsor Regulator

Figure 2-Summary of the literature review results

In second place, no strategic role model makes specific reference to service or service-oriented value creation. Instead, it is left unclear whether the value arises through service or goods. In general, the term offering is used, or goods and service are bundled together, thereby treating them as if they were similar when it comes to creating value.

As a conclusion, service-oriented value creation is not specified in the different SRM, reaffirming the necessity of the evaluation of these SRM, assessing their adequacy to model SOVCS (V).

5. Analysis of strategic role models

To assess the adequacy of existing strategic role models for SOVCS central aspects of the Service- Dominant Logic are used.

5.1 Criteria development

Service-Dominant Logic emerged in the marketing field in 2004, providing an alternative lens to the Goods-dominant logic (GDL) perspective for understanding the creation of value and exchange between actors. On the one hand, Vargo & Lusch argued that knowledge and skills applied collaboratively among actors in the pursuit of mutual benefit is the source of value, rather than material goods (GDL). On the other hand, this pursuit of mutual benefit, called service-for-service exchange, implied the creation of value among multiple actors, termed co-creation, rather than the creation of value embedded in a good by an individual actor (i.e., a manufacturing firm) subsequently delivered to a consumer (GDL) [27,28]. The viewpoint for continuous transfer, generation and application of knowledge provided by the SDL, is of vital relevance to the practitioners, better enabling them to fulfil their potential [29]. The evolution of the SDL is reflected in the foundational premises (FP), whereby the SDL provides a framework for observing the actors in the exchange process [10]. In summary, through FP, it is conveyed that by means of the interaction in which service is exchanged, as well as through the integration of resources between actors, value is created [30].

As a guideline for the development of the criteria, the following questions were addressed to capture the essence of the SDL and its perspective on value co-creation:

1) What are the activities actors carry out in the service-oriented value creation process and how do they behave to co-create service-oriented value?

2)How is the service-oriented value co-creation process characterized and which are the prerequisites or optimal conditions for it to take place?

3) How do service ecosystems function and what distinguishes them from the original BE as VCS notion?

The following Figures 3 and 4 provide a summary of the criteria a-e, as well as the foundational premises that were used for their development, further explained in the following.

11 Foundational Premises		5 Axioms
1	Service is the fundamental basis of exchange	1
2	Indirect exchange masks the fundamental basis of exchange	
3	Goods are distribution mechanisms for service provision	
4	Operant resources are the fundamental source of strategic benefit	
5	All economies are service economies	
6	Value is cocreated by multiple actors, always including the beneficiary	2
7	Actors cannot deliver value but can participate in the creation and offering of value propositions	
8	A service-oriented view is inherently beneficiary oriented and relational	
9	All social and economic actors are resource integrators	3
10	Value is always uniquely and phenomenologically determined by the beneficiary	4
11	Value co-creation is coordinated through actor-generated institutions and institutional arrangements	5

Figure 3-SDL - Foundational premises

Criteria	Criteria description	FP - Axiom
a	All actors, member of a SOVCS, integrate different kind of resources (knowledge and skills being the most relevant), thus enabling the co-creation of value	FP3 - FP4 - FP6 FP7 - FP9
b	The customer/beneficiary is included in the service-oriented value co-creation process and determines the value; acting as co-creator and not as a consumer.	FP6 - FP8 - FP10
c	The interaction between actors who are members of a SOVCS seek mutual benefit, ruling out parasitism.	FP1 - FP2 - FP8
d	In an SE (SOVCS), rules, norms and standards generated by actors are necessary for the coordination, collaboration, and cooperation in the value co-creation process.	FP2 - FP7 - FP11
e	Service innovation is performed in conjunction with the customer/beneficiary and entails the recombination of existing knowledge.	FP4 - FP6 - FP9

Figure 4- Developed service-oriented criteria

a) Resource Integration (FP3, FP4, FP6, FP7, FP9)

In the SDL it is crucial to differentiate between operand and operant and their contribution to service-oriented value creation through their integration and application. Although operant resources (knowledge and skills) are considered the basis of strategic benefit (FP4), this does not diminish the relevance and value of the goods (operand), since these are used for the creation of value acting as intermediaries or vehicles, indirectly providing service (FP3) [31]. Service provision is possible through the integration of resources, which is an ongoing process performed by all actors (FP9) consisting of the combination and utilization of resources, both possible through the application of knowledge and skills [32].

According to the SDL, integrating resources together with other actors is necessary, especially since no single actor has all the resources it needs [29]. This dependence and need to combine and apply resources with other actors is reflected in FP6, which stresses the fact that value creation is interactional and performed by multiple actors (co-creation), with the co-created value resulting from a unique combination of resources [30]. In this context of value co-creation between several actors (FP6) through the integration of both operand and operant resources (FP3, FP4, FP9) seeking to benefit another actor or itself (service), value propositions (FP7) become essential. The latter can be seen as an invitation to co-create value, implying that an actor cannot create, but only co-create value (FP6, FP7) [10].

The FPs addressed explain how value co-creation is inherently collaborative among all members of a SOVCS (FP6, FP7) and resource usage (FP9) of operand and operant resources (FP3, FP4) and their integration is essential for the co-creation of value. All actor's, member of a SOVCS, integrate different kind of resources (knowledge and skills being the most relevant), thus enabling the co-creation of value.

b) The customer/beneficiary role (FP6, FP8, FP 10)

For this second criterion, a role mentioned several times in the conducted systematic literature review, the customer or, as it is called in the SDL, the beneficiary is highlighted.

Building on and being directly associated with FP6, where the interactional nature of service-oriented value co-creation was highlighted, FP10 highlights the integrative and key role of the beneficiary (i.e. customer) in all instances of value co-creation, being the actor who determines the value and consequently mandatorily being part of its creation process [10,33]. For this reason, the beneficiary is always part of the value co-creation process (FP6) and according to SDL, a service-oriented point of view is inherently beneficiary-oriented (FP8). To distance itself from the inadequate GDL, the SDL developed a lexicon of its own. This was also reflected in the rejection of the term consumer, since in the value creation context, consuming would imply the use of the value until there is no more of it left and its consequent destruction [10,32].

The customer/beneficiary is central as, depending on the context and use, the value is determined by him/her, being obligatorily part of the value co-creation process and discarding the value consumption, which is rather reminiscent of a Goods-Dominant Logic. The customer/beneficiary is included in the value co-creation process and determines the value, acting as co-creator and not as a consumer.

c) Service Exchange (FP1, FP2, FP8)

This third criterion c focuses on the interaction between the actors within a SOVCS, addressing all three guiding questions, as well as one of the central core processes in the SDL, namely service-exchange.

Vargo & Lusch (2004) defined service as the application of operant (knowledge and skills) resources to benefit oneself or another entity [34]. Building on this definition of service, the first two FP explain how service is basically always exchanged for service (FP1), and how this service exchange often goes on unnoticed as the exchange sometimes involves complex combinations of resources, as well as operand resources (i.e. money as an intermediary in service exchange) (FP2) [30].

On the other hand, through FP8, already mentioned in the previous criterion, seeking once again to distance itself from the GDL in which the customer is exogenous to the creation of value, the SDL stresses the need for a relationship or multiple relationships for the co-creation of value as well as for the exchange of service. Furthermore, the wording beneficiary oriented of FP8 refers to the definition of service, in which activities are not performed for the customer/beneficiary, but jointly with the latter [10]. This focus on collaboration and good intentions between service providers and beneficiaries in the exchange according to the SDL, drew multiple criticisms from other scholars. Authors such as Plé and Chumpitaz Cáceres (2010) introduced the term value co-destruction, arguing that there are interactions between service systems that result in the decline of one of the parties involved, arguing that resources can harm in a detrimental way other parties despite being used with a good intention and introduce terms such as misuse of resources as well as intentional value co-destruction [35].

Criterion c builds up on this mutualistic perception to describe the co-creation of value through service-exchange between members of a SOVCS. The definition of service in the SDL, as well as the FP considered for this criterion (FP1, FP2, FP8) can be described by using terms and concepts from biology, just like in the BE notion. More precisely with mutualism, in which both actors profit from the interaction or exchange, simultaneously discarding parasitism, in which one is harmed by the exchange while the other benefits [36].The interaction between actors, members of a SOVCS seek mutual benefit, ruling out parasitism.

d) Institutions & institutional arrangements (FP2, FP7, FP11)

The criterion d arose through the third guiding question. Institutions & institutional arrangements go hand in hand with the service ecosystem (SE) concept. In this criterion, the role of institutions & institutional arrangements in the co-creation of value according to the SDL is outlined. The essential feature of a service ecosystem are the institutions, which are rules, norms, standards, meanings, symbols and practices intended to aid collaboration, as well as institutional arrangements, which are defined as independent assemblies of institutions [33]. These rules, norms and standards enable the exchange of service and can be formalized, e.g., in the form of laws, or exist informally, also called soft or implicit contracts and are generated by actors within the service ecosystem itself [37,10].

Institutions as well as institutional arrangements, are necessary primarily for the coordination, but also for the communication process taking place between actors exchanging service in service ecosystems [10]. Specifically, it is the network effects with their increasing returns, originating when several actors share an institutional arrangement or institution that causes the institutions & institutional arrangements to be critical in achieving an increasing level of service-exchange as well as service-oriented value co-creation [33]. Furthermore, institutions and institutional arrangements can also be regarded as resources actors can draw on [38]. This is of particular interest, given that by integrating these rules, norms and standards, actors in a SOVCS can increase the potential value of their Value propositions (FP7) [29]. In summary, institutions & institutional arrangements act as enablers of coordination, collaboration, as well as cooperation of the actors in the value co-creation process [33]. Focusing on the notion and relevance of institutions and institutional arrangements as coordinating rules, norms, and standards, enabling the creation of value through service-exchange in a Service ecosystem (FP2, FP11), as well as the ability of the actors in a SOVCS to integrate them to their advantage, eventually enhancing their VP as an invitation to co-create value and collaborate (FP7), the criteria d addressing the three FP considered can be summarized this way: In an SE (SOVCS), rules, norms and standards generated by actors are necessary for the coordination, collaboration, and cooperation in the value co-creation process.

e) Service Innovation (FP4, FP6, FP9)

Considering the relevance of innovations in the original BE notion and in the definition of VCS, this criterion addresses the concept of innovation from the SDL-perspective. In the SDL, collaboration as well as coordination are essential to innovate and gain competitive advantage, considering for example the employees of a firm as operant resources and a primary basis for innovation (FP4) [39]. It should be noted that innovation, according to the SDL, is closely linked to the integration of resources. Once again, a clarification is made between operand and operant resources. According to the service-oriented innovation, there is no real difference between innovation through tangibles or knowledge and skill (FP3, FP4), since according to the SDL, all product innovations are nothing more than service innovations [39].

Like the value co-creation process, in the service-innovation process, beneficiaries are crucial (FP6). Actors in a SOVCS, as in a VCS with a BE-approach, can adopt different roles. The beneficiary/customer role, already discussed in the criterion c, can assume several roles depending on the service-exchange in the innovation process; among these roles are the ideator and the designer. Beneficiaries taking the role of ideator, are characterized by sharing their knowledge about their needs as well as how they use the existing offerings in the market, thus converting tacit knowledge to explicit; while customers/beneficiaries taking on the designer role, directly mix and match different resources to configure new service [39]. According to the SDL, service innovation consists of bundling different types of resources (FP9), giving rise to the creation of new innovative resources. Presenting big similarities to the criterion a, for this process to be successful operant resources are crucial (FP4), thus being considered the key type of resource for innovation. As outlined, the customer/beneficiary is involved in the process, taking on roles in the collaborative endeavour (i.e., ideator & designer) (FP6). Service innovation is performed in conjunction with the customer/beneficiary and entails the recombination of existing knowledge.

5.2 Evaluation of strategic role models

By means of the analysis conducted it was possible to answer the research question posed in the introduction, demonstrating that a) none of the existing SRM from BE as VCS archetype is completely adequate to model/describe SOVCS and b) each of the SRM manages to fulfil different levels of service- oriented criteria. The results of the qualitative analysis are presented in Figure 5.

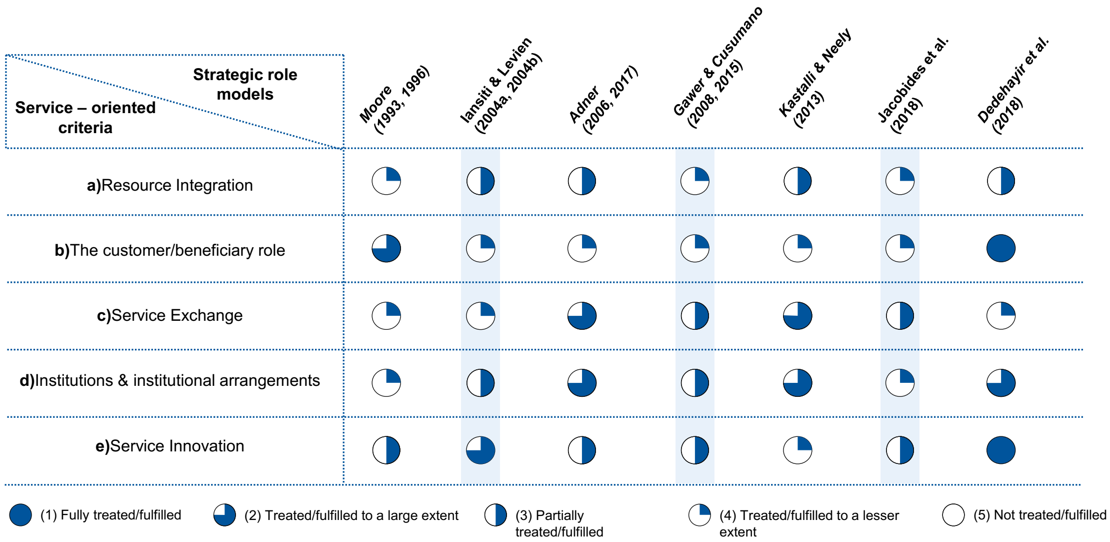

Figure 5-Results of the conducted analysis

6. Conclusion

This paper was intended to analyze the strategic role models (SRM) of value creation systems (VCS) with a business ecosystem (BE) approach, thereby assessing their adequacy to model service-oriented value creation systems (SOVCS).

In the research process, we managed to combine two very comprehensive topics: value creation in business ecosystems and service-oriented value creation, reducing them to a more tangible level of analysis by emphasizing on different SRM of BE and integrating the SDL through the development of five criteria.

Through the literature review, an overview of the different roles that actors can take in a business ecosystem according to seven different scholars was provided, this being useful for researchers studying ecosystems and their roles and for practitioners wanting to be part of an ecosystem or to create one (Fig. 2). Through the evaluation the strategic role models of the different authors, we demonstrated that none of them is completely adequate to explain service-oriented value creation (Fig. 5). We believe that based on the conducted analysis, new strategic positioning models can be developed to help practitioners identify the best fitting role to co-create value along other actors in a SOVCS.

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References

[1] Richardson, G.B., 1972. The Organisation of Industry. The Economic Journal 82 (327), 883.

[2] Cepa, K., 2021. Understanding interorganizational big data technologies: How technology adoption motivations and technology design shape collaborative dynamics. J. Manage. Stud. 58 (7), 1761–1799.

[3] Siaw, C.A., Sarpong, D., 2021. Dynamic exchange capabilities for value co-creation in ecosystems. Journal of business research : JBR 134.

[4] Ng, I.C., Vargo, S.L., 2018. Service-dominant logic, service ecosystems and institutions: an editorial. JOSM 29 (4), 518–520.

[5] Ostrom, A.L., Bitner, M.J., Brown, S.W., Burkhard, K.A., Goul, M., Smith-Daniels, V., Demirkan, H., Rabinovich, E., 2010. Moving Forward and Making a Difference: Research Priorities for the Science of Service. Journal of Service Research 13 (1), 4–36.

[6] Lusch, R.F., Vargo, S.L., Wessels, G., 2008. Toward a conceptual foundation for service science: Contributions from service-dominant logic. IBM Syst. J. 47 (1), 5–14.

[7] Maglio, P.P., Spohrer, J., 2008. Fundamentals of service science. J. of the Acad. Mark. Sci. 36 (1), 18–20.

[8] Burkhalter, M., Betz, C., Auge-Dickhut, S., Jung, R., 2021. Orchestrating Value Co-Creation in Business Ecosystems, in: Wendt, K. (Ed.), Theories of change. Change leadership tools, models and applications for investing in sustainable development. Springer International Publishing AG, Cham, pp. 4–26.

[9] Parolini, C., 1999. The value net: A tool for competitive strategy. Wiley, Chichester, Weinheim, 239 pp.

[10] Lusch, R.F., Vargo, S.L., 2014. Service-dominant logic: Premises, perspectives, possibilities, First published. ed. Cambridge University Press, Cambridge, 225 pp.

[11] Jacobides, M.G., Cennamo, C., Gawer, A., 2018. Towards a theory of ecosystems. Strat Mgmt J 39 (8), 2255–2276.

[12] Conrad, R., Hoeborn, G., Betz, C., Neudert, P. Seizing the Potential of Ecosystems.

[13] Hoeborn, G., Conrad, R., Götzen, R., Betz, C., Neudert, P.K., 2022. Understanding Business Ecosystems Using a Morphology of Value Systems. Research-Technology Management 65 (5), 44–53.

[14] Mirva Peltoniemi, Elisa Vuori, 2008. Business Ecosystem as the New Approach to Complex Adaptive Business Environments.

[15] Moore, J.F., 2016. The death of competition: Leadership and strategy in the age of business ecosystems. Harper Paperbacks, [Place of publication not identified], 1 online resource.

[16] Dedehayir, O., Mäkinen, S.J., Roland Ortt, J., 2018. Roles during innovation ecosystem genesis: A literature review. Technological Forecasting and Social Change 136, 1–12.

[17] Müller-Stewens, G., Lechner, C., 2016. Strategisches Management: Wie strategische Initiativen zum Wandel führen, 5. überarbeitete Auflage 2016 ed. Schäffer-Poeschel, Stuttgart, 702 pp.

[18] Archpru Akaka, M., Chandler, J.D., 2011. Roles as resources: A social roles perspective of change in value networks. Marketing Theory 11 (3), 243–260.

[19] Webster, J., Watson, R.T., 2002. Analyzing the Past to Prepare for the Future: Writing a Literature Review. MIS Quarterly 26 (2).

[20] Snyder, H., 2019. Literature review as a research methodology: An overview and guidelines. Journal of Business Research 104, 333–339.

[21] Vom Brocke, J., Simons, A., Niehaves, B., Riemer, K., Cleven, A., 2009. Reconstructing the Giant: On the Importance of Rigour in Documenting the Literature Search Process, in: . 17th European Conference on Information Systems (ECIS).

[22] Cooper, H.M., 1988. Organizing knowledge syntheses: A taxonomy of literature reviews. Knowledge in Society 1 (1), 104–126.

[23] Torraco, R.J., 2005. Writing Integrative Literature Reviews: Guidelines and Examples. Human Resource Development Review 4 (3), 356–367.

[24] Antons, D., Breidbach, C.F., Joshi, A.M., Salge, T.O., 2021. Computational Literature Reviews: Method, Algorithms, and Roadmap. Organizational Research Methods, 1-12.

[25] van de Schoot, R., Bruin, J. de, Schram, R., Zahedi, P., Boer, J. de, Weijdema, F., Kramer, B., Huijts, M., Hoogerwerf, M., Ferdinands, G., Harkema, A., Willemsen, J., Ma, Y., Fang, Q., Hindriks, S., Tummers, L.,

Oberski, D.L., 2021. An open source machine learning framework for efficient and transparent systematic reviews. Nat Mach Intell 3 (2), 125–133.

[26] Wang, Z., Nayfeh, T., Tetzlaff, J., O'Blenis, P., Murad, M.H., 2020. Error rates of human reviewers during abstract screening in systematic reviews. PloS one 15 (1), e0227742.

[27] Vargo, S.L., Lusch, R.F., 2004. Evolving to a New Dominant Logic for Marketing. Journal of Marketing 68 (1), 1–17.

[28] Vargo, S.L., Lusch, R.F., 2017. Service-dominant logic 2025. International Journal of Research in Marketing 34 (1), 46–67.

[29] Akaka, M.A., Vargo, S.L., Lusch, R.F., 2012. An Exploration of Networks in Value Cocreation: A Service-Ecosystems View, in: Vargo, S.L. (Ed.), Special Issue. Toward a Better Understanding of the Role of Value in Markets and Marketing, vol. 9. Emerald Publishing Limited, Bingley, pp. 13–50.

[30] Vargo, S.L., Lusch, R.F., 2008. Service-dominant logic: continuing the evolution. J. of the Acad. Mark. Sci. 36 (1), 1–10.

[31] Vargo, S.L., Lusch, R.F., Archpru Akaka, M., He, Y., 2010. Service-Dominant Logic. Review of Marketing Research 6, 125–167.

[32] Vargo, S.L., Lusch, R.F., 2011. It's all B2B…and beyond: Toward a systems perspective of the market. Industrial Marketing Management 40 (2), 181–187.

[33] Vargo, S.L., Lusch, R.F., 2016. Institutions and axioms: an extension and update of service-dominant logic. J. of the Acad. Mark. Sci. 44 (1), 5–23.

[34] Vargo, S.L., Lusch, R.F., 2008. Why "service"? J. of the Acad. Mark. Sci. 36 (1), 25–38.

[35] Plé, L., Chumpitaz Cáceres, R., 2010. Not always co-creation: introducing interactional co-destruction of value in service-dominant logic. JSM 24 (6), 430–437.

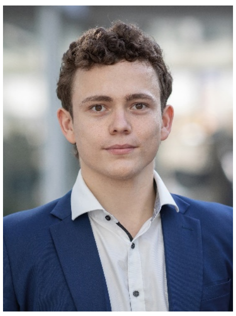
[36] Manikas, K., Hansen, K.M., 2013. Software ecosystems – A systematic literature review. Journal of Systems and Software 86 (5), 1294–1306.

[37] Fujita, S., Vaughan, C., Vargo, S.L., 2018. Service Ecosystem Emergence from Primitive Actors in Service Dominant Logic: An Exploratory Simulation Study, in: . Hawaii International Conference on System Sciences.

[38] Lusch, R.F., Vargo, S.L. (Eds.), 2006. The service-dominant logic of marketing: Dialog, debate, and directions. Routledge, London, New York, 449 pp.

[39] Lusch, R.F., Nambisan, S., 2015. Service Innovation: A Service-Dominant Logic Perspective. MIS Quarterly 39 (1), 155–175.

Biography



Gerrit Hoeborn, M. Sc. M. Sc., is head of the business transformation department. He joined the department after his studies in industrial engineering at RWTH Aachen University and Tsinghua University. His research focuses on ecosystem design, circular economy-based business models and leadership in the era of digital transformation.

Agustin Gonzalez, B. Sc. studies industrial engineering at RWTH Aachen and has worked in the business transformation department since 2021. He conducts his research on business ecosystems with a focus on the construction sector.

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Reference Data Model For Customer Success Management In The Subscription Business Of Manufacturing Companies: Findings From The German Manufacturing Industry

Lennard Holst[1], Günther Schuh[1], Volker Stich[1]
[1]*Institute for Industrial Management (FIR) at RWTH Aachen University, Aachen, Germany*

Abstract

Competitive differentiation in the manufacturing sector is no longer based on product and service innovations alone but on the ability to monetize the usage phase of products and services. To this end, manufacturers are increasingly looking at so-called subscription business models as a way of supplementing the traditional sale of products and services. Since supplier success in the subscription business is directly dependent on customer success, the setup and expansion of a so-called Customer Success Management (CSM) is required. While CSM has already been established in the software industry for several years, companies in the manufacturing sector are often still in the conceptual phase of a CSM, parallel to the setup and expansion of their subscription business. Therefore, this paper aims to support the set-up of a CSM by providing a reference data model, based on case study research, that can be used to support the organizational or daily CSM tasks and to serve as a blueprint for conceptualizing CSM-specific IT systems.

Keywords

Customer Success Management; Subscription Business; Product-as-a-Service Business; Value-in-use, Manufacturing Firms; Reference Data Model

1. Introduction

The Covid-19 crisis once again showed the world its natural limits. For individuals and companies alike, the ability to adapt to the radically changing environmental conditions has become a decisive survival criterion [1]. Covid-19 thus accelerated two global, industrial trends to an unexpected extent: on the one hand, the need for consistent digitization of existing value creation activities [2], and on the other hand, the paradigm shift in industry, from the “throwaway economy” to a circular economy geared towards the preservation of resources [3]. The manufacturing sector, as an integral part of the German economy [4], has been dealing with the digitization of value-added activities in the course of Industry 4.0 for several years [5]. It is currently much easier for companies that have already invested in digital technologies before the crisis to adapt to the new environmental conditions [6]. Nevertheless, despite the considerable investments in the development of digital infrastructures and forecasted annual sales increases of 2.5 percent on average due to digitization and Industry 4.0 in 2014 [7], there is still no broad breakthrough in monetizing digital solutions in 2020 [6]. According to Schuh et al. the lack of monetization of digitization in the manufacturing sector is due to the fact that above all, there is still a focus on (digital) service and product innovations while at the same time sticking to the transactional business model based on the principles "money for products" and "money for service hours" [8]. However, differentiation in the competition of manufacturing companies is no longer taking place solely through innovations of (digital) services, products and their functionalities [9], but rather through the ability to monetize the usage phase of smart connected products within a so-called subscription business [10]. In the subscription business, a service is "subscribed" by the customer and thus regularly

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purchased or rented after signing a subscription contract [11]. The possibilities of digitization lead to a reinterpretation of the term subscription in manufacturing contexts [12]. Subscription businesses in manufacturing contexts can occur in various forms [13, 14]: Starting with the offer of the availability of a machine or a software, billed e.g., via pay-per-availability, up to the provision of complex product service systems that are remunerated based on usage time or intensity, e.g., via pay-per-use, or depending on the production result, e.g., via pay-per-outcome [15].

However, the establishment and expansion of the subscription business, in which the manufacturer links its economic success to the individual success of its customers, is fraught with numerous problems. From the supplier's point of view, success in the subscription business is determined not only by the number and volume of subscription contracts sold, but above all by the improvement in the utilization phase, the result achieved in the customer process, the "share of wallet" achieved with the customer, the duration of the customer relationship and thus the long-term recurring monthly or annual sales [16]. Existing organizational units in manufacturing companies, which are traditionally responsible for customer management, are often not equipped to perform these proactive tasks aimed at customer success [10]. For example, marketing traditionally acquires customers and generates new prospects, sales or key account management explain the product or service benefits and close the (repeat) sale, while service is responsible for mostly reactive problem solving in the event of a claim [17].

For this reason, a new management system is establishing itself in the context of the subscription business in manufacturing companies that is completely focused on individual customer success. The so-called Customer Success Management (CSM) operates in the overlap zone of the common, aligned interests between manufacturer and customer [18]. The CSM has a counterpart in the subscription business of the software industry in which it acts as the trustworthy partner for the customer in order to support customer goal achievement and thus individual customer success through the use of the software solution [10, 19]. In literature, first contributions exist to describe CSM tasks in manufacturing companies and differentiate them from established customer-oriented functions like Customer Relationship Management, Key Account Management or Service [18-20]. However, given the data-driven and proactive focus of CSM tasks, there is a lack of reference to necessary data entities (defined as real life data objects within a data model) in order to support CSM processes and the alignment of IT-system functionalities. The research question of this paper is therefore: What data entities are sufficient for CSM in manufacturing companies, leading towards a conceptual reference data model for easy reuse and adjustment in company specific CSM contexts?

2. State of research

2.1 Subscription Business in Manufacturing

In the current scientific literature and in practice, there are numerous terms that are related to the term "subscription" in manufacturing contexts, which are subsumed under the term "subscription" in the following, e.g., “equipment-as-a-service” [21, 22], “everything-as-a-service” [23] or pay-per-use business models [24, 25]. The principle of subscription business in manufacturing contexts is to offer customers access to a constantly improving digital performance system in return for regular fees instead of a one-off sale of products and services [8]. In the subscription business, the customer pays continuously for the availability, use, or result of a digital performance system and no longer for the individual performance components such as products or services [17]. Manufacturers and customers thus align their interests and benefit equally from increasing customer performance [12].

As a result, risks of low customer productivity, system failures, operating errors, or low efficiency in service delivery increasingly shift to the provider [8, 26]. The distinction from a classic operator model, in which the manufacturer is also responsible for operations and production staff [24], is fluid due to the close, collaborative service relationship with the customer in the subscription business [17].

Considering the current state of research, the following four attributes can be used for a characterization of the subscription business in manufacturing contexts [10, 28]:

- **Recurring, performance-based revenues** via various revenue mechanisms such as pay-per-use or pay-per-outcome
- **Focus on actual realized customer success**, such as increasing productivity, saving energy costs, or achieving other customer goals in the customer process
- **Dynamic, digital and continuously improving performance systems**, consisting of machines or plants, services and software, which are networked with each other via the so-called "Internet of Things" (IoT)
- **A long-term, collaborative customer relationship** with high value customers, i.e., customers with projected growth potential via sharing of future economic profits.

2.2 Customer Success Management

The overarching task of the CSM is to proactively support customer success, i.e., the achievement of measurable customer goals, at all levels of the customer organization using suitable, data-based methods and processes, to ensure consistently positive customer experiences, and to prevent customer churn [10]. In the subscription business, the success of the customers is linked to the entrepreneurial success of the provider via a participative, performance-based revenue model, so that the provider's interest in achieving or exceeding previously agreed customer goals [18-20]. A core question that the CSM in the subscription business must answer to this end is: "How do I succeed in getting my customers to use my product more often [author's note: more efficiently and effectively]?" [17, p. 202]. In the scientific and the management-oriented literature, various definitions of the terminology of Customer Success Management exist, which differ primarily in scope, concretization, and regarding the responsibilities of CSM tasks. Table 1 provides an overview of current definitional approaches. However, the authors of previous CSM literature focus mainly on the general definition of tasks for a CSM in the subscription business of software companies [19, 20, 28, 29]. Furthermore, there is no contribution, that puts focus on the necessary data entities that are sufficient for performing CSM related tasks in the subscription business of manufacturing firms.

Table 1: Existing definitions of the term "Customer Success Management"

Definition of the term Customer Success Management	**Source**
„[CSM] takes charge of the ongoing customer relationship and ensures that customers gain maximum value from the product." „This task is crucial with smart, connected products, especially to ensure renewals in product-as-a-service models. The customer success management unit does not necessarily replace sales or service units but assumes primary responsibility for customer relationships after the sale. This unit performs roles that traditional sales and service organizations are not equipped for and don't have incentives to adopt: monitoring product use and performance data to gauge the value customers capture and identifying ways to increase it."	[10, p. 15 f.]
„[CSM] is a management process comprising all activities of the customer and the provider firm aiming at aligning their customer and supplier goal achievement."	[18, p. 124]
„[CSM is] the proactive (versus reactive) relational engagement of customers to ensure the value potential of product offerings is realized by the customer."	[19, p. 3]
„[CSM] is generally a non-billable service that provides post-implementation assistance to the customer to help them generate value from the products/services they have purchased. It typically provides advice, assistance and resources relating to adopting and using the products/services and to measuring and reporting on the value attained from their use."	[28, p. 12]
"CSM draws on the foundation of CRM by considering customers' demographic and transactional data but goes further by utilizing streaming sensor data and other unstructured customer data to	[20, p. 362]

derive value-in-use insights and predict customers' future value-in-use. CSM draws on a foundation of Customer Experience by seeking to improve customers' product experience, but CSM goes further by prioritizing customers' more distant financial, social, operational, and strategic goals. CSM draws on a foundation of Customer Engagement by considering customers' loyalty but goes further by prioritizing customers‘ goal achievement over engagement behavior.”	
“With complex and evolving technology products, customers need ongoing help to adapt and realize value. Customer value realization is the flywheel that keeps customers coming back. The CSM can be the power that accelerates the flywheel.”	[29, p. 1]

3. Methodology

3.1 Research approach

The selection and application of the research methods described below are based on a grounded theory approach according to Glaser and Strauss for the systematic collection and comparative analysis of data with the aim of generating theories from (management) practice [30, 31]. For this purpose, data collection is carried out as so-called "theoretical sampling", i.e., data are collected and analyzed in a cyclical process based on preliminary theoretical considerations. During the research process, the researcher decides which data and research methods will be used next for the investigation [30, 32]. Based on the collected data, recurring elements are identified, from which action patterns and categories are derived, also referred to as "coding" in grounded theory [30]. In this work, these are referenceable data attributes related to performing CSM tasks in manufacturing contexts. The identification of the action patterns and categories takes place iteratively over the entire research process of this work, until a theoretical saturation is reached, i.e., no more new relevant action patterns and categories can be added [30]. Data analysis is carried out with the aid of "memo writing," i.e., after each round of data collection, hypotheses about the relationships between the data are recorded and the theory, i.e., the reference data model of CSM, is continuously refined [30]. In addition, the results of the literature analysis will be used to enrich the reference model with secondary data.

3.2 Data collection

The application of the research process took place between the years 2019 and 2021 with a focus on collecting data from German manufacturing companies, which have already a proven record of successful subscription business and CSM attempts. Table 2 gives an overview of the examined companies, the CSM status within the company, the role of the interview partner and the specific research methods that were applied.

Table 2: Overview of the data collection phase [35]

Company	CSM status	Interview partner role	Applied research methods
Machine tool manufacturer	CSM in preparation	Head of Subscription Head of Process Management	3 interviews, 1 company visit, 2 joint workshops between 2019 and 2020
Printing press manufacturer	CSM in action	Head of Customer Success Management Operative CS Manager	4 interviews, 1 observation of a customer success meeting with customers between 2019 and 2021
Machine tool manufacturer	CSM in action	Operative CS Manager	1 interview in 2020
Software as a Service	CSM in action	Director Marketing Campaigns & Channels	3 interviews, 1 joint workshop in 2020
Software as a Service	CSM in action	Success Management Lead	2 interviews in 2019

Various manufacturing companies	CSM in preparation	Various roles	Focus group in the context of a joint remote workshop in 2020

4. Research Outcome

The reference data model, developed based on the ARIS framework [33, 34], is used to provide researchers and practitioners a structured overview of the data entities and attributes required to perform the core CSM functions in manufacturing contexts. Based on this overview, IT systems can be conceptualized or adapted. It also provides operational CSM managers with a tool to navigate within the complex system of co-creation of value with subscription customers during the utilization phase. Figure 1 shows the conceptual data model developed in the course of this research process focusing on a provider, a customer and a joint interaction pillar. The 13 data entities are described in further detail within the next sections. must be positioned and aligned organizationally in the company of the CSM provider. To this end, the internal objectives of CSM and the human and technological resources required to achieve them must be defined.

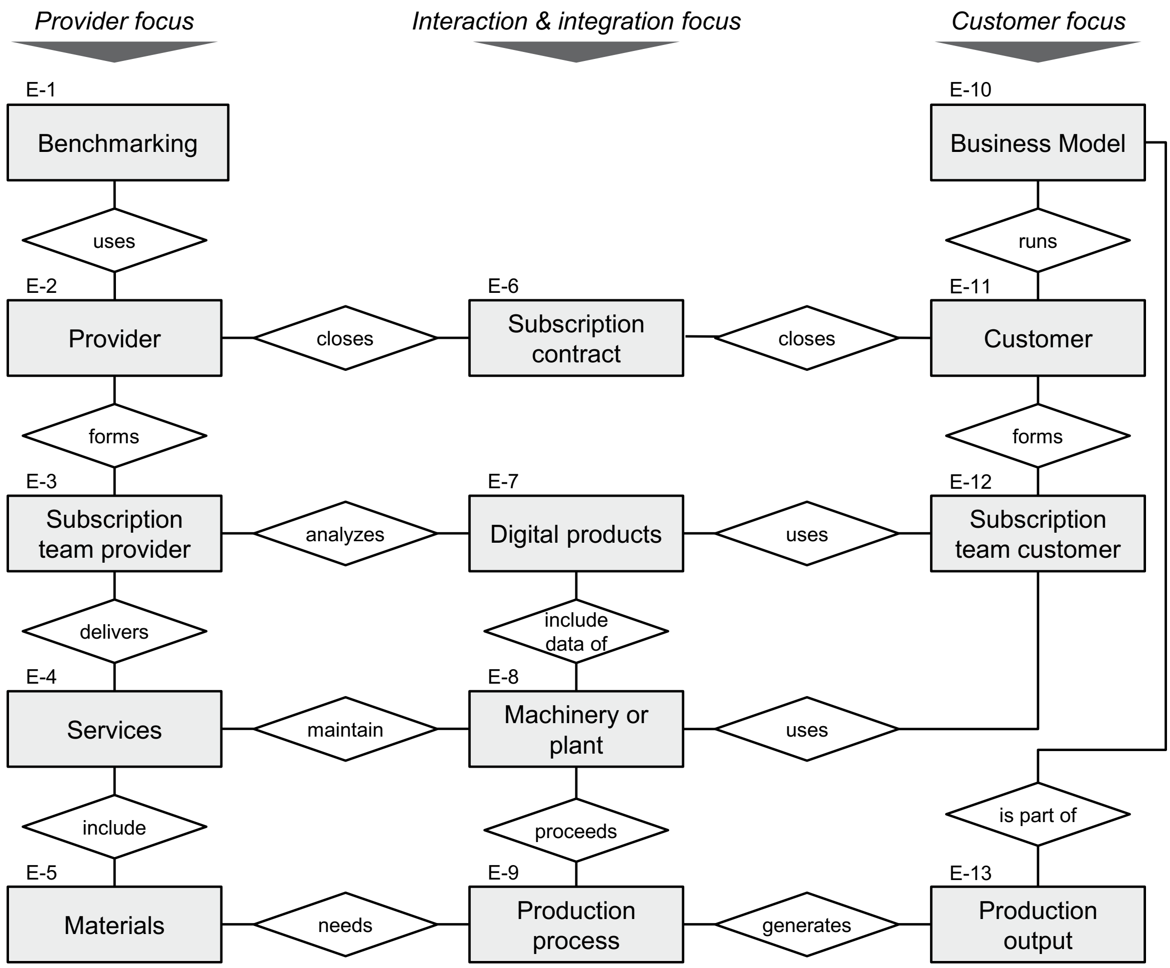

Figure 1: Reference data model for CSM in manufacturing

4.1 The Entity E-1: Benchmarking

All relevant benchmarking data for comparing individual customer performance with "best-in-class" reference customers are subsumed under the "benchmarking" entity. Best-in-class reference customers are companies that produce significantly better than others or use subscription services more effectively based on defined comparison criteria. A premise for the supplier to increasingly assume risks from the customer process is the data-based learning from the subscription business with other customers and the determination of benchmarks. The benchmarking data is also one of the initial reasons for the individual customer to enter into a subscription relationship and to share their own data with the provider. This is done in the hope or under the promise of the provider to use the shared data anonymously for comparison purposes and thus help each individual customer to succeed.

4.2 Entity E-2: Provider (collective)

The "provider" entity includes the subscription provider as a collective of people and subsumes the internal, provider-side data in the service system, e.g., on the individual subscription components, costs, and prices. Furthermore, the entity "provider" includes the data for measuring targets or key figures of the CSM. This includes, for example, the monetary growth targets with specific subscription customers and the data required on the supplier side to determine and increase the customer lifetime value.

4.3 Entity E-3: Subscription team of the provider (individual)

The entity "subscription team of the provider (individual)" subsumes all natural persons on the provider side who are deployed to implement the subscription services at the individual customer. In addition to the CSM team, this primarily includes the service and sales departments. Attributes include, for example, the names, contact details, experience such as industry or language skills, and the organizational roles of the people involved on the provider side.

4.4 Entity E-4: Services

The entity "services" subsumes the services required to maintain production on the part of the supplier or by service partners. Services are provided by both the technical service and the CSM itself. Services form the central basis for a functional subscription business. From a CSM perspective, relevant attributes for technical services to maintain the availability of a machine or system are, for example, the date of a service ticket, the content of a service message, a customer's interaction with the service, or the status of a specific service order. Attributes for consulting-intensive services, such as user training conducted by the CSM, include, for example, the date of training, the content, and the specific training participants.

4.5 Entity E-5: Materials

The entity "materials" includes all raw materials, consumables and supplies that are provided by the supplier and fed into the customer's production process, especially in results-based subscription transactions. The supply can also take place by partners in the ecosystem of the subscription. Attributes include, for example, inventory levels or changes in inventory levels over time. In the subscription business, the vendor needs insight into the enterprise resource planning system or supplementary IT systems for the customer's inventory and materials management for the so-called vendor-managed inventory. Furthermore, so-called consignment warehouses may be set up in the subscription business. Consignment warehouses are warehouses supplied with goods by the supplier on the customer's premises or in the vicinity, which are used, for example, to supply customer processes with consumables and service materials, such as spare parts and tools.

4.6 Entity E-6: Subscription contract

The entity "subscription contract" subsumes the contractual framework data for the subscription relationship between provider and customer. Attributes include, for example, the subscription contract number, the start and end date of the subscription, the specific scope of the subscription, and contractually agreed subscription guarantees. In particular, the contractually agreed risk allocation between customer and provider in the subscription business is of central importance for the CSM as the entity responsible for realizing the customer's success.

4.7 Entity E-7: Digital products

The entity “digital products" primarily subsumes the interaction data of the customer with the software solutions provided by the provider. The focus is on cloud-capable software for which the provider can collect and evaluate near-real-time interaction data. Furthermore, continuous functional improvements and enhancements, so-called releases, can be made via cloud software. In some cases, the provider can use cloud-based software or the IoT to access the machine control system or the operating panel of the machine directly and make changes here as well. In the CSM, the focus is on specific cloud software for continuous communication with subscribers. This communication software serves a digital assistance system used by both the customer and the provider or CSM for the presentation and automated analysis of relevant data about the usage phase of the subscription in the cloud. In the practice of the subscription business in the manufacturing industry, an increasing integration of various, previously separate functionalities in the communication software can currently be observed. Such assistance systems increasingly integrate numerous functionalities for production optimization in customer operations. At the same time, the software serves as a (communication) platform for collaboration or co-value creation with customers on a personal level. It enables self-services, i.e., the customer can carry out certain activities himself, such as searching for instructions or viewing the status of a machine, without having to contact the manufacturer. For the manufacturer, in turn, there are no direct, resource-intensive efforts. Further attributes for the entity “digital products” are, for example, core functions used, times of login and logout by software users, and all click activities in the so-called user interface.

4.8 Entity E-8: Machinery or plant

The "machine or plant" entity subsumes the status data of the physical core products. This includes, for example, the attributes "machine type or number", the "temporal and local geodata of the machine", the "connectivity status of the machine" and the "machine status", e.g., in the form of machine hours (time during which the machine is switched on) or existing fault reports. In particular, monitoring the connectivity status of the machines, i.e., an existing data connection to the provider via the IoT, is essential not least for performance-based billing. Any other products used, such as sensor systems, can generally be treated in the same way as entity E-8 and described by means of the attributes mentioned.

4.9 Entity E-9: Production process

The entity "production process" subsumes the data of a specific production process in the customer usage phase of the subscription. This includes attributes such as parameter settings, production times, downtimes, energy consumption or temperature and vibration data. Furthermore, supplementary data about the specific production order as well as planning data for the production process, such as quantity, shift or maintenance plans, can be counted here. In the course of the production process, further peripheral data, such as ambient temperature or noise, can be collected.

4.10 Entity E-10: Business model (customer)

The entity "business model (customer)" subsumes the data on the current business situation of the individual customer. Particularly in the case of deep integration into the customer's value chain, e.g., in the course of results-oriented subscription transactions, the provider must obtain comprehensive knowledge about the customer's customers, the value proposition, the value chain with its own or competing products, and the revenue mechanics, i.e., also the pricing modalities of the products. Furthermore, the supplier must obtain in-depth insights into the economic situation of the customer in order to be able to estimate possible production or payment defaults for the individual customer.

4.11 Entity E-11: Customer (collective)

The entity "customer (collective)" includes all available data about the customer as a collective, i.e., about the specific customer account. This primarily includes the available, interaction-related customer data from the CRM system, such as:

- Master data (e.g., company name, industry, legal form, customer type).
- Sales activities (e.g., last meetings, last inquiries, last orders)
- Reactions to sales campaigns (e.g., trade fair offers)
- Order overview with sales values for new and used machines
- Last service call and last spare parts order
- Description of quality problems on installed machines

At the level of the customer as a collective, data on the customer's business objectives, i.e., the customer's economic, factual, environmental, or social objectives, are relevant for Customer Success Management. Customer success is measured on the basis of the achievement of these customer goals. Furthermore, the payment behaviour and any open invoice items of the individual customers are also of interest for the CSM and the proactive assessment of the customer status in a subscription relationship.

4.12 Entity E-12: Subscription team of the customer (individual)

Analogue to the provider's subscription team, the entity "subscription team of the customer (individual)" subsumes all natural persons of the customer involved in the subscription. As CSM-relevant attributes, the roles of the persons in the buying or usage center, the contact data, the interaction data of the persons with the CSM, and the possibly anonymized, individual usage data of the persons with the subscription services are of high relevance. From the CSM perspective, in addition to the customer's business goals, it is also a matter of capturing and fulfilling the personal goals of the customers in the buying and usage center.

4.13 Entity E-13: Production output

The "production output" entity subsumes all product-related data following the production process. This includes, for example, attributes such as the product quantity, the number of good and reject parts, and quality data such as geometry specifications, surface quality, and tolerances.

5. Conclusion

In this paper, a model with 13 data entities and corresponding data attributes was developed that can serve as a reference for designing the tasks and IT systems for a Customer Success Management in the manufacturing sector. The model was developed and tested based on research with practitioners in German mechanical engineering. By its very nature, the model in this paper only represents an excerpt in the temporal course of the development of the subscription business and the CSM, so there is a need for further development with regard to quality assurance, adaptation and further development of the reference model regarding upcoming research projects. In the future, parallel to the company-specific development of a CSM, it will be necessary to measure the effects and performance of the CSM in order to quantify the long-term benefits of the CSM and its corresponding data entities. On the other hand, from a research perspective, the comparison of different organizational variants of the CSM should also be addressed in this course in order to support companies in the still open question regarding the most suitable company-specific form of CSM (IT) organization. A central object of further investigation can be the future integration of sales, service and CSM in companies of the manufacturing industry. While the basic orientation of the CSM reference data model developed in this work is based on the role of the CSM as a integrator for value co-creation with the customer coexistence with sales or key account management in particular still appears questionable.

Especially the questions who "owns" the customer in the long run and whether a "one face" or "one team to the customer" approach is more successful cannot be answered with this work yet.

References

[1] M. Leach, H. MacGregor, I. Scoones, A. Wilkinson, "Post-pandemic transformations: How and why COVID-19 requires us to rethink development", In: World development 138, February 2021.

[2] P. Soto-Acosta, "COVID-19 Pandemic: Shifting Digital Transformation to a High-Speed Gear", In: Information Systems Management 37, April 2020, pp. 260 - 266.

[3] R. Panwar, E. Niesten, "Advancing Circular Economy", In: Business Strategy and the Environment 29, June 2020, pp. 2890 - 2892.

[4] VDMA, Mechanical engineering – figures and charts 2019, Frankfurt am Main, 2019.

[5] A. Schumacher, T. Nemeth, W. Sihn, "Roadmapping towards industrial digitalization based on an Industry 4.0 maturity model for manufacturing enterprises", In: Procedia CIRP 79. July/August 2019, pp. 409 - 414.

[6] VDMA, McKinsey & Company, Kundenzentrierung als Chance für den digitalen Durchbruch. Was sich die Endkundenindustrien vom Maschinenbau bei digitalen Plattformen und Mehrwertdiensten wünschen, Frankfurt am Main, 2020.

[7] V. Koch, S. Kuge, R. Geissbauer, S. Schrauf, Industrie 4.0. Chancen und Herausforderungen der vierten industriellen Revolution, Munich, 2014.

[8] G. Schuh, J. Frank, P. Jussen, C. Rix, T. Harland, "Monetizing Industry 4.0: Design Principles for Subscription Business in the Manufacturing Industry", In: Proceedings, 2019 IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC). Sophia Antipolis Innovation Park, France, June 2019.

[9] A. Tiffert, Customer Experience Management in der Praxis. Grundlagen – Zusammenhänge – Umsetzung. Springer Gabler, Wiesbaden, 2019.

[10] M. E. Porter, J. E. Heppelmann, "How Smart, Connected Products Are Transforming Competition", In: Harvard Business Review 92, 2014, pp. 64 - 88.

[11] T. Tzuo, G. Weisert, Subscribed. Why the subscription model will be your company's future – and what to do about it, Penguin, London, 2018.

[12] G. Schuh, J. Boshof, C. Dölle, C. Kelzenberg, J. Tittel, "Subskriptionsmodelle im Maschinen- und Anlagenbau", In: Internet of Production: Turning Data Into Value. Statusberichte aus der Produktionstechnik, Fraunhofer-Gesellschaft, Aachen, 2020, pp. 282 – 299.

[13] T. Döbler, O. Bendig, J. Janik, Der zweite Frühling für den Maschinenbau. Servicedigitalisierung als Wachstumstreiber, Deloitte, Munich, 2020.

[14] M. Mansard, J.M. Cagin, Reaping The Recurring Benefits of Industry 4.0. A manufacturing executive playbook for business model transformation towards new revenue streams, Roland Berger, 2020

[15] E. Stoppel, S. Roth, "The conceptualization of pricing schemes: From product-centric to customer-centric value approaches", In: Journal of Revenue and Pricing Management 16, January 2017, pp. 76 – 90.

[16] M. S. Hansen, How to build a subscription business, Kopenhagen, 2019.

[17] U. Hermann, Digitalisierung im Industrieunternehmen – Die Chancen der digitalen Ökonomie der Dinge erkennen, entwickeln und erfolgreich umsetzen, Apprimus, Aachen, 2019.

[18] A. Eggert, W. Ulaga, A. Gehring, "Managing Customer Success in Business Markets: Conceptual Foundation and Practical Application", In: Journal of Service Management Research 4, February/March 2020, pp. 121 - 132.

[19] B. Hochstein, D. Rangarajan, N. Mehta, D. Kocher, "An Industry/Academic Perspective on Customer Success Management", In: Journal of Service Research 23, January 2020, pp. 3 - 7.

[20] B. Hilton, B. Hajihashemi, C. M. Henderson, R. W. Palmatier, "Customer Success Management: The next evolution in customer management practice?", In: Industrial Marketing Management 90, 2020, pp. 360 - 369.

[21] I. Stojkovski, A.-K. Achleitner, T. Lange, Equipment as a service: The transition towards usage-based business models, SSRN online, March 2021.

[22] P. Kirchhartz, Intelligent services and new business models. Equipment-as-a-service for digital products, services and production equipment. SMS group #magazine online, January 2021

[23] M. Claasen, C. Blum, P. Osterrieder, T. Friedli, "Everything as a service? Introducing the St.Gallen IGaaS Management Model", In: 2nd Smart Services Summit, Thun, 2019, pp. 61 – 65.

[24] H. Gebauer, C. J. Saul, M. Haldimann, A. Gustafsson, "Organizational capabilities for pay-per-use services in product-oriented companies", In: International Journal of Production Economics 192, 2017, pp. 157 – 168.

[25] N. M. P. Bocken, R. Mugge, C. A. Bom, H.-J. Lemstra, "Pay-per-use business models as a driver for sustainable consumption: Evidence from the case of HOMIE", In: Journal of Cleaner Production 198, 2018, pp. 498 – 510.

[26] S. Fischer, S. Steger, N. D. Jordan, M. O'Brien, P. Schepelmann, Leasing Society, Brussels, 2012.

[27] G. Schuh, L. Wenger, V. Stich, J. Hicking, J. Gailus, "Outcome Economy: Subscriptio Business Models in Machinery and Plant Engineering", In: Procedia CIRP 93, 2020, pp. 599 – 604.

[28] R. Adams, Practical customer success management. A best practice framework for rapid generation of customer success, Routledge, New York (NY), 2019.

[29] A. A. Zoltners, P. K. Sinha, S. E. Lorimer, "What Is a Customer Success Manager?", HBR online, 2019.

[30] B. G. Glaser, A. L. Strauss, The discovery of grounded theory. Strategies for qualitative research, Aldine, New Brunswick, 1967.

[31] K. D. Locke, Grounded theory in management research, Sage, London, 2001.

[32] J. Strübing, Grounded Theory. Zur sozialtheoretischen und epistemologischen Fundierung eines pragmatistischen Forschungsstils, Springer, Wiesbaden, 2004.

[33] P. P.-S. Chen, "The entity-relationship model – toward a unified view of data", In: ACM Transactions on Database Systems 1, 1976, pp. 9 – 36.

[34] A.-W. Scheer, ARIS – Vom Geschäftsprozess zum Anwendungsprozess, Springer, Berlin, 2002.

[35] L. Holst, G. Schuh, V. Stich, J. Frank, "Customer Success Management In The Subscription Business Of Manufacturing Companies: Towards A Task-Oriented Reference Model.", In: CPSL Proceedings, 2021.

Biography

Dr.-Ing. Lennard Holst is head of the department of Service Management at the Institute for Industrial Management (FIR) at the RWTH Aachen University since 2021. Dr.-Ing. Lennard Holst leads various research and industrial projects in the fields of subscription business management, digital business model transformation and industrial service management.

Prof. Dr.-Ing. Volker Stich is head of the Institute for Industrial Management (FIR) at the RWTH Aachen University since 1997. Prof. Dr.-Ing. Volker Stich worked for the St. Gobain Automotive Group for 10 years and led the management of European plant logistics. In addition, he was responsible for the worldwide coordination of vehicle development projects.

Prof. Dr.-Ing. Dipl.-Wirt. Ing. Günther Schuh is director of the Institute for Industrial Management (FIR) at the RWTH Aachen, holds the Chair of Production Systems at the Laboratory for Machine Tools and Production Engineering WZL at RWTH Aachen University and is a member of the board of directors of the Fraunhofer Institute for Production Technology IPT. He is the founder of Schuh & Co. Group and the e.GO Mobile AG. Prof. Schuh is a member of several supervisory boards and boards of directors.