Proceedings of the
Conference on Production Systems and Logistics

CPSL 2023-2

14th – 17th November 2023
Stellenbosch Institute for Advanced Study (STIAS),
Stellenbosch, South Africa

by
publish-Ing.

www.cpsl-conference.com

Conference on Production Systems and Logistics

Stellenbosch Institute for Advanced Study (STIAS),
Stellenbosch, South Africa

14th – 17th November 2023
Proceedings

Editors:
Dr.-Ing. David Herberger
M. Sc. Marco Hübner

https://doi.org/10.15488/15326
ISSN: 2701-6277

publish-Ing.

Senator-Burda-Straße 31a,
77654 Offenburg
Germany

E-mail: info@cpsl-conference.com
USt-IdNr.: DE324911115

Conference Website www.cpsl-conference.com

If contents of the proceedings are used for further work, these are to be clearly referenced in accordance with good scientific practice. The recommended citation is:

'Name 1, Given Name 1'; 'Name 2, Given Name 2';'…': 'Titel'. In: Herberger, D.; Hübner, M. (Eds.): Proceedings of the Conference on Production Systems and Logistics (CPSL 2023-2), 2023, publish-Ing., S. XX-XX.

Foreword

We are delighted to present the proceedings of the fifth Conference on Production Systems and Logistics (CPSL 2023 - 2), held at the beautiful Stellenbosch Institute for Advanced Study (STIAS) in Stellenbosch, South Africa.

After three years, we came back to our roots - hosting the CPSL in South Africa, where we have already held our very first conference in 2020. At that time, we were only able to welcome around 20 participants on site due to the upcoming covid-19 restrictions. For this reason, we decided to return to Stellenbosch a little earlier than originally planned.

At CPSL 2023 - 2 we had over 87 very interesting paper presentations, giving a broad overview of the latest research results in production and logistics. We are very proud that the CPSL has grown to a conference committee of 28 contributing research institutions making it possible to publish all the accepted papers in its fifth proceedings.

The intention of the CPSL is to create a platform for scientists to network and exchange ideas – a place to discuss groundbreaking research findings and share perspectives on current topics with like-minded individuals. All the interesting presentations, the exciting discussions in-between the sessions and of course the networking during and after the conference make us proud to be part of the CPSL and let us look forward to the next conferences with great excitement.

We extend our deepest gratitude to all partners who made this conference possible. A special thanks go to the reviewers who participated in the rigorous yet supportive review process, and our keynote speakers for their captivating and inspiring presentations. It was again a pleasure to host the conference at STIAS in South Africa – the entire team was caring and supportive and contributed greatly to the success of the event. Lastly, we thank all participants and fellow researchers who generously shared their research knowledge and experiences, making the CPSL a remarkable event.

We eagerly anticipate welcoming you again at CPSL 2024.

Dr.-Ing. David Herberger	M. Sc. Marco Hübner
Conference Chair	Conference Chair

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 and Change Management
- Lean & Operational Excellence
- 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.

CPSL

Acknowledgements

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

Publishing

Scientific Societies

Venue

Reviews & Scientific Support

Keynote Speakers 2023 - 2

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

Sustainability of future manufacturing systems

Prof. Dr.-Ing. Sebastian Thiede

Full Professor, Chair Of Manufacturing Systems at University of Twente

Technological advancements over the last decades lead to significant changes in the design and operation of manufacturing systems and those developments are likely to continue in the future. The introduction of advanced manufacturing approaches such as flexible (matrix) manufacturing systems, additive manufacturing, stronger robotization/automation as well as the introduction of digital support solutions certainly incorporate promising potentials in terms of productivity and flexibility. But the question remains to which extend those approaches can also contribute to an improved sustainability of manufacturing systems – are there inherent advantages or also potentially challenges and conflicts of goals?

Providing a Roadmap for Small and Medium Sizes Industries Towards Sustainable Manufacturing Processes

Sekhar Rakurty, PhD

The M. K. Morse Company

Due to the current growth rate of the world's consumption and supply chain challenges, developing and implementing a sustainable manufacturing process is essential. The US Environmental Protection Agency states, "A sustainable manufacturing process makes products using methods that reduce environmental impacts while concurrently conserving energy and natural resources." Sustainable manufacturing process implementation in small and medium size industries has been challenging and met with limited success. This presentation will focus on implementing the principles of the sustainable manufacturing process, such as the 6Rs (Reduce, Reuse, Recycle, Recovery, Redesign, and Remanufacture) in a (small/medium scale) cutting tool company. The presentation will focus on case studies such as reducing cutting fluid usage, improving manufacturing efficiency through automation, recycling cemented carbide, revamping the manufacturing process to reduce the supply chain impact, etc. Through academic and industrial collaboration, the presentation will propose a roadmap for sustainable manufacturing processes for small and medium size industries.

CPSL

Keynote Speakers 2023 - 2

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

Research – Industry Collaboration: Joining Forces for the Acceleration of E-Mobility Production

Simon Voss, M.Sc.

Managing Director E-Mobility Lab of RWTH Aachen University & Head of E-Mobility Office of RWTH Aachen University

The current dynamics of e-mobility innovation are without example; technological challenges meet promising potential with a market craving for solutions. Hence, time to market is the critical key enabler to commercial success. For this, the driving forces are fast transitions of innovation from the laboratory environment into industrial operation. Systematization of this “Innovation Chain” offers decisive advantages, here showcased for the innovation of battery production technologies

Table of Contents

1 Identification of Text Mining Use Cases In Manufacturing Companies 1
Florian Clemens, Hasan Hüseyin Özdemir, Günther Schuh

2 Framework For The Rapid Development And Deployment Of Customized Industrial Robotic Applications 13
Paul Geng, Lisa Heuss, Thomas Rauh, Julian Müller, Rüdiger Daub

3 Planning And Controlling Multi-Project Environments In The Factory 23
Justin Hook, Lars Nielsen, Peter Nyhuis

4 Testing The Limits: A Robustness Analysis Of Logistic Growth Models For Life Cycle Estimation During The COVID-19 Pandemic 33
Louis Steinmeister, Burim Ramosaj, Leo Schröter, Markus Pauly

5 Product Development through Co-Creation Communities - General Measures For A Distributed And Agile Planning Preparation in Cross-Company Production 45
Dominik Saubke, Pascal Krenz, Tobias Redlich

6 Design Elements Of Corporate Functions In The Trade-Off Between Efficient Goal Achievement And Prevention Of Disturbance Impacts 56
Michael Riesener, Maximilian Kuhn, Jonas Tittel, Pawan Singh, Günther Schuh

7 Towards Enabling Human-Robot Collaboration in Industry: Identification of Current Implementation Barriers 67
Johannes Bauer, Mohammed-Amine Abdous, Sebastian Kurscheid, Flavien Lucas, Guillaume Lozenguez, Rüdiger Daub

8 A systematic literature review of communications standards in discrete manufacturing 80
Furkan Ercan, Maximilian Bega, Bernd Kuhlenkötter

9 Conceptualizing A Digital Twin Based On The Asset Administration Shell For The Implementation Of Use Case Specific Digital Services 90
Henry Himmelstoss, Roland Hall, Bernd Vojanec, Paul Thieme, Thomas Bauernhansl

10 An Approach For Analysis Of Human Interaction With Worker Assistance Systems Based On Eye Tracking And Motion Capturing 100
Fabian Hock, Joachim Metternich

11 Machine Learning Driven Design Of Experiments For Predictive Models In Production Systems 110
Sebastian Maier, Patrick Zimmermann, Rüdiger Daub

12 Investigation of Deep Learning Datasets for Intralogistics 119
Dimitrij-Marian Holm, Philipp Junge, Jérôme Rutinowski, Johannes Fottner

13 Classification Of Flow-Based Assembly Structures For The Planning Of Flexible Mixed-Model Assembly 129
Nils Föhlisch, Peter Burggräf, Tobias Adlon, Verena Meier

14 A Production Model based in Lean 4.0 Principles And Machine Learning To Enhance The Productivity Of Small And Medium-Sized Enterprises (SMEs) In Peru's Food Manufacturing Sector 139
Adrian Ricardo Komori-Zevallos, Fernando Matias Montedoro-Garay, Yvan Jesus Garcia-Lopez, Juan Carlos Quiroz-Flores

15 Local Manufacturing - Strategic Operationalisation Of Lean Methods In Manufacturing-related Small And Medium-sized Enterprises (SME) 151
Dominik Saubke, Fabian Ponert, Pascal Krenz, Jens P. Wulfsberg

Table of Contents

16 Improving OEE in a Peruvian SME: A Case Study on the Application of Lean Manufacturing Tools in the Metalworking Sector 162
Carlos Mundaca-Lopez, Christopher Villar-Farfan, Juan Carlos Quiroz-Flores, Yvan Jesús García-López

17 Improvement Proposal To Increase Productivity Of A SME In The Primary Manufacturing Sector Using Standardized Labor and TPM Tools 176
Diego Niño De Guzmán-Lunarejo, Dahana Obregon-Leon, Alberto Flores-Perez

18 Investigation Of Laser-Based Drying Of Electrodes For Lithium-IonBattery Production Using Vertical-Cavity Surface-Emitting Lasers (VCSEL) 191
Daniel Neb, Sebastian Wolf, Benedict Ingendoh, Simon Klein, Benjamin Dorn, Heiner Heimes, Achim Kampker

19 Building a Knowledge Graph from Deviation Documentation for Problem-Solving on the Shop Floor 201
Yuxi Wang, Beatriz Bretones Cassoli, Joachim Metternich

20 Material Flow Simulation in Lithium-Ion Battery Cell Manufacturing as a Planning Tool for Cost and Energy Optimization 212
Maximilian Lechner, Paul Mothwurf, Lasse Nohe, Rüdiger Daub

21 Comparative Analysis of Lithium Metal Anode Production Methods: Evaluating Liquid-Based Manufacturing Technology for Mass Production and Overcoming Production Challenges for Next-Generation Battery Cells 222
Gerrit Bockey, Jan Felix Plumeyer, Sarah Wennemar, Benjamin Dorn, Heiner Hans Heimes, Achim Kampker

22 From Machinery to Insights: A Comprehensive Data Acquisition Approach for Battery Cell Production 234
Achim Kampker, Benjamin Dorn, Robert Ludwigs, Henning Clever, Felix Kirchmann

23 DesignChain: Process Automation From Recording Of Customer Requirements To Production Release 245
Lars Rödel, Gregor Müller, Jonas Krebs, Timo Denner, Thomas Bauernhansl

24 Towards a Service-Oriented Architecture for Production Planning and Control: A Comprehensive Review and Novel Approach 255
Sebastian Behrendt, Florian Stamer, Marvin Carl May, Gisela Lanza

25 Identification Of Investigation Procedures To Predict Work Roll Fatigue For Developing Machine Learning Applications - A Systematic Literature Review 268
Tobias Moser, Johannes Seitz, Enes Alp, Bernd Kuhlenkötter

26 The job role as a reference category for the design of continuing education in production companies 282
Pia Mozer, Bernd Dworschak

27 Application of the dynamic tolerancing approach to the assembly of fuel cell stacks 291
Andreas Aichele, Oliver Mannuß, Alexander Sauer

28 Proposing a Solution for a Self-Managed Data-Ecosystem in Production: Use-Case-Driven IT-OT-Integration with an Event-Driven IT-Architecture 300
Sebastian Kremer, Christian Mennerich, Max-Ferdinand Stroh, Günther Schuh

29 A Control Strategy Architecture for Energy Systems with Multiple-Energy-Carrier Devices 313
Kerim Torolsan, Mirja Mannigel, Janosch Hecker, Alexander Sauer

Table of Contents

30 Overview and Roadmap of Hydrogen Utilization in Industry 323
Laura Jung, Verena Lampret, Alexander Sauer

31 Hype cycle assessment of emerging technologies for battery production 336
Achim Kampker, Heiner Heimes, Benjamin Dorn, Daniel Neb, Henning Clever, Jennifer Machura

32 Transforming AC-powered production machines for operation in DC microgrids 348
Dietmar Hölderle, Janosch Hecker, Alexander Sauer

33 Methodical Implementation Of Digital Data Consistency In Assembly Lines Of A Learning Factory 358
Marius Knott, Tobias Schmelter, Tom Nowak, Christopher Prinz, Bernd Kuhlenkötter

34 Method for Semi-Automated Improvement of Smart Factories Using Synthetic Data and Cause-Effect-Relationships 371
Vera Hummel, Jan Schuhmacher

35 A Methodological Framework for Analysis and Theorization of Circular Supply Chain at the System Context Level 382
Shiva Abdoli, Thomas Stringer Cochingyan, Bahador Bahramimianrood, Sijia Xie, Moahmmed Malaibari

36 Framework For The Successful Set-up Of A Common Data Model In The Context Of An Industry 4.0-ready Plant Design Process 393
Tobias Drees, Alexander Große-Kreul, Daniel Syniawa, Lars Niklas Josler, Alfred Hypki, Bernd Kuhlenkötter

37 Polygon Interface Analysis: A Concept For Analyzing Production Site Interactions In Urban Areas 405
Severin J. Görgens, Kolja H. Meyer, Anne Wetzel, Mark Mennenga

38 Manufacturing Change Management - A Survey On Current Challenges, The State Of Digitalization And The Application Of Change Impact Analysis In Industrial Practice 417
Jan-Philipp Rammo, Jennifer Graf

39 Comparing Research Trends and Industrial Adoption of Manufacturing Operations Management Solutions 427
Michael Oberle, Daniel Schel, Monika Risling, Thomas Bauernhansl

40 Accuracy Assessment of Tactile On-Machine Inspection for Milling Operations 437
Jonas Krebs, Gregor Müller, Lars Rödel, Jan Prochnau, Josip Florian Strutz, Thomas Bauernhansl

41 Transfer Learning Approaches In The Domain Of Radial-Axial Ring Rolling For Machine Learning Applications 447
Johannes Seitz, Tobias Moser, Simon Fahle, Christopher Prinz, Bernd Kuhlenkötter

42 Towards A Holistic Cost Estimate Of Factory Planning Projects 459
Leonard Rieke, Luca Philipp, Peter Nyhuis

43 Assessing Risk Mitigation Preference Effect on Supplier Commitment and Procurement Performance in the Public Health Industry in South-Africa 472
Osayuwamen Omoruyi, Matthew Quayson

44 Method For Creating A Control Cabinet Model With Realistic Wires 486
Stefanie Bartelt, Matthias Bartelt, Bernd Kuhlenkötter

Table of Contents

45 Action Management - Status, Requirements And Implementation Strategies for SMEs 496
Jens Kiefer, Tara Rauch, Valesca Zeller

46 Enhanced Planning Of Production Plants: A Case-Based Reasoning Driven Approach 506
Daniel Syniawa, Robert Egel, Jan Schachtsiek, Alfred Hypki, Bernd Kuhlenkötter

47 An Investigation Of Cost-Benefit Dimensions Of 5G Networks For Agricultural Applications 517
Tim Benedikt Walter, Kerstin Lörsch, Max-Ferdinand Stroh, Wolfgang Boos

48 Organizational, Sociological and Procedural Uncertainties in Statistical and Machine Learning: A Systematic Literature Review 527
Nick Große, Maximiliane Wilkesmann, Andrea Bommert

49 Self-Optimization In Gear Manufacturing And Assembly For Automotive Electric Drive Production 538
Bastian Friedrich, Daniel Buschmann, Robert H. Schmitt

50 Concept of a Data-Driven Business Model for Circular Production Equipment 548
Michael Riesener, Maximilian Kuhn, Aileen Blondrath, Balaj Tariq, Günther Schuh

51 Reducing Wastage In Manufacturing Through Digitalization: An Adaptive Solution Approach For Process Efficiency 559
Valesko Dausch, Sebastian Beckschulte, Louis Huebser, Tobias Schulze, Robert H. Schmitt, Matthias Kreimeyer

52 Comparison of sealing processes for Polymer Electrolyte Membrane 569
Gregor Müller, Rebecca Pahmeyer, Aleksandar Radlovic

53 Fixed Route Refueling-Strategy for Fuel Cell Trucks 579
Achim Kampker, Heiner Heimes, Fabian Schmitt, Maximilian Bayerlein, Philipp Scheffs

54 Design and analysis of mechanical gripper technologies for handling mesh electrodes in electrolysis cell production 589
Martin Römer, Benjamin Winter, Edgaras Mazeika, Klaus Dröder

55 Deficits of Innovation Management in the Application to the Disruptive Battery Industry 600
Achim Kampker, Heiner Heimes, Schmied Jessica, Paul Lingohr, Henning Clever, Benjamin Dorn

56 Mini-Environments In Lithium-Ion Battery Cell Production: A Survey On Current State, Challenges And Trends 611
Lorenz Plocher, Marius Heller, Benedict Ingendoh, Hasibe Turhan, Matthias Burgard, Sarah Wennemar, Achim Kampker, Marc Kissling

57 Interoperable Architecture For Logical Reconfigurations Of Modular Production Systems 622
Sebastian Behrendt, Marco Wurster, Matthias Strljic, Jan-Felix Klein, Marvin Carl May, Gisela Lanza

58 Modelling The Digital Twin For Data-Driven Product Development - A Literature Review 634
Henry Himmelstoss, Thomas Bauernhansl

59 Evaluating Retail Distribution Strategies During Covid-19 Pandemic in South Africa Using Best Worst Method Multicriteria Decision Technique 644
Osayuwamen Omoruyi, Edward Dakora, Albert Antwi, Matthew Quayson, Alfred Mwanza, Emmanuel Mabugu, Leonard Ndlovu

60 The Process Mining Use Case Canvas: A Framework for Developing and Specifying Use Cases 659
Dino Hardjosuwito, Fynn Leon Braucks, Tobias Schröer, Christopher Schwanen, Wil M.P. van der Aalst

CPSL

Table of Contents

61 Assessment of a Novel Process to Enable Roll-to-roll Production of Catalyst Coated Membranes 670
Achim Kampker, Heiner Heimes, Mario Kehrer, Sebastian Hagedorn, Niels Hinrichs, Philip Heyer

62 Contamination control for sensitive products in the era of electrified vehicles 680
Patrick Brag, Bálint Balogh, Péter Gordon

63 FlexEnergy - A Prosumer-based Approach For The Automated Marketing Of Manufacturing Companies' Energy Flexibility 691
Philipp Pelger, Can Kaymakci, Lukas Baur, Alexander Sauer

64 Development of scalable production concepts for the cost-efficient assembly of PEM fuel cell systems for mobile applications 702
Achim Kampker, Heiner Heimes, Mario Kehrer, Sebastian Hagedorn, Julius Hausmann, Johann von Harling

65 Ecological evaluation of h2 energy supply in industry 716
Yvonne Eboumbou Ebongue, Felix Schnell, Alexander Emde, Alexander Sauer

66 Simulation Game Concept For AI-Enhanced Teaching Of Advanced Value Stream Analysis and Design 727
Mick Geisthardt, Lutz Engel, Monika Schnegelberger

67 On the Effectiveness of Bottleneck Information for Solving Job Shop Scheduling Problems using Deep Reinforcement Learning 738
Constantin Waubert de Puiseau, Lennart Zey, Merve Demir, Hasan Tercan, Tobias Meisen

68 Innovation Management in Manufacturing - A Study on Industrial Application, Deficits, and Opportunities 750
Quirin Gärtner, Xuezhou Zhang, Fabian Sippl

69 Bridging The Gap: A Framework For Structuring The Asset Administration Shell In Digital Twin Implementation For Industry 4.0 760
Monika Risling, Henry Himmelstoss, Alexander Brandstetter, Dachuan Shi, Thomas Bauernhansl

70 A Framework For The Domain-Driven Utilization Of Manufacturing Sensor Data In Process Mining: An Action Design Approach 771
Jonathan Brock, Niclas Rempe, Sebastian von Enzberg, Arno Kühn, Roman Dumitrescu

71 Adaptive Multi-Priority Rule Approach To Control Agile Disassembly Systems In Remanufacturing 782
Marco Wurster, Finn Bail, Sebastian Behrendt, Gisela Lanza

72 Towards A Modular IT-Landscape For Manufacturing Companies: Framework For Holistic Software Modularization 793
Sebastian Junglas, Martin Perau, Dino Hardjosuwito, Tobias Schröer, Wolfgang Boos, Günther Schuh

73 Development Of An Adaptive Augmented Reality Qualification System For Manual Assembly And Maintenance 804
Maximilian König, Lukas Merkel, Benedikt Arndt, Christoph Berger, Maik Heller, Michael Eisenbarth, Johannes Schilp

74 Modelling The Influence Of Production Planning And Production Scheduling On Business Performance In The Manufacturing Industry Of South Africa 814
Elizabeth Chinomona, Mamonare Minky Kgaogelo Mogano

Table of Contents

75	Design Guidelines For Digital Kanban Systems With High Service Level *Roman Ungern-Sternberg, Christoph Kilian Merz*	824
76	A Concept For The Development Of A Maturity Model For The Holistic Assessment Of Lean, Digital, and Sustainable Production Systems *Olivia Bernhard, Michael F. Zaeh*	837
77	Backlog control in optoelectronic production using a digital twin *Jonas Schneider, Tobias Hiller, Peter Nyhuis*	848
78	Reducing Customer Complaints in Air Conditioning Installation Services through Lean and MRP Tools: A Case Study *Silvana Aguilar-Cevallos, Yersson Aguilar-Cevallos, Juan Carlos Quiroz-Flores, Yvan Jesus García-López*	860
79	From Complexity To Clarity In Sustainable Factory Planning: A Conceptual Approach For Data-driven Integration Of Green Factory KPIs In Manufacturing Site Selection *Michael Riesener, Tobias Adlon, Esben Schukat, Jan Salzwedel, Carsten Engeln, Felix Passlick*	874
80	Concept And Exemplary Application Of Industrialized Re-Assembly To An Automotive Use Case In The Context Of Circular Economy *Michael Riesener, Maximilian Kuhn, Nikolai Kelbel, Günther Schuh*	882
81	Scenarios Of Glass Disposal In Australia From Circular Economy And Life Cycle Assessment Perspective *Brian Smith, Shiva Abdoli*	893
82	Comparative Life Cycle Assessment Of Conventionally Manufactured And Additive Remanufactured Electric Bicycle Motors *Julian Grosse Erdmann, Alexander Mahr, Patrick Derr, Philipp Walczak, Jan Koller*	903
83	Developing A Key Performance Indicator System To Integrate Sustainable Corporate Objectives Into Maintenance Using The Analytic Hierarchy Process *Christina Bredebach*	914
84	Enhancing Decision-Making In SCM - Investigating The Status Quo And Obstacles Of Advanced Analytics In Austrian Companies *Patrick Brandtner*	925
85	Sustainable Urban Logistics Model Applied to Food Trucks. Case Study and Descriptive Analysis *Andrea Fernanda Peirano Madrid, Arianna Zuñiga Novaro, Yvan Jesus García-López, José Antonio Taquía Gutiérrez*	935
86	Resilience Maturity Assessment in Manufacturing Supply Chains *Maria Thomassen, Bjørnar Henriksen*	947
87	Demand Forecast Model and Route Optimization to Improve the Supply of an SME in the Bakery Sector *Emory Pablo Bazan Flores, Candice Maria Fe Gamarra, Jose Antonio Taquía Gutiérrez, Yván Jesús García López*	957

CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
CPSL 2023-2

5th Conference on Production Systems and Logistics

Identification of Text Mining Use Cases In Manufacturing Companies

Florian Clemens[1], Hasan Hüseyin Özdemir[1], Günther Schuh[1]

[1] *FIR an der RWTH Aachen, Aachen 52074, Germany*

Abstract

Manufacturing companies face the challenge of managing vast amounts of unstructured data generated by various sources such as social media, customer feedback, product reviews, and supplier data. Text mining technology, a branch of data mining and natural language processing, provides a solution to extract valuable insights from unstructured data, enabling manufacturing companies to make informed decisions and improve their processes. Despite the potential benefits of text mining technology, many manufacturing companies struggle to implement use cases due to various reasons. Therefore, the project VoBAKI (IGF-Project No.: 22009 N) aims to enable manufacturing companies to identify and implement text mining use cases in their processes and decision-making processes. The paper presents an analysis of text mining use cases in manufacturing companies using Mayring's content analysis and case study research. The study aims to explore how text mining technology can be effectively used in improving production processes and decision-making in manufacturing companies.

Keywords

Data Mining; Text Mining; Manufacturing Company; Use Case Modelling; Text Data;

1. Introduction

1.1 Problem definition

Text mining technology, a branch of data mining, offers a promising solution to extract valuable insights from text data, helping manufacturing companies make informed decisions and improve their operational processes [1]. However, despite the potential benefits, many manufacturing companies struggle to implement relevant text mining use cases due to certain obstacles.

One challenge is the lack of technical expertise and infrastructure needed to successfully integrate text mining technology [2]. Implementing text mining solutions requires specialized knowledge and resources that might not be readily available within the company, making it a significant barrier [4,3].

Additionally, manufacturing companies often find it difficult to identify use cases. Figuring out which aspects of their business processes can benefit from text mining technology and how to use it effectively poses a considerable hurdle [5,6]. Without a clear understanding of the potential use cases, manufacturing companies may be hesitant to invest in text mining solutions or fail to maximize their benefits.

1.2 Objective and project description

The objective of the research project VoBAKI (IGF-Project No.: 22009 N) is to enable SME to independently identify text mining use cases and internal skill gaps regarding the development and implementation of text mining applications. To achieve this, the project is structured in five steps. The results are elaborated in cooperation with a user committee that is composed of 18 companies of different industries and sizes (see Table 1)

DOI: https://doi.org/10.15488/15241
ISSN: 2701-6277

Table 1: User committee

Branch	Number of Employees	SME
Manufacturing	11 – 50	x
Manufacturing	51 – 250	x
Manufacturing	11 – 50	x
Manufacturing	11 – 50	x
Manufacturing	11 – 50	x
Manufacturing	11 – 50	x
Manufacturing	251 - 500	
IT & Service	251 - 500	
IT & Service	< 10	x
IT & Service	11 – 50	x
IT & Service	251 - 500	
IT & Service	> 5000	
IT & Service	11 - 50	x
IT & Service	501 - 5000	
Consulting	< 10	x
Consulting	501 - 5000	
Consulting	11 - 50	x
Consulting	< 10	x

First, the project examines text mining use cases and regarding objectives of manufacturing companies to implement them. Second, the project identifies tasks in the lifecycle of text mining applications and determines the specific skills required for the execution of these tasks. Third, potential sourcing strategies will be described and evaluated with respect to their practical relevance for manufacturing companies. Eventually, the results of the project will be combined in an approach for the specific identification of skill gaps and the selection of the proper sourcing strategy to close these gaps.

This paper presents the interim results from the first step of the project. It proposes an analysis of potential text mining use cases in manufacturing companies, employing case study research and Mayring's content analysis. The objective of this study is to explore how text mining technology can be effectively employed to enhance production processes and decision-making in manufacturing companies. By identifying and examining practical text mining use cases, this research aims to provide manufacturing companies with valuable insights and guidance for implementing text mining technology. The outcomes of this study have the potential to help companies facilitate the identification of relevant use cases that align with their specific operational requirements.

1.3 Structure of the paper

Chapter 2 presents a systematic literature review regarding text mining use cases in manufacturing companies and derives the research gap. Chapter 3 displays the research approach to identify and describe text mining use cases. Chapter 4 describes the results achieved. Eventually, chapter 5 sums up the results presented in the paper.

2. Related Work

2.1 Text mining in manufacturing companies

Text mining, also known as text data mining or text analytics, is a computational technique that involves the extraction of meaningful information and patterns from large collections of textual data [7]. It encompasses a range of methods and algorithms for processing, analysing, and understanding unstructured text [8]. By utilizing natural language processing (NLP), statistical modelling, and machine learning techniques, text mining aims to uncover insights, discover relationships, and derive valuable knowledge from text-based sources such as documents, articles, social media posts, emails, and more [7,8]. However, to assess the status of use case diagrams for text mining use cases in manufacturing companies a systematic literature review was conducted. The research question "What are the current text mining use cases represented as use case diagrams?" and the inclusion criteria were defined. The following inclusion criteria were established. The text includes the terms "text mining" and "use case" or "use case diagram" and the text includes the term "text mining use case". Subsequently, the keywords "text mining AND use case diagram AND manufacturing company" were utilized to search for relevant papers in the IEEE Xplore, arXiv and google scholar databases. Table 2 shows an overview of the results of the searches:

Table 2: Results of the systematic literature review

Database	Search results
arXive	0
IEEE Xplore	0
google scholar	23

The systematic literature search using Google Scholar yielded 23 results, while IEEE Xplore and ArXiv yielded 0 results. However, none of the papers met the inclusion criteria. That is why the research was extended through unsystematic literature search which results are summarized below.

Shotorbani et. al. propose a new method for organizing and mining information in the growing volume of online manufacturing data. It suggests using K-means for document clustering and Latent Dirichlet Allocation (LDA) for topic modelling. Through experiments, the authors demonstrate that this combined approach enables automated annotation, classification of manufacturing webpages, and extraction of valuable patterns, leading to improved information search and organization in the manufacturing domain. [9] Sutanto et. al. introduce a novel framework for a complaint management system aimed at quality management. The framework utilizes text mining and potential failure identification to support organizational learning. Customer email complaints serve as input, and the most frequent complaints are visualized through a Pareto diagram. The framework involves three main parts: creating a defect database, text mining customer complaints, and matching the results with the defect database to present them in a Pareto diagram. The proposed method is illustrated through a case study, showcasing its applicability. The framework enables companies to interpret customer complaints, identify most common defects, and take anticipatory actions to prevent potential failures in the future. This approach is the first of its kind in this domain. [10] Mishra et. al. discuss the growth of manufacturing processes driven by advancements in procedure and computer technology. It highlights the increasing volume and variety of unstructured data generated in today's digital manufacturing compared to flexible manufacturing in the past. This data can be utilized to improve manufacturing processes, predict equipment failures, design equipment, and explore new technologies. However, managing and extracting valuable information from this vast amount of data pose challenges. Traditional methods like keyword search are insufficient for efficient information retrieval. The paper focuses on unsupervised machine learning techniques for text mining in manufacturing processes to address these challenges. [11] Biegel et al. use process monitoring by sensors on machine tools and combine them with text mining methods to detect anomalies in the manufacturing process. As text data information recorded by the machine operators about the existing machine parameters and corresponding process states were used as text data. [12] Hrcka et al. analyse production data in the form of text documents and forms in the automotive industry. They combine shutdowns with responsible employees to gain approaches for improving the production process. Thereby, the focus of the implementation is more on technical implementation than on business benefits. [13] Ansari et al. show that AI-assisted evaluation of digital shift of digital shift logs can increase Overall Equipment Efficiency (OEE), using an example from the automotive industry, can be increased. The digital shift employees were analysed with the help of text mining methods. evaluated. Based on these logs, the following three functions were implemented: A downtime prediction for aggregates, a dynamic word recommendation for documentation to improve the quality of the data, and a selection of the most suitable technician for troubleshooting. As a result, the machine running time by more than 6%, reduced the average fault detection time and thereby increasing the overall OEE by over 5%. [14] Li et al. use text mining methods to analyse unstructured accident reports from Chinese coal mines to identify risks in coal production. Based on over 700 accident reports, 78 risk factors were identified, which were assigned to six main categories. The main risks identified were lack of management, lack of training and over-supervision. [15] Wang et al. analyse 245 weakly structured accident reports from the Chinese cement industry using text mining methods. They identified four types of accidents and 35 causes of accidents, which in turn were classified into five categories. These were then combined to produce recommended actions for safety management. [16] Müller et al. combine NLP methods and clustering to identify the problems most frequently reported by a ticket system. Improvement projects can then be derived from the problem topics found. During validation on the field, the results were found to be representative. [17] May et al. have analysed fault descriptions digitally recorded by machine operators using NLP methods and classification methods to improve the accuracy of downtime estimation. In addition, the results of the different combinations of methods were compared. [18] In addition to the publications described above, there are a number of non-scientific texts and websites that provide lists of text mining applications and therefore should not remain uncited [21,20,19,22].

2.2 Research gap

The review of existing literature has highlighted a significant gap in comprehensive studies that specifically tackle the challenge of identifying text mining use cases for manufacturing companies. Current research predominantly emphasizes the technical dimensions of text mining algorithms, data preprocessing techniques, and broader methodologies for text mining. However, a noticeable lack exists when it comes to in-depth investigations into distinct use cases.

Hence, bridging this research gap demands a concerted effort to explore and document the array of text mining use cases in manufacturing, framed within the context of use case diagrams. This endeavour would not only contribute to the existing pool of knowledge but also extend practical guidance to organizations embarking on the integration of text mining into their enterprise.

3. Approach and Methodology

This chapter describes the approach adopted to elaborate the research results on text mining use cases within the context of manufacturing companies. The process involved three key stages, including content analysis using Maying’s method, case studies with experts of the companies of the user committee, and the exemplary application of the use case modelling technique complemented by literature research (see Figure 1).

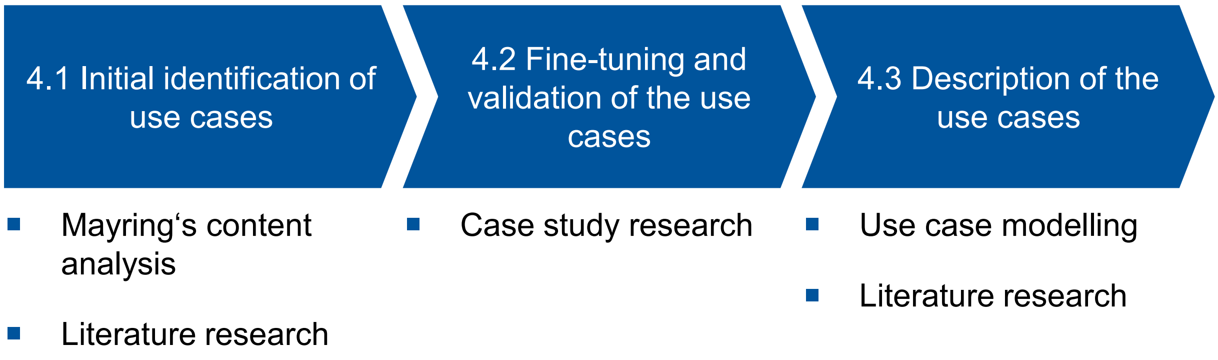


Figure 1: Approach

The research was commenced by conducting a comprehensive content analysis utilizing Maying's approach (see chapter 4.1). The objective was to systematically examine textual data related to manufacturing companies, thereby identifying, and categorizing potential text mining use cases. This initial step provided a foundation for understanding the varied scenarios where text mining techniques could be applied in manufacturing companies.

The next crucial phase involved engaging in case studies with experts from companies of the user committee (see chapter 4.2). The preliminary list of use cases obtained from the content analysis served as a starting point for interviews with these experts. During the case studies, the list of use cases was fine-tuned based on the insights and feedback provided by the knowledgeable participants. A use case was considered identified if it was already implemented, planned for implementation, or known by the experts of the respective companies. This validation process helped ensure the relevance and applicability of the preliminary list of use cases.

The final step of the research encompassed a comprehensive description of some of the validated use cases through the application of the use case modelling technique (see chapter 4.3). Although the models are not the core result of the research, they show manufacturing companies that implementation is much easier with the help of such models. The step involved creating detailed representations of each use case, outlining the specific actions and expected outcomes. The use case models serve as a valuable tool for understanding the practical implications of text mining in manufacturing settings. Moreover, supplementary literature research was conducted to enrich the understanding of each use case.

4. Text mining use cases

4.1 Results from Mayring's content analysis

In Appendix 7.1, the paper presents a detailed account of the primary findings from the content analysis. These findings not only laid the groundwork for subsequent case studies but also illuminated the diverse landscape of potential applications for text mining methods within manufacturing companies. In total, the content analysis identified a remarkable 17 distinct use cases. These findings can be assigned to different business areas.

Customer engagement:

- **Offer segmentation and proposal**: Tailoring product offers to individual customer segments, enhancing personalization and faster processing of offers.
- **Customer segmentation**: Gaining a deeper understanding of customer demographics and preferences for targeted marketing.

Production and logistics

- **Preparation of shipping documents**: Streamlining logistics and ensuring accurate order fulfilment.
- **Assistance with picking**: Providing support and guidance to warehouse staff in selecting items for order fulfilment, ultimately optimizing the picking process in manufacturing companies.

Documentation:

- **Evaluation of documents**: Analysing documents for compliance, accuracy, and decision-making.
- **Information extraction from documents**: Automating data extraction from unstructured documents, improving data access.

Customer support and service:

- **Chatbot**: Providing instant customer support and assistance through AI-powered chatbots.
- **Assignment of customer inquiries**: Efficiently routing customer queries to appropriate personnel.

Marketing and product management:

- **Creation of product descriptions**: Generating compelling product descriptions for marketing materials.
- **Flexible marketing**: Adapting marketing strategies based on real-time data and insights.
- **Summary of customer reviews**: Extracting key insights from customer feedback to inform product development.

Security and Strategy:

- **Early detection of cyberattacks**: Identifying potential cybersecurity threats before they escalate.
- **Prediction of market developments**: Forecasting market trends and adjusting strategies accordingly.

Human resources and employee engagement:

- **Identification of employee needs**: Understanding employee needs for better retention and satisfaction.
- **Control of recruitment strategy**: Optimizing recruitment efforts based on market and organizational trends.
- **Early detection of health Risks**: Monitoring employee health and well-being to mitigate risks.

Customer relationship management:

- **Management of customer cooperation**: Enhancing customer relationships and collaboration.

These findings underscore the transformative potential of text mining in processes of various business areas of manufacturing companies. From improving customer engagement to bolstering security and risk management, these use cases showcase the relevance of text mining in today's business landscape. Furthermore, they provide a rich foundation for future research and case studies, enabling organizations to harness these insights for sustainable growth and competitiveness.

4.2 Results from the case studies

The validation and refinement of the results from Mayring's content analysis were integral to ensuring the accuracy of text mining use cases within the context of business processes in manufacturing companies. The engagement of subject matter experts, carefully selected from both manufacturing companies and IT-service providers for manufacturing, added a layer of real-world validation and practicality to the initial findings. This process not only confirmed the relevance of some use cases but also uncovered new insights that had not been initially captured in the content analysis.

The 12 expert interviews provided a platform for in-depth discussions and knowledge exchange. These discussions involved presenting the findings from Mayring's content analysis, as outlined in Appendix 7.1. Importantly, these expert interviews allowed for a critical examination of the proposed use cases and their alignment with actual industry practices.

As a result of these expert interviews and discussions, several changes and adjustments were made to the original longlist of text mining use cases (see Appendix 7.2). These changes are summarized as follows:

Changed and newly identified use cases:

- **Assistance to the preparation of offers**: The experts validated this use case, emphasizing the importance of text mining in tailoring offers to meet customer needs effectively and create them faster based on former offers.
- **Automated document processing and management**: While the original use case of "Evaluation of Documents" was not entirely confirmed, the experts highlighted the significant role of text mining in processing and managing digitized documents, including classification and analysis.
- **Proposal of solutions for troubleshooting**: This new use case emerged from the interviews, focusing on the generation of solutions based on error codes in machinery.

Use cases not confirmed:

- **Assistance with picking**: This use case was not confirmed as text-based, as it involves speech-based interactions in warehouse logistics.
- **Information extraction from documents**: The experts clarified that reading paper documents like invoices primarily relies on image recognition rather than text mining.
- **Flexible marketing, early detection of cyberattacks, early detection of health risks, management of customer cooperation, and control of recruitment strategy**: These use cases could not be confirmed as text mining use cases based on current industry practices.

The refinement of the longlist through expert interviews led to a final longlist containing 11 validated text mining use cases (see Appendix 7.2), ensuring that only those with practical applicability were retained for further consideration. The integration of expert-driven enhancements with the initial content analysis findings provided a more comprehensive understanding of the text mining use cases relevant to manufacturing companies. In conclusion, the validation process not only confirmed the value of certain use cases but also demonstrated the need for a nuanced understanding of text mining applications within the manufacturing industry. This research, founded on both data-driven content analysis and expert insights, contributes significantly to the body of knowledge in this field.

4.3 Description of text mining use cases in manufacturing companies

This chapter provides an exemplary in-depth analysis of two use cases of the case studies using the use case modelling technique.

Customer Segmentation

Understanding which customer groups are interested in specific products and determining their value is crucial [23,24]. This process is known as customer segmentation, where the customer base is divided into distinct segments based on characteristic features (see Appendix 7.3) [25]. This segmentation enables more personalized marketing campaigns, better customer analysis, and improved control of sales and marketing activities [26]. Customer segmentation involves five essential steps, regardless of the chosen method [26]. Firstly, the target group must be defined around which the segmentation efforts will revolve. The starting point may vary depending on the product or marketing strategy being considered. Next, the criteria for dividing the target group into segments must be determined. [23–25] In the main analysis phase, various data sources such as customer surveys, online data, and social media evaluations are used to gain valuable insights. Text mining techniques can be employed to extract valuable information from unstructured data like customer feedback, reviews, and social media posts. Using this information, customers are classified and grouped into distinct segments based on their characteristics and preferences. Finally, the impact of these customer segments on marketing and product development is evaluated. [24,26] Customer segmentation not only enables the recognition of specific customer needs but also allows for tailored marketing concepts. It serves as a foundation for product development and overall company strategy, supporting the further growth and optimization of the business. [25] By effectively leveraging text mining, businesses can gain deeper insights from vast amounts of textual data, leading to more informed decisions and better customer understanding.

Identification of employee needs

One of the essential pillars of successful personnel and organizational development in a company is employee surveys to identify employee needs (see Appendix 7.4). These surveys collect information that is then processed and evaluated through a reflective process involving both employees and management. The objective of employee surveys is to develop and implement measures that enhance success within the organization. There are two types of success factors: general success factors and company-specific success factors. [27] In general, there are three methods for conducting employee surveys: distributing paper questionnaires, conducting online surveys through the intranet, and using a Tele-Dial system or Audience-Response system for projecting questions onto a screen and obtaining responses. The trend clearly favours online surveys due to their high acceptance among employees. This preference is driven by the benefits of high data quality, automation capabilities, and time efficiency in data collection and analysis. After conducting the survey, data analysis occurs in six stages: data input, data quality check and validation, generating key performance indicators, analysing patterns and correlations, contrasting with benchmarks, and creating a comprehensive analysis report. [27] Text mining can be applied during the data analysis process to extract valuable insights from unstructured data sources, such as open-ended responses in the survey, employee feedback, and comments. Text mining techniques can help identify sentiment, themes, and topics that are not easily captured through structured data analysis. Integrating text mining in the analysis can provide deeper and more nuanced understanding of employee sentiments and concerns, enriching the overall insights gained from the survey.

5. Conclusion

In conclusion, this research paper presents a validated longlist of text mining use cases specifically tailored to manufacturing companies. Through the synergy of Mayring's content analysis and real-world case studies, this study yields practical insights. The detailed exploration of two specific use cases underscores the relevance of these technologies and highlights their impact on critical business areas. These findings demonstrate how text mining can be instrumental in optimizing processes, enhancing decision-making, and fostering innovation within manufacturing companies. In essence, this research paper serves as a guide for professionals seeking to increase efficiency and innovation within their manufacturing operations, as the manufacturing industry continues to embrace digital transformation.

6. Acknowledgements

We would especially like to thank the user committee for attending several interviews and providing us with insights and feedback that helped to shape our research. Moreover, we would like to express our gratitude to the Federal Ministry for Economic Affairs and Climate Action for their support of VoBAKI (IGF-Project No.: 22009 N). The project is supported by Federal Ministry for Economic Affairs and Climate Action based on a decision of the German Bundestag.

7. Appendix

7.1 Results of the literature analysis according to Mayring

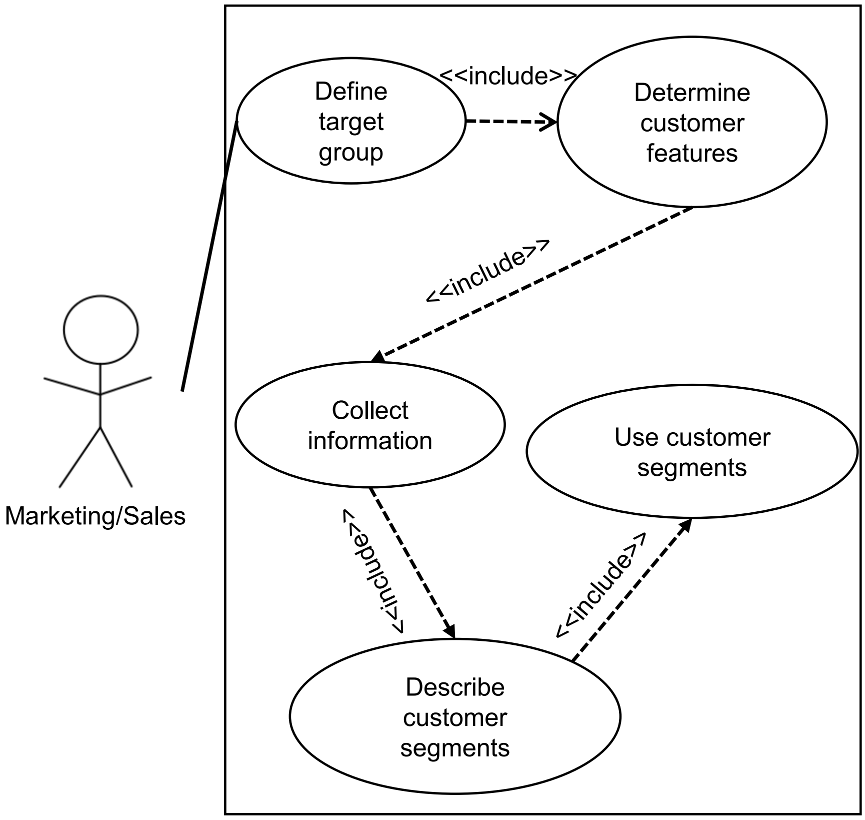
Results Mayrings's content analysis
Assignment of customer inquiries
Assistance with picking
Chatbot
Control of recruitment strategy
Creation of product descriptions
Customer segmentation
Early detection of cyberattacks
Early detection of health risks
Evaluation of documents
Flexible marketing
Identification of employee needs
Information extraction from documents
Management of customer cooperation
Offer segmentation and proposal
Prediction of market developments
Preparation of shipping documents
Summary of customer reviews

7.2 Results of the case studies (final longlist)

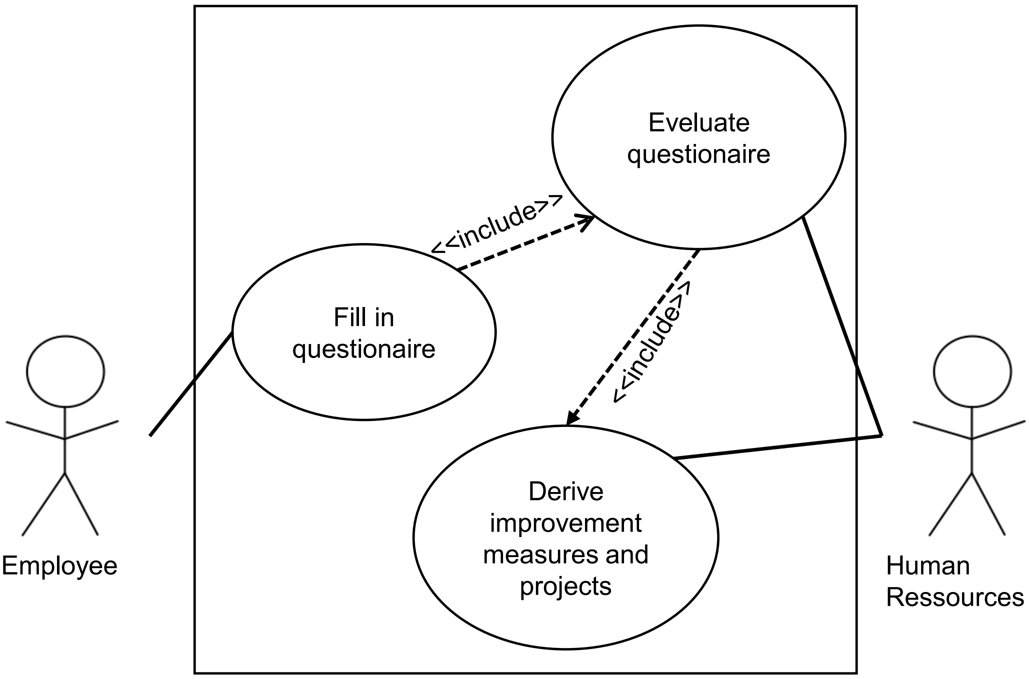
Results Mayrings's content analysis	Validated or added through case studies (final longlist)
Assignment of customer inquiries	Assignment of customer inquiries
Assistance with picking	
Chatbot	Use of data-based chatbots
Control of recruitment strategy	
Creation of product descriptions	Creation of product descriptions
Customer segmentation	Customer segmentation
Early detection of cyberattacks	
Early detection of health risks	
Evaluation of documents	Automated document processing and management
Flexible marketing	
Identification of employee needs	Identification of employee needs
Information extraction from documents	
Management of customer cooperation	
Offer segmentation and proposal	Assistance to the preparation of offers
Prediction of market developments	Prediction of market developments

Preparation of shipping documents	Preparation of shipping documents
Summary of customer reviews	Summary of customer reviews
	Proposal of solutions for troubleshooting

7.3 Use case diagram "Customer segmentation"



7.4 Use case diagram "Identification of employee needs"



References

[1] Hippner, H., Rentzmann, R., 2006. Text Mining. Informatik Spektrum 29 (4), 287–290.

[2] Lundborg, M., Guli, I., 2021. Künstliche Intelligenz im Mittelstand, Siegburg, 22 pp.

[3] La Justicia de Torre, C., Sánchez, D., Blanco, I., Martín-Bautista, M.J., 2018. Text Mining: Techniques, Applications, and Challenges.

[4] Hassani, H., Beneki, C., Unger, S., Mazinani, M.T., Yeganegi, M.R., 2020. Text Mining in Big Data Analytics. BDCC 4 (1), 1.

[5] Bernd W. Wirtz, Jan C. Weyerer, Carolin Geyer, 2019. Artificial Intelligence and the Public Sector—Applications and Challenges. International Journal of Public Administration 42 (7), 596–615.

[6] Quirin Demlehner, Daniel Schoemer, Sven Laumer, 2021. How can artificial intelligence enhance car manufacturing? A Delphi study-based identification and assessment of general use cases. International Journal of Information Management 58, 102317.

[7] Cohen, K.B., Hunter, L., 2008. Getting started in text mining. PLoS computational biology 4 (1), e20.

[8] Jo, T., 2019. Text Mining: Concepts, Implementation, and Big Data Challenge, 1st ed. 2019 ed. Springer International Publishing; Imprint: Springer, Cham, 1 online resource (XIII, 373 pages 236 illustrations, 148 illustrations in color.).

[9] Shotorbani, P.Y., Ameri, F., Kulvatunyou, B., Ivezic, N., 2016. A Hybrid Method for Manufacturing Text Mining Based on Document Clustering and Topic Modeling Techniques, in: Nääs, I., Vendrametto, O., Mendes Reis, J., Gonçalves, R.F., Silva, M.T., Cieminski, G. von, Kiritsis, D. (Eds.), Advances in Production Management Systems. Initiatives for a Sustainable World, vol. 488. Springer International Publishing, Cham, pp. 777–786.

[10] Astanti, R.D., Sutanto, I.C., Ai, T.J., 2022. Complaint management model of manufacturing products using text mining and potential failure identification. TQM 34 (6), 2056–2068.

[11] Devendra Kumar Mishra, Arvind Kumar Upadhyay, Sanjiv Sharma, 2021. Text mining in manufacturing process using unsupervised techniques of Machine learning. Materials Today: Proceedings 47, 6679–6681.

[12] Biegel, T., Jourdan, N., Madreiter, T., Kohl, L., Fahle, S., Ansari, F., Kuhlenkötter, B., Metternich, J., 2022. Combining Process Monitoring with Text Mining for Anomaly Detection in Discrete Manufacturing. SSRN Journal.

[13] Hrcka, L., Simoncicova, V., Tadanai, O., Tanuska, P., Vazan, P., 2017. Using Text Mining Methods for Analysis of Production Data in Automotive Industry, in: Silhavy, R., Senkerik, R., Kominkova Oplatkova, Z., Prokopova, Z., Silhavy, P. (Eds.), Artificial Intelligence Trends in Intelligent Systems, vol. 573. Springer International Publishing, Cham, pp. 393–403.

[14] Ansari, F., Kohl, L., Giner, J., Meier, H., 2021. Text mining for AI enhanced failure detection and availability optimization in production systems. CIRP Annals 70 (1), 373–376.

[15] Li, S., You, M., Li, D., Liu, J., 2022. Identifying coal mine safety production risk factors by employing text mining and Bayesian network techniques. Process Safety and Environmental Protection 162, 1067–1081.

[16] Wang, B., Gong, Y., Zhou, J., 2023. Text mining and association rules-based analysis of 245 cement production accidents in a cement manufacturing plant.

[17] Müller, M., Alexandi, E., Metternich, J., 2021. Digital shop floor management enhanced by natural language processing. Procedia CIRP 96, 21–26.

[18] May, M.C., Neidhöfer, J., Körner, T., Schäfer, L., Lanza, G., 2022. Applying Natural Language Processing in Manufacturing. Procedia CIRP 115, 184–189.

[19] Silipo, R., 2020. From Words to Wisdom - Towards Data Science. Towards Data Science, April 12.

[20] Shankar Chauhan, D., 2023. Text Mining offers Powerful Techniques for Manufacturers to Reduce Accounts Receivables Risk | LinkedIn. https://www.linkedin.com/pulse/text-mining-powerful-techniques-manufacturers-reduce-accounts/. Accessed 19 July 2023.

[21] Dialani, P., 2019. Top 5 Business Use Cases of NLP and Text Mining. Analytics Insight, July 21.

[22] Team, E., 2022. 10 Practical Text Mining Examples to Leverage Right Now. expert.ai, May 13.

[23] Adobe Experience Cloud Team, 2023. 21 reale Beispiele für Kundensegmentierung. https://business.adobe.com/de/blog/basics/real-world-examples-of-customer-segmentation. Accessed 31 July 2023.

[24] Raddao, N., 2018. Potenzialorientierte Kundensegmentierung zur Optimierung des Leistungsportfolios in der Firmenkundenbank: Konzeption und Implementierung einer "efficient customization" am Beispiel von Genossenschaftsbanken. Peter Lang International Academic Publishing Group, Bern, 141 pp.

[25] Wuttke, L., 2023. Kundensegmentierung: Definition, Methoden und Vorgehen. datasolut GmbH, May 24.

[26] Survey Monkey, 2023. Kundensegmentierung: Modelle, Ablauf, Beispiele: Mit einer professionellen Kundensegmentierung können Sie den Erfolg Ihres Unternehmens steigern. https://www.surveymonkey.de/mp/kundensegmentierung-modelle-ablauf-und-beispiele/#:~:text=Unter%20Kundensegmentierung%20versteht%20man%20die,anpassen%20und%20nachhalti g%20Erfolge%20erzielen. Accessed 31 July 2023.

[27] Nürnberg, V., 2022. Mitarbeiterbefragungen: Durch Mitarbeiterbeteiligung mit Feedback zum Unternehmenserfolg, 2. Auflage ed. Haufe Group, Freburg, München, Stuttgart, 180 pp.

Biography

Florian Clemens (*1993) received his M. Sc. degree in industrial engineering at University Paderborn. He is a researcher at FIR at RWTH Aachen University since 2019 in the department Information Management, working on the transfer of AI to production.

Hasan Hüseyin Özdemir (*1995) received his B. Sc. Production Engineering at the RWTH Aachen University and is writing his master's thesis in the field of information management at the FIR of the RWTH Aachen.

Prof. Dr.-Ing. Dipl.-Wirt. Ing Günther Schuh (*1958) 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. He is the founder of the Schuh & Co. group of companies based in Aachen, St. Gallen and Atlanta.

5th Conference on Production Systems and Logistics

Framework For The Rapid Development And Deployment Of Customized Industrial Robotic Applications

Paul Geng[1], Lisa Heuss[1], Thomas Rauh[2], Julian Müller[1], Rüdiger Daub[1]

[1]*Institute for Machine Tools and Industrial Management (iwb), Technical University of Munich, Garching near Munich, Germany*

[2]*Rohde & Schwarz Messgerätebau GmbH, Memmingen, Germany*

Abstract

Automation and industrial robots enable today's enterprises to increase productivity. Due to current challenges, such as a shortage of skilled workers, the trend is toward using industrial robots more and more in high-mix low-volume production. For this, enterprises must be able to develop and deploy robotic applications for various products, variants, and tasks easily and quickly. In previous works, we demonstrated the increased flexibility and efficiency of robot programming via a skills-based software framework. In this paper, we expand this framework by considering the overall development and deployment procedure of robotic applications. In addition to modular programming, we address the development of the necessary hardware for the robotic application. Here, we focus on the design of the gripper system. As an exemplary use case we present the handling and testing of variant-rich electronic products. Finally, based on the introduced framework, we show implementation results for this use case.

Keywords

industrial robot; skills; programming; gripper system; application development; high-mix low-volume production

1. Introduction

In the last decades, manufacturing companies have faced the trend toward high-mix low-volume (HMLV) production [1]. Therefore, they still heavily rely on manual labor, which leads to a high staffing level. However, due to the upcoming demographic change, there is and will be a more severe shortage of skilled workers [2]. Consequently, companies are increasingly interested in integrating automation into their production processes to support their employees with monotonous and tedious tasks. However, the development and deployment of robotic applications still require expert knowledge and are time-intensive [3]. Due to the high amount of product variants, many manufacturers still need to integrate automation into their production, mainly due to economic reasons [4].

To simplify and accelerate the development of robot applications in HMLV production, manufacturing companies need robot applications that can be easily customized for new product variants or changes in the robot's operating environment (e.g., component supply systems). This equally involves the design of hardware components, such as gripper systems for the robot system and its control software. This publication presents a novel approach that combines automated gripper design and flexible robot programming using skills. This allows easy configuration of a robot system for changing requirements. In this way, we aim to quickly deploy robot applications and quickly react to changes in products, variants, or tasks in the future. As a promising application field for our approach, we present the printed circuit board assemblies (PCBA) handling and testing task in electronics production for two main reasons. First, this sector is nowadays the

DOI: https://doi.org/10.15488/15305
ISSN: 2701-6277

leading industry for robotic systems [2]. Second, this sector has an increasing trend toward HMLV production [5].

The remainder of the paper is structured as follows: In chapter 2, we demonstrate various concepts for automatic gripper development to handle products in a HMLV production. Additionally, we show the state of the art in skills-based robot programming, which allows flexible control of industrial robots. Chapter 3 introduces the concept of the novel framework for developing and deploying robotic applications in HMLV production and details the necessary steps therein. In chapter 4, we present our exemplary use case for HMLV production and point out the current challenges in automating it. Afterward, in chapter 5, we present our first implementation results. Finally, we discuss the framework's potential and give an outlook for future work.

2. State of the art

In recent years, there have been several efforts to simplify the development of robotic applications. The commercial solutions from *drag&bot*, *D:PLOY,* and *intrinsic.ai* are particularly worthy of mentioning here [6–8]. These allow users to assemble the desired application from a marketplace of different robot systems, grippers, etc. Users are guided through the development process, which reduces the amount of expert knowledge required and speeds up time. This includes support for the selection of the right gripper as well as simplified graphic programming of the robotic application.

Taking a closer look into the development of robot applications for HMLV production, the design of flexible grippers and a modular structure of the robot program take on a central role. The robot interacts with the workpiece to be handled via its gripper system. Therefore, changes in the product design between different variants directly impact the gripper design. The robot program describes the processes to be performed on the product that may differ between different variants in HMLV production. Based on these preliminary considerations, the combination of automated gripper design and modular skills-based robot programming holds great potential for developing robot applications in HMLV production.

2.1 Gripper design

Gripper systems play an essential role in automated production systems because they are the link between the workpiece and the industrial robot [9]. These must be given special attention in HMLV production since the gripper must be able to compensate for the product, variant, or task change. Several approaches exist to make gripper systems more flexible. For instance, these are universal grippers, modular systems, or gripper-changing systems. However, all these approaches have the common drawback of high costs [10]. For this reason, several approaches have been investigated in recent years to automate the design process of gripper systems. The general idea is to use the CAD model of the workpiece to be handled and automate various aspects of the design phase. For example, this can be the identification of suitable grasp surfaces (grasp synthesis), the analysis of the grasp quality of these surfaces (grasp analysis), and the design of the gripper itself [11]. In the last few years, these automated methods have been mainly applied to the design of gripper yaws [12]. Please refer to Honarpardaz et al. [11] for a more detailed insight into this field.

In many production areas, such as electronics production, vacuum grippers are used primarily [13]. Therefore, there is great potential for the automated design of these systems. However, only a few approaches have dealt with the automated design of vacuum grippers. For example, Wan et al. [14] present an approach to identify suitable grasp surfaces in CAD models. Schmalz [15] elaborated a method for the automated selection and dimensioning of gripper systems. Here, vacuum grippers with only one operational element were considered, and the workpieces had simple geometries like polyhedra and cylinders or combinations.

2.2 Skills-based robot programming

The skills-based programming approach allows a modular design of robot applications, which is why it has steadily gained interest in recent years. In this field, most works use a three-layered approach [16]: On the lowest level, primitives are the most straightforward actions of the robotic system (e.g., a simple linear movement). Next, different primitives can be united to execute higher-level skills (e.g., a pick-and-place movement). Lastly, tasks for a robot are specified by a sequence of skills.

Previous work presented a skills-based control framework for developing modular and intelligent robot applications [17]. Within this framework, users can design their own primitives and skills, freely combine the skill set of a robot according to their requirements, and finally use these to complete various tasks. Based on a first evaluation with a simulated robot, it was demonstrated that the modular control structure allows for easy combination and reuse of skills, reducing workloads during application development. The integration of this skills-based programming framework into the overall development procedure of robot application and its more thorough application in real industrial use cases represents the next steps.

2.3 Need for research

This publication aims to investigate combining automated gripper design with skills-based robot programming to quickly and easily set up robot applications in HMLV production. These steps heavily rely on expert knowledge and are time intensive, which brings a lot of potential for savings. In this context, there is a need for research to merge both technologies in an integrated procedure. This contains, first, the elaboration of a methodology for the automated design of vacuum grippers. Second, a reusable skill set for robotic PCBA handling and testing tasks needs to be defined. Finally, we aim to design a procedure for extracting the required characteristics from the designed grippers for skills parametrization. The contribution of this publication is the presentation of a first concept for this approach and the analysis of its application in robotic PCBA handling and testing as a promising use case in HMLV production.

3. Concept

To reduce the overall development time for new robotic applications and to speed up the deployment when changes occur, such as a new product variant, a new framework was developed, shown in Figure 1.

3.1 Initial development

The first step is developing the components required for the intended robotic application. In general, the task to be automated is known in advance. In addition, an existing robot system often needs to be extended to handle the new automation task. The robot program and the necessary peripheral devices, such as gripper systems, must be developed for this. Thus, these are put into the focus of the framework. In the following, the steps for developing these components are described in the mentioned order.

Skill framework: The development of the robot program is based on the skills-based programming framework previously presented in [17]. Here, the skills are distributed via a central marketplace and can be combined as required to configure the robot for an individual application. In addition, expansion stages have been defined, which support users in a step-by-step development of their robotic applications. The first expansion stage represents the state of the art, where skills can be combined for the robot to perform various tasks. In the second expansion stage, a so-called skills blackboard is introduced. The skills blackboard serves as a central instance for storing information and exchanging it between different skills. Using the skills blackboard, a robot program can be easily adapted to new product variants by simply changing the relevant parameters on the blackboard (e.g., the size of different product variants). Thus, in the initial development phase, the aim is to design skills that can be easily reused for different product variants by adapting their execution based on the product parameters available from the skills blackboard. In this way, development time will be sped up as previously designed skills can be reused for other product variants.

Gripper design pipeline: The pipeline for developing gripper systems contains mainly tools for analyzing and configuring the necessary gripper systems. This allows us to build gripper systems tailored to the individual process instead of relying on existing ones on the market, ensuring the best handling solution for a given use case [9]. The input information required by the pipeline is primarily a CAD model of the workpiece and additional physical properties (e.g., the mass of the product or additional process information). Based on the CAD model, suitable grasp poses are identified and necessary gripping forces are calculated. For a detailed description, please refer to the work published in [18]. The pipeline output is a design of the gripper system as a CAD model. This model can be used to manufacture the gripper and configure the robot simulation environment for motion planning. Additionally, relevant information for the adaption of the robot program, for example, grasp poses on the workpiece, are extracted and provided. The developed gripper system and robot program, respectively skills, are stored in a database for the deployment that follows in the next step.

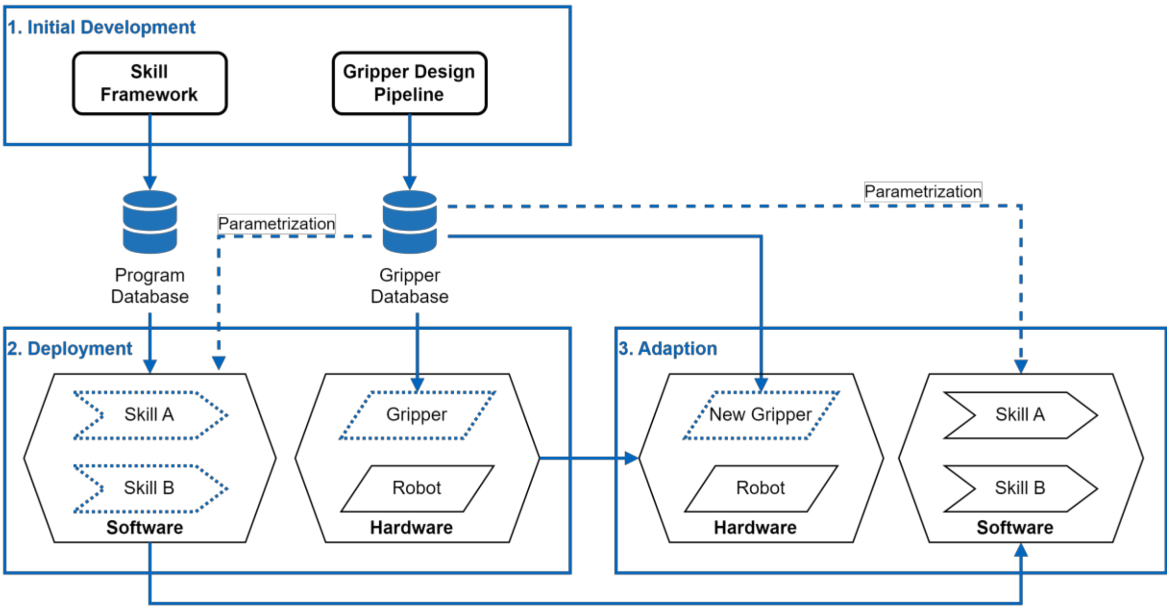


Figure 1: Overview of the framework. In the initial development, the necessary robot program and the gripper system are developed. During the deployment, the already existing robot is extended by the gripper system and the new robot program, while the information from the gripper design is used to parametrize the robot program. In the final step, adaptation, only the gripper is redesigned and replaced. The robot program remains the same and is parameterized again using the information from the gripper development.

3.2 Deployment of the robotic application

After the individual component of the robotic application has been developed, the application's deployment takes place. The gripper system is attached to the robot and all skills required for this application are downloaded onto the robot’s controller. Additionally, some robot skills might be configured for the considered product variant. For instance, selected poses for workpieces or supply components need to be changed. Here, the focus lies on speeding up the deployment time through two extensions: Firstly, the parametrization of the robotic application is simplified using the skills blackboard. Here, relevant information about the process (e.g., the workpiece’s location) can be adapted at one central point. In the later operation phase, skills will adapt their motion sequences based on the stored information. Secondly, instead of manually defining parameters (e.g., gripping points), the goal is to automatically provide these from the previous design phase of the gripper system.

3.3 Adaption to product changes

Since product changes occur frequently, providing a method to respond quickly to these changes is necessary. Instead of repeating the overall process of developing robotic applications again, the framework supports users in adapting these for new product requirements to reduce the overall workload. First, based on a CAD model of the new product variant and some additional parameters, users can utilize the automated design pipeline to construct a new and suitable gripper system. Second, no further implementation effort arises since the robot skills are designed for reuse. Third, during deployment of the adapted robot application, modifications resulting from the new product variant can be quickly added to the skills blackboard. Based on this information, the robot program adapts to the new product variant. This means that only the gripper system is a new development, while the robot program relies on parameterization. This speeds up the development and deployment.

4. Exemplary use case: PCBA testing

The following application example is from Rohde & Schwarz Messgerätebau GmbH (R&S). R&S manufactures complex products for high-frequency signal analysis, processing, and generation. In the exemplary use case, we focus on testing PCBAs. The high product complexity causes increased efforts in the test field. In the testing process, the finished PCBAs are loaded into a test adapter, where a test cycle is executed. Afterwards, the PCBAs are separated into scrap and good parts depending on the test results. Good PCBAs will be mounted into devices, while the scrap parts will be checked and repaired by human workers. A high variability characterizes the testing field. The test duration can vary from a couple of minutes to an hour. The lot size of one type of PCBA to be tested daily is typically between six and 24. Because of the frequent product changes, manual operations are often used here. However, due to the scarcity of skilled workers and the tiring nature of this work, R&S aims to automate the PCBA testing.

Thus, to relieve the employees, specialized robot cells were developed to perform this task. The robot cells' general procedure starts with picking the PCBA from a buffer system using a customized 3D-printed vacuum gripper. The PCBA is then placed into the test adapter and connected to several electronic test and measurement devices. The robot closes the test adapter and moves various levers. These are connected to a manual kinematic for connecting the ports of the PCBA. After the successful connection, the electrical test program starts, and the robot waits for completion. After finishing the test run, the robot opens the adapter, removes the PCBA, and sorts it into the good or scrap bin based on the test result. Then, the process starts over with the next PCBA. The system can run autonomously for several hours depending on the number of PCBAs and the testing times.

The benefit of the depicted robot cells is the possibility of using the test station in manual and automatic modes. Since all levers are operated by the robot and the human operator in the same way, the worker can use the testing cell, e.g., during the day shift for troubleshooting measurements. Here, non-working PCBAs can be examined and repaired, while the robot is operating the test equipment at night. This concept ensures a high utilization rate of the expensive test equipment while relieving the operator of the repetitive handling task and night shifts.

There are many challenges in building these robotic cells, some of which have already been addressed. For example, due to the frequent changes in PCBAs, the automated system must be able to handle multiple PCBAs. This is done via PCBA-specific test adapters and grippers, which can be manually changed.

Nevertheless, some challenges still need to be addressed. These include the construction of such a cell for multiple PCBAs in a more economically feasible way. In detail, the following challenges need to be addressed to enable economic automation for even more PCBAs:

1. Positions of the buffers and PCBAs stored in them change for every new variant. This causes high effort in teaching the robot, which needs to be reduced.
2. For each new variant, an individual gripper system is required. Thus, the recurring and intense design effort for new grippers needs to be reduced.
3. Until now, the buffers have been designed explicitly for every variant. In the future, the introduction of variant-independent buffer systems is needed. However, this requires a new design for the buffer systems as well as image recognition algorithms to automatically detect the test objects in the buffer.
4. A software framework for communication with edge devices, e.g., the robot and the test system, needs to be developed. In addition, it should be able to orchestrate the individual jobs and skills of the system depending on the variant.

5. Implementation

We apply our concept presented in chapter 3 to the use case of PCBA testing. In this way, we aim to demonstrate how the stated challenges, typically for HMLV production, can be addressed. In the following, we present our conceptual procedure for realizing this use case based on the current state of implementation. The setup of our test environment for PCBA testing is depicted in Figure 2.

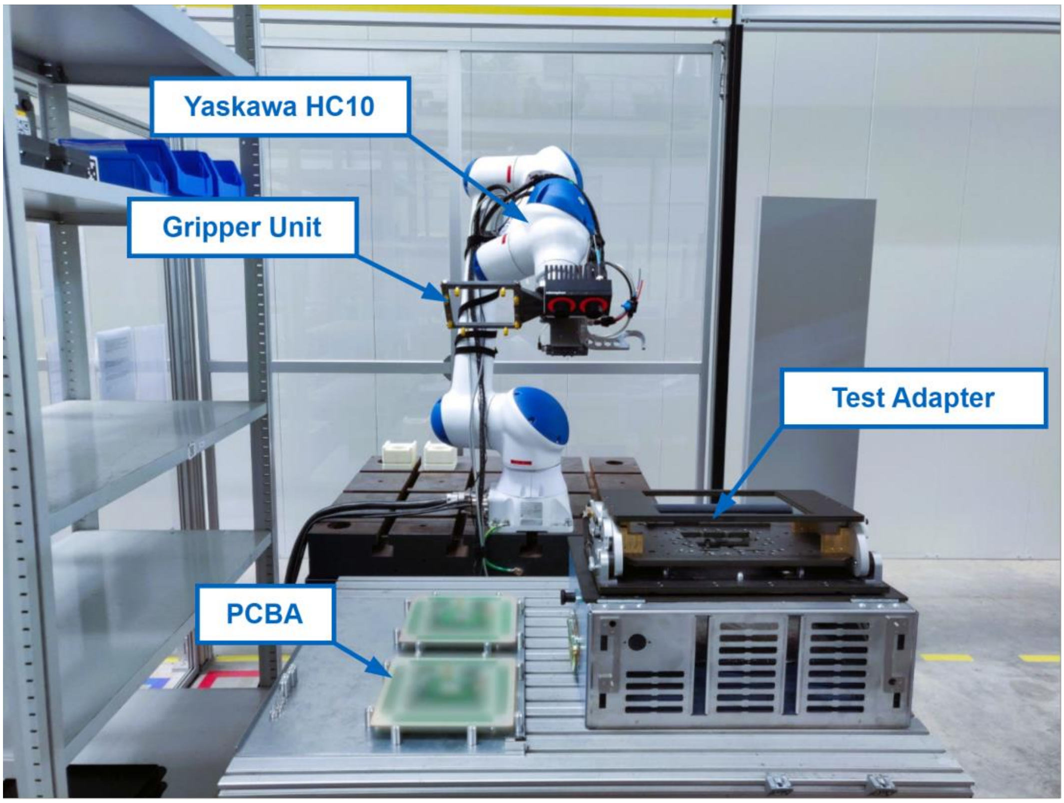


Figure 2: Demonstrator of the robot cell for the automated testing of PCBAs. The PCBAs are blurred in the picture.

In our initial implementation, we focus on the first challenge described in chapter 4 to reduce the time required for teaching the robot a new variant. For this purpose, we designed the necessary skills for the handling task. Here, we have particularly emphasized reusability and ease of parameterization. This is also achieved by integrating the skills blackboard into the use case, which can be easily adjusted for new product variants. The whole process, including the implemented skills and the exchanged parameters with the blackboard, is illustrated in Figure 3.

In the first step, we analyzed the task described in chapter 4 and divided it into the following subtasks:

1. Picking up a PCBA from the storage space on the shelf.
2. Inserting the PCBA into the test adapter.
3. Executing the test procedure.
4. Taking the PCBA out of the test adapter.
5. Delivering the PCBA back into its storage space on the shelf.

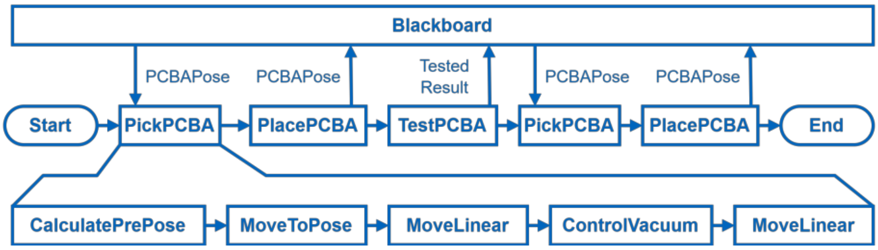


Figure 3: Flowchart of the entire test procedure as a task, which exchanges parameters with the blackboard, and a detailed breakdown of the *PickPCBA* composite skills into its primitive skills.

To implement the flexible handling of PCBAs, we used the skills-based approach developed in [17]. It is developed based on the *Robot Operating System* (ROS). It already provides a stock of primitives and skills to plan and perform robot movements using the ROS package MoveIt and other simple tasks. These skills have already been developed for another use case and can be directly used for our implementation. For example, we use *MoveToPose* skills, which provide a point-to-point movement of the robot and *MoveLinear* skills for linear movements. In addition, the skill *CalculateGraspPose* is also available and allows the calculation of the gripper pose or the prepose based on the location of the workpiece to be handled.

Based on the analysis of the subtasks, we decided to implement one skill for picking (*PickPCBA)* and one for placing PCBAs (*PlacePCBA)*. For instance, picking a PCBA from the shelf storage or the test adapter relates to the same basic behavior. For the subtask of picking up a PCBA (*PickPCBA*), the following actions need to be performed within the skill:

1. Calculate a pre-pose based on a gripping pose of a workpiece. For PCBAs, the pre-pose is a few millimeters above the PCBAs' surface, while the gripping pose is directly at the surface.
2. Move the gripping unit to the pre-pose.
3. Slowly approach the gripping pose.
4. Activate the vacuum flow and, therefore, grip the PCBA.
5. Slowly move back to the pre-pose.

The set of skills provided by [17] was reused and extended with missing primitives. These primitives control the vacuum flow that lets the PCBA hold onto the gripper (*ControlVaccum*) and initiate the PCB testing inside the adapter (*TestPCBA*). The second skill, placing the PCBA (*PlacePCBA*), follows the same structure as *PickPCBA*, except that the gripper is switched off. This structure of the skills also allows us to use them to return the tested PCBAs. In addition, the focus was placed on the parameters exchanged with the blackboard to make a simplified adaptation to new product variants possible.

As mentioned above, the blackboard can be seen as a central instance for storing information that provides skill parameters. For example, the skill *MoveToPose* takes a pose to move to as an input parameter. This is provided via the blackboard and can be adjusted when the product variant is changed. In the blackboard, additional information about the process is also provided, for example, if a PCBA has been tested yet and whether it has passed. The blackboard allows skills to exchange data with other skills, even if they are not directly linked. This means that, for example, the position of a PCBA can change during the handling task, and the entries in the blackboard are updated and reused. Figure 4 shows an excerpt from the blackboard used to implement the use case.

ObjectType	ObjectName	ParamName	Key	Value
pcba	pcba_1	PCBAPose	position_x, ...	0
		Result	-	succesful
pcba	pcba_2	PCBAPose	position_x, ...	0
		Result	-	-

Figure 4: Exemplary entries in the blackboard, used as a database for skills to exchange parameters. Every object, e.g., a PCBA, has a name (ObjectName) and belongs to a specific type (ObjectType). All objects of a type have the same parameters. In the case of PCBA, these are, for example, the grip poses for motion planning.

6. Discussion

The new framework aims to reduce the overall time during the development and deployment of robotic applications. In this first implementation, the goal was to reduce the time for implementing the exemplary use case of PCBA testing while lowering the high effort for teaching the robot new variants. Compared with the implementation described in chapter 4, the solution offers two advantages. First, the robot program is implemented, reusing existing skills, which sped up the initial development time. In addition, it is implemented so that reusage for new variants during deployment is guaranteed. Second, the skills blackboard serves as a central instance for the relevant process parameters, which means that the relevant poses of the components and the test adapter can be adjusted in one central location. This allows an easy setup of the robotic application and fast adaption to product changes.

However, upon closer inspection of the *PickPCBA* skill, it can be noted that the tasks of picking up and placing down a PCBA are schematically identical, with different parameters. Instead of approaching a gripping pose to grip a PCBA, the same pose can be approached and the PCBA placed by stopping the vacuum flow. The place-down-pose and its pre-pose are not defined by a PCBA but by either the slot in the test adapter or the storage place on the shelf. In the end, we decided against a combined skill for the sake of clarity. With the two separate skills, *PickPCBA* and *PlacePCBA*, each has a clear allocation.

7. Conclusion

This paper addresses the problem of automating HMLV productions with industrial robots. Until now, frequent changes in products, variants, and tasks hinder economical automation. For this reason, a framework for the rapid development and deployment of robotic applications is presented. This framework is based on our previous work and has been extended to combine the implementation of reusable robot programs with developing gripper systems. An exemplary use case from HMLV electronics production and associated automation challenges were presented. The first implementation of the use case with the framework was conducted, allowing the reuse of existing skills that can be easily adapted for new variants.

In future work, the focus lies on three open tasks, already stated in chapter 4. First, by now, individual PCBAs can be handled based on the presented implementation. In the next step, the implementation will be improved for easy parametrization and robust handling of various PCBAs. Second, the implementation of the necessary modules to automate the design of the individual gripper systems will be finished. Third, computer vision will be used to further reduce the efforts for adapting the robot system to new variants. Here, the focus lies on reducing the effort of manually specifying the position of workpieces in the robot's workspace by automating this process using image recognition. In parallel, we will further expand the test bench to strengthen the results based on quantitative analyses.

Acknowledgments

The research leading to this publication has received funding from the Bavarian Ministry of Economic Affairs, Regional Development, and Energy (StMWi), as part of the project “KIRO – KI-basierte Roboterapplikationen für eine einfache Skalierung und optimierte Auslastung” (DIK0357/01).

References

[1] Koren, Y., Gu, X., Guo, W., 2018. Reconfigurable manufacturing systems: Principles, design, and future trends. Front. Mech. Eng. 13 (2), 121–136.

[2] IFR, 2022. World Robotics - Industrial Robots 2022: Statistics, market analysis, forecasts and case studies. VDMA Services GmbH, Frankfurt am Main.

[3] Siciliano, B., Khatib, O., 2016. Springer Handbook of Robotics. Springer International Publishing AG, Cham, SWITZERLAND.

[4] Gan, Z.L., Musa, S.N., Yap, H.J., 2023. A Review of the High-Mix, Low-Volume Manufacturing Industry. Applied Sciences 13 (3), 1687.

[5] S. Ruggeri, G. Fontana, V. Basile, M. Valori, I. Fassi, 2017. Micro-robotic Handling Solutions for PCB (re-)Manufacturing. Procedia Manufacturing 11, 441–448.

[6] Plattform für Automatisierte Kollaborative Roboteranwendung, 2023. https://onrobot.com/de/l%C3%B6sungen/dploy. Accessed 6 July 2023.

[7] drag&bot, 2022. drag&bot – Grafisches Roboter-Betriebssystem - drag&bot. https://www.dragandbot.com/de/. Accessed 6 July 2023.

[8] Intrinsic, 2023. Home | Intrinsic. https://intrinsic.ai/. Accessed 6 July 2023.

[9] Schmalz, J., Giering, L., Hölzle, M., Huber, N., Reinhart, G., 2016. Method for the Automated Dimensioning of Gripper Systems. Procedia CIRP 44, 239–244.

[10] Löchte, C.W., 2016. Formvariable Handhabung mittels granulatbasierter Niederdruckflächensauger. Dissertation, [1. Auflage] ed.

[11] Honarpardaz, M., Tarkian, M., Ölvander, J., Feng, X., 2017. Finger design automation for industrial robot grippers: A review. Robotics and Autonomous Systems 87, 104–119.

[12] Honarpardaz, M., Ölvander, J., Tarkian, M., 2019. Fast finger design automation for industrial robots. Robotics and Autonomous Systems 113, 120–131.

[13] Fantoni, G., Santochi, M., Dini, G., Tracht, K., Scholz-Reiter, B., Fleischer, J., Kristoffer Lien, T., Seliger, G., Reinhart, G., Franke, J., Nørgaard Hansen, H., Verl, A., 2014. Grasping devices and methods in automated production processes. CIRP Annals 63 (2), 679–701.

[14] Wan, W., Harada, K., Kanehiro, F., 2021. Planning Grasps With Suction Cups and Parallel Grippers Using Superimposed Segmentation of Object Meshes. IEEE Trans. Robot. 37 (1), 166–184.

[15] Schmalz, J.K.B., 2018. Rechnergestützte Auslegung und Auswahl von Greifersystemen. Dissertation, 220 pp.

[16] Pantano, M., Eiband, T., Lee, D., 2022. Capability-based Frameworks for Industrial Robot Skills: a Survey, in: 2022 IEEE 18th International Conference on Automation Science and Engineering (CASE), Mexico City, Mexico. 20.08.2022 - 24.08.2022. IEEE, pp. 2355–2362.

[17] Heuss, L., Gonnermann, C., Reinhart, G., 2022. An extendable framework for intelligent and easily configurable skills-based industrial robot applications. Int J Adv Manuf Technol 120 (9-10), 6269–6285.

[18] Geng, P., Daub, R., 2023. Automated Configuration and Flexibilization of Vacuum Grippers, in: 2023 IEEE 28th International Conference on Emerging Technologies and Factory Automation (ETFA), pp. 1–4.

Biography

Paul Geng (*1995) is a research associate at the Institute for Machine Tools and Industrial Management (*iwb*) at the Technical University of Munich. He works in the department Assembly Technologies and Robotics focusing on automated design of gripper systems for industrial robotic applications.

Lisa Heuss (*1992) is a research associate at the Institute for Machine Tools and Industrial Management (*iwb*) at the Technical University of Munich. She works in the department Assembly Technologies and Robotics focusing on control architectures and automated task planning for flexible and intelligent industrial robotic applications.

Thomas Rauh (*1991) is the head of the robotic applications team at Rohde & Schwarz. From 2016 to 2020 he earned his doctorate at the Institute for Machine Tools and Industrial Management (*iwb*) at the Technical University of Munich, focusing on structural dynamics of production machines.

Julian Müller (*1995) has been studying "mechatronics and robotics" in the master's program at the Technical University of Munich since 2021. He has been a student assistant at the Institute for Machine Tools and Industrial Management (*iwb*) since 2022, focusing on industrial robotics and computer vision.

Rüdiger Daub (*1979) is the holder of the Chair of Production Engineering and Energy Storage Systems at the Technical University of Munich since June 2021. Prof. Dr.-Ing. Rüdiger Daub is also head of the Institute for Machine Tools and Industrial Management (*iwb*) and of the Fraunhofer Institute for Casting, Composite and Processing Technology (IGCV).

5th Conference on Production Systems and Logistics

Planning And Controlling Multi-Project Environments In Factories

Justin Hook[1], Lars Nielsen[2], Peter Nyhuis[1]

[1]*Leibniz University Hannover, Institute of Production Systems and Logistics, 30823 Garbsen, Germany*
[2]*Hannover Rück SE, 30625 Hanover, Germany*

Abstract

Companies regularly undertake projects to maintain their competitiveness by adapting and embracing change. Multi-project management (MPM) is crucial for companies as it enables efficient planning and control of multiple projects, ensuring they are executed effectively and delivered on time. It helps to optimise resource allocation, minimise conflicts, and maximise overall project success, ultimately contributing to the organisation's competitiveness and growth. However, existing MPM models often lack a specific focus on the goals and requirements of the factory setting, as they aim for broad applicability. A process model should consider the project context and the interdependencies among its tasks. To address this, a new concept is necessary to efficiently plan and control a multi-project environment within a factory. To develop a suitable process model for MPM in a factory, insights from MPM practices and the production environment are required. Including those insights, project landscapes can be planned and controlled effectively and efficiently. This article provides a summary of the approach developed by the Institute of Production Systems and Logistics, with a particular emphasis on the relationships between actuating, control, and target variables.

Keywords

Factory planning; Project Portfolio Management; Resource Allocation; Process Model; Project Management

1. Introduction

Many companies face an increasingly volatile, uncertain and turbulent market environment, forcing them to make permanent adjustments and changes in their factories [1–4]. This pressure to adapt is often met with an increasing project orientation. As a result, a steadily increasing complexity and dynamism in the project landscape can often be observed. Such an environment cannot be mastered with project management approaches at the individual project level alone. It also requires a complementary multi-project management (MPM) that enables the project landscape to be designed and steered systematically and in line with the company's overall strategy [5,6]. The task of manufacturing companies is to ensure a good selection and prioritisation of suitable projects, considering the right timing in the face of numerous parallel projects to strive for the best possible allocation of resources [7,8]. A systematic, efficient and effective MPM considers the project context and the mutual influence of the projects [9].

2. Need for research

A brief overview of the topic of multi-project management and the deficits of existing approaches is given below. Also, results already published regarding this framework are summarised to give an understanding of the underlying concept of MPPC before introducing further findings and consolidating the results. First,

DOI: https://doi.org/10.15488/15246
ISSN: 2701-6277

the process model, i.e. the task view, and then the effects model, i.e. the interrelationships of the model, are addressed.

2.1 Multi-project management

According to DIN 69901-5 a project is essentially characterised by the uniqueness of the conditions in their entirety [10]. Examples of such conditions might be targets, limitations, e.g. of a temporal, financial or personnel nature or a project-specific organisation [10]. Similar projects can be interconnected within a project programme [11]. Project programmes are set up to achieve a superordinate target as effectively and efficiently as possible [12,11]. All planned, approved and ongoing projects and programmes of an organisation or division comprise a project portfolio responsible for the permanent overall planning and control of the project landscape [7]. Such a portfolio is periodically monitored and controlled by a portfolio management in charge of accepting and prioritising project applications [13]. Limited resources force companies to make an effective project selection among numerous project plans at the right time and with sensible resource allocation, which is why efficient and powerful multi-project management is needed [7]. MPM can be subdivided into tasks that can be combined into a continuous procedure as a process model [13]. The goals of planning and controlling multi-project environments include 'alignment with the targets of the organisation', 'creation of transparency and synergies' as well as 'establishment of standardised structures, processes and tools' or 'assessment of opportunities and risks' and 'initiation of countermeasures in the event of an upset [7].

2.2 Existing MPM Approaches

Several generic MPM approaches exist, for example, by SEIDL or DIN 69909-2 [14,13]. Project management can typically be divided into phases like 'Initialisation', 'Definition', 'Planning', 'Control' and 'Closure'. Necessary project management tasks are assigned to those phases and are related to each other by a temporal sequence. Such models also usually indicate the responsibilities for different tasks, often suggesting the frequency with which individual tasks are to be processed. A project landscape can be managed at an individual project level, including tasks such as project preparation or approval of project results, and at the programme and portfolio level containing operational and strategic tasks, such as managing the project portfolio. The duration of tasks at the individual project level varies depending on factors such as project type, industry, environment, and project-specific considerations. Since tasks at the individual project level follow the project life cycle, these factors also dictate the timing of task cycles at the programme and portfolio levels [13]. While common approaches to MPM enable the planning and control of multi-project environments in factories, they lack a perspective on interrelationships that could consider dependencies between projects and, therefore, cannot align the MPM tasks with the portfolio or overall factory goals [15]. According to BERGE AND SEIDL, a project portfolio summarises all planned, approved, and ongoing projects for a company or business unit [12]. NIELSEN sums up that no process model for MPM currently combines a process-oriented description with an effects model and uses its influence on company or factory goals as orientation. Without this positioning aid, conflicts of objectives cannot be resolved based on a superordinate framework model [16]. There is no holistic process model which managers in the factory can use to plan and control multi-project environments.

To close this research gap, a research project has been carried out at the Institute of Production Systems and Logistics, in which MPM approaches were enriched with insights from a systematic investigation of production planning and control (PPC). Findings were to be adapted to the context of project management, leading to a concept of multi-project planning and control (MPPC). By applying the methodology utilised in PPC models, tasks can be effectively associated with targets within the multi-project environment. For the MPPC model, the MPM approach by SEIDL was used as a primary input [17,13].

2.3 Multi-project planning and control (MPPC)

Since general MPM approaches lack abilities in supporting decision-making, findings from PPC and MPM topics were combined to create the concept of multi-project planning and control (MPPC) with a focus on factories. In this context, SCHMIDT established the Hanoverian supply chain model (HaLiMo), which comprehensively classifies PPC tasks and consolidates them within a generic framework model. This approach also considers the interrelations between PPC tasks and their respective target objectives. Using the methodology known from PPC models, tasks could be linked to targets of the multi-project environment, allowing for positioning in case of conflict of objectives.

2.3.1 Relevant tasks

To develop a task model, contents from MPM and PPC were merged into a joint knowledge base. The basis for the combination was an analogy analysis, starting from comparing project (MPM) and product (PPC) [17]. Within the framework of a deviation analysis, any gaps, different focal points and levels of abstraction were systematically uncovered. Based on the deviation analysis, combining the approaches to PPC according to SCHMIDT and MPM according to SEIDL, a comprehensive knowledge base of MPPC in the factory was developed, structured, and, where necessary, complemented by other approaches [18,13]. The result was a catalogue of generally valid tasks for MPPC from the approaches of MPM and PPC [16]. The task profiles of the MPPC in the factory were formulated. After the tasks were reviewed for redundancies and gaps, validation took place in interviews with experts in multi-project management in factories to finalise the task model. Figure 1 comprises the main tasks along the project management phases. In the figure, the different responsibilities for the main tasks can also be seen, structuring the tasks horizontally.

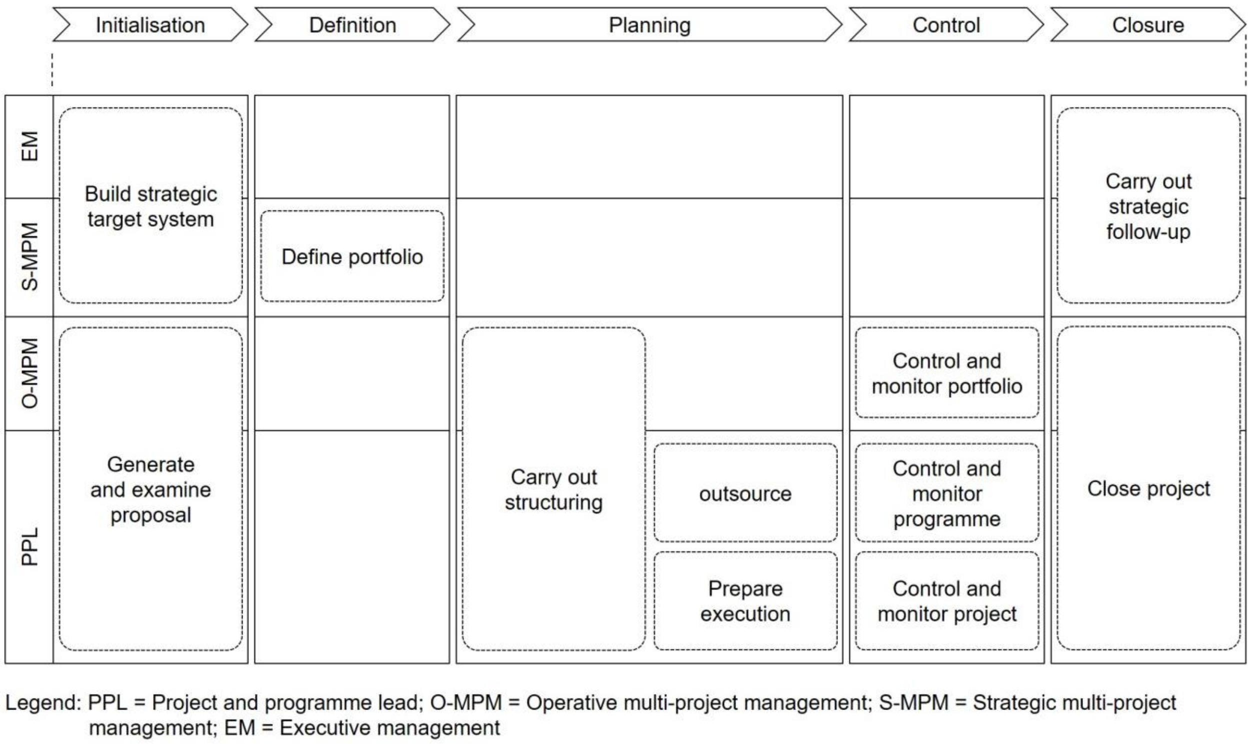


Figure 1: Main tasks of MPPC (based on [16])

2.3.2 Interrelationships

It is necessary to introduce an effects model to represent interrelationships between tasks and, ultimately, the factory targets, which consideration is elementary for effective planning and control. In PPC, the variables of the effects model are divided into actuating variables, control variables and target variables. Together the variables enable target-oriented decision-making and are crucial in target achievement [19,18]. Actuating variables can be influenced directly by fulfilling tasks and influence control variables. Target variables result from control variables and can thus indirectly be influenced by task fulfilment. By considering the effects variables, managers are enabled to make timely and professional decisions and consider interactions with other projects or company divisions. Following this logic, a catalogue of actuating and control variables is first created for MPPC. The qualitative interactions between the actuating variables are examined with the help of binary design structure matrices (DSM). Interrelationships between the actuating and control variables are described by a binary domain mapping matrix (DMM) and a causal diagram [20]. The determined actuating and control variables are shown in Figure 2.

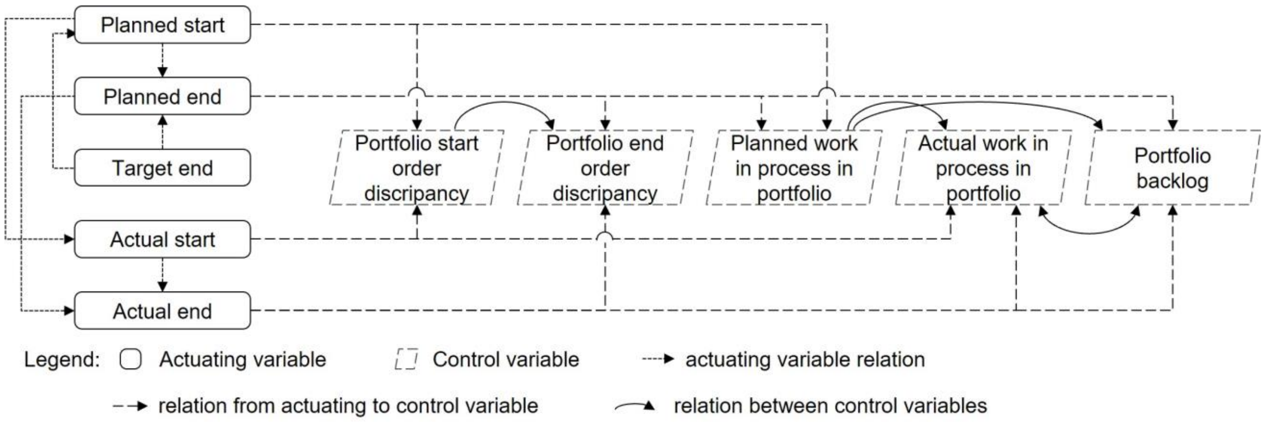


Figure 2: Actuating and Control variables with their relations (based on [16])

In addition to the relationships shown, other interactions between actuating and control variables may exist indirectly. For better readability, these relationships are not included in the figure above. An example of such indirect interrelation is the possible influence of the portfolio end order discrepancy on a future portfolio start order discrepancy. This applies, for example, if shifts in the project end order result in resource bottlenecks which in turn require a deviation from the initially planned project start order.

3. Consolidation of the MPPC process model

This section introduces the target variables to complement the part of the effects model presented so far with the control variables. In 3.1, it is shown how the target variables of a portfolio can ultimately be manipulated during processing tasks that influence control variables. Additionally, in 3.2, it is outlined how correlations between deviations in the portfolio targets and possible causes can be determined.

3.1 Target variables in MPPC and consolidation of the process model

The MPPC target variables can also be derived from the production environment by comparing PPC and MPM based on the analogy analysis mentioned above. For multi-project planning and control, five target variables can be derived from PPC approaches: portfolio utilisation, portfolio schedule reliability, portfolio throughput time deviation, portfolio transparency and portfolio delivery capability [15,16,18].

3.1.1 Target variables

In the context of MPPC, the portfolio utilisation target is introduced to show the profitability of the MPM target system. Resource availability and utilisation in projects are similar to production orders, whereby all factory components can be potential project resources. However, in contrast to PPC, the utilisation of a portfolio needs an auxiliary variable. Portfolio capacity gives a theoretical maximum to which the utilisation can be compared. This step is necessary since the available resource capacity in a portfolio can be enhanced by reducing their integration into daily business tasks. In MPPC, the target variable portfolio schedule reliability provides information on the adherence to deadlines for completed projects in the portfolio. If a project is completed within a tolerance range around the planned end date, it is considered on schedule. The use of portfolio schedule reliability is important because individual projects can have a negative impact on the rest of the portfolio due to their content and resource dependencies, both through early and mainly delayed projects. The average relative portfolio throughput time deviation is used to assess the throughput time behaviour of all ongoing projects in the portfolio. Here, the percentage deviation of the throughput time is calculated for each project in the considered period and then averaged for the entire portfolio. A positive throughput time deviation in the portfolio can be due to factors such as unavailable resources, changes in the project schedule or excessive multi-tasking. The portfolio throughput time deviation allows a statement on the actual duration in relation to the previously planned duration of the control phase, whereby systematic planning errors or disruptive influences leading to variance come to light. When analysing the throughput time deviation, it is essential to ensure positive deviations do not balance out negative deviations. Therefore, the standard deviation describes the mean spread from the expected value. In the context of MPPC, the target value of the work in process from the PPC is replaced by the target value of the portfolio transparency. The more cumulative project effort is generated by numerous or very large projects in process, the less transparent the portfolio becomes. Portfolio transparency is defined as an overview of the projects and programmes in the portfolio and is also needed for efficient cooperation between different projects, preventing multi-tasking. The target variable portfolio delivery capability provides information on fulfilling the client's desired deadlines through the target end dates of the different projects.

In general, the fulfilment of targets is made more difficult because these conflict with each other. Since portfolio utilisation is to be maximised, a high work in process benefits this target. Portfolio transparency and portfolio schedule reliability should also be as high as possible but decrease with increasing projects making up the work in process. Because the standard deviation of relative throughput time deviation increases undesirably with increasing work in process, this also advises limiting the work in process to a certain degree. The target variables conflict, leading to a positioning range in which the projects accounting for the work in process should be kept. In the positioning range, the benefits of a high portfolio utilisation concerning its saturation can be kept while mitigating the adverse effects for the other target variables.

3.1.2 Consolidation of the process model

Having described the target variables and their behaviour with increasing work in process, the effects model and the tasks of MPPC can be combined. To effectively control the multi-project environment, it is necessary to know the relationship between task processing and the effects model of portfolio management. Only based on these relationships can tasks be processed in such a way that a desired effect on the portfolio targets can be achieved through control variables. In addition to assigning the tasks to the actuating variables, they were also assigned to the project management phases: initialisation, definition, planning, control and closure. By doing so, the tasks can also be characterised in terms of planning or controlling function based on the assigned phase along the project management phases. The characterisation of the tasks allows a clear assignment to defined responsibilities provided as swimlanes. This assignment makes it possible to conclude the status of a project, especially since the project life cycle is shown along the project management phases.

Figure 3 uses the example of the task plan project structure to show how target variables may be manipulated. Through the actuating variables planned start and planned end, there is an influence on different control variables, which then affect the target variables. In this case, all MPPC targets are affected by planning the project structure, indicating that possible target conflicts may impact task fulfilment.

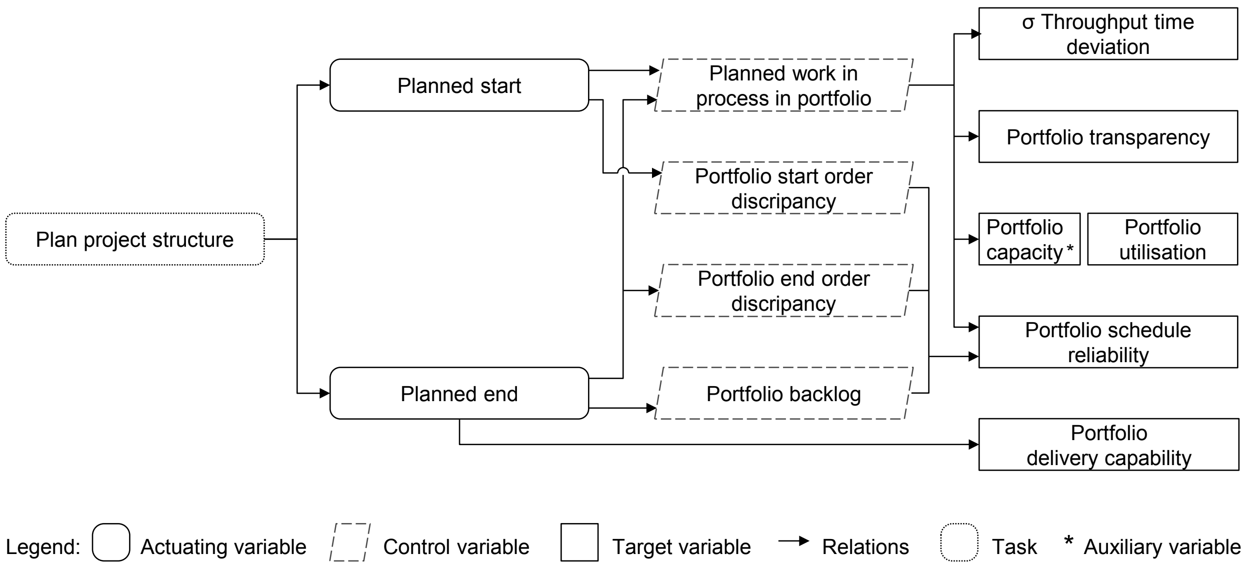


Figure 3: Example for the influence on target variables (based on [16])

How many projects to approve and, thus, where to position regarding the work in process must be determined individually for each company. It is a business decision that depends, among other things, on the opportunity costs and the priorities of the target variables. Knowing the positioning range and the conflict of targets is a prerequisite for carrying out the task in accordance with the portfolio target. The planned start and planned end, in particular, can be influenced by many tasks. This connection is based on the fact that both values will be overwritten in the course of the project management phases as soon as new information is available in a subsequent step. This observation makes it clear how important it is to have a good overview of the project in the early phases and to keep an eye on the utilisation and other target values of the portfolio. In contrast, the actuating variables actual start and actual end can only be influenced once by a task, as they are not planned values that can be overwritten but events that actually occur on a singular occasion. The target end is an actuating variable with a special status, representing the customer's wish for project completion and only providing information about the portfolio delivery capability compared to the planned end. By planning start and end dates for a project and by actually realising them, it is possible to influence the control variables, as shown in Figure 2, steering the target fulfilment.

3.2 Determining causes for deviations regarding portfolio targets

Since one aim is to ensure effective use of the process model, it is crucial to go beyond describing the interrelationships and to indicate causes for possible deviations from portfolio targets. In particular, users with little competence in multi-project management may otherwise be able to plan a portfolio but not know how to take the necessary countermeasures in the event of deviations. To prevent this, cascades of possible causes are introduced to provide assistance. Figure 4 shows such a cascade of effects based on the example of portfolio schedule reliability.

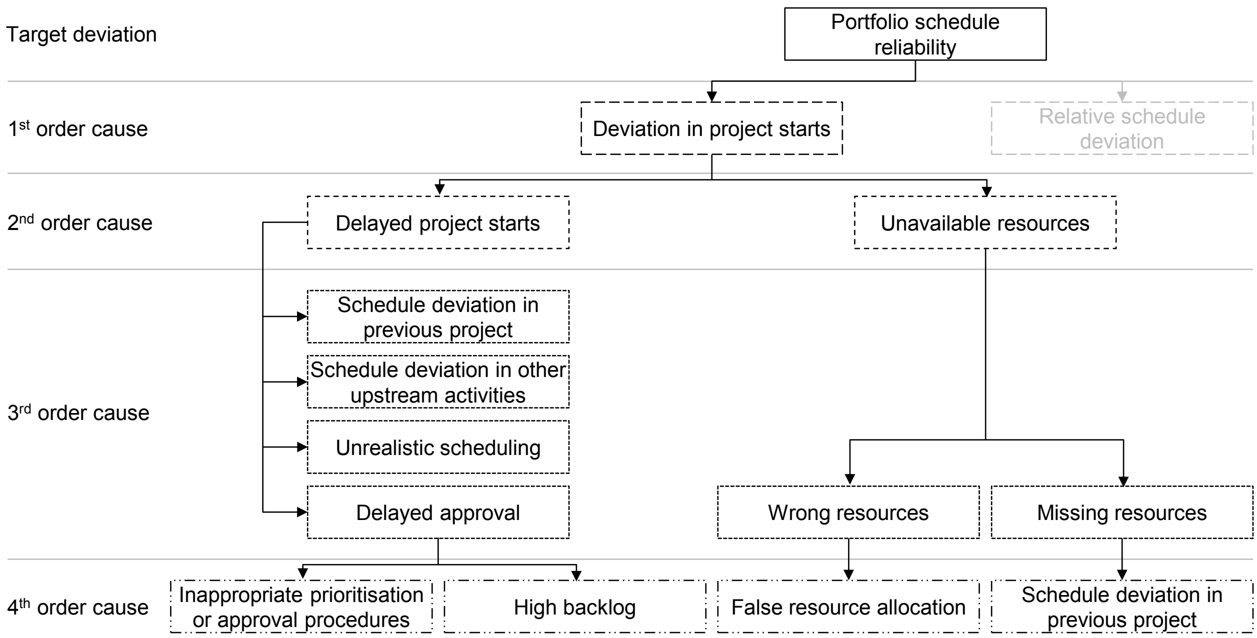


Figure 4: Causes for target deviations by the example of portfolio schedule reliability

The causes for deviations can be divided into different orders. A first-order cause directly affects the target variable and is affected by one or several second-order causes. For example, deviations in portfolio schedule reliability may be caused by a deviation in project starts (1st order) caused by unavailable resources (2nd order). This might have been the case because the wrong resources (3rd order) were provided, resulting from a false resource allocation (4th order). Even though this example may appear self-explanatory, it is essential to demonstrate these relationships, as causes can be present in a wide variety, with significant variance, and in significantly more complicated relationships. Taking into account causes for deviations in target fulfilment allows for a holistic observation of a project landscape, from task descriptions to causes of target deviations.

3.3 Validation of Findings

After building the process model of MPPC, the validation aimed to examine the results in terms of applicability and practicality. The process model was validated through interviews with experts from different backgrounds. A project portfolio manager working in the biopharmaceutical industry and the managing director of a company from the field of project management consulting and software development supported the validation process. Taken together, these experts were able to bring in the experience of many different approaches and portfolio conditions. Both were involved at the beginning of the project, after establishing the task profiles and again after developing the effects model to reflect on the intermediate status, ensuring a legitimate base for further steps. During these validation phases, the process model was analysed in comparison to the existing conditions, metrics and processes within the companies.

During the first validation phase, the developed MPPC task profiles were discussed in short workshops concerning their practicality and degree of detail. An example of an updated task refers to the definition phase. That task initially described the determination of portfolio cost behaviour, which was then adapted to focus more on the resources behind the costs. Discussing the task model within the validation process revealed that the execution of some tasks may differ according to the company's size, industry or business model. Therefore, the tasks kept in the process model were designed and checked to fit a broad application. Based on this validated interim status, the effects model was then developed. Subsequently, the whole process model was validated with the experts, this time focusing on the effects model and the decision points of the task processing. An example of input from the second validation stage is the idea of dividing the target variable portfolio transparency into qualitative and quantitative factors since not every project can be tracked in the same way. As a result of the discussions during validation, minor additions and adjustments could be made to both the tasks and the effects model. However, even though the validation took place considering different companies, portfolios and areas of responsibility, the validation results cannot guarantee the usability of the process model for any manufacturing company and its factories. Further studies need to be conducted to assure further applicability.

4. Conclusion and Outlook

Within the scope of developing a model for the planning and controlling of multi-project environments in factories, the contents of PPC and MPM were merged based on an analogy examination. It was possible to derive generally valid tasks and an effects model from its joint knowledge base, which then had to be consolidated. The entire process model allows decisions in a portfolio to be made considering overall portfolio targets by connecting tasks with the actuating variables of the effects model. Possible causes for target deviation have been identified to assist in the case of failing to reach target fulfilment. As part of developing the process model, a fast lane for more efficient planning and control of individual projects along the project management phases was also introduced [21]. For this purpose, a project categorisation was described concerning the degree of novelty. Based on that categorisation, statements can be made about which tasks have the potential for standardisation. More efficient planning and control of these project types could ultimately free up resources for urgent or high-priority projects. The validation of the developed process model successfully confirms the basic statements on the tasks and interdependencies of the MPPC, as well as its practical relevance and suitability.

Additional validation cases may be examined in the future, further evaluating the model's applicability. There is a need for research on the quantitative modelling of the presented interdependencies. In particular, the mathematical modelling of the interrelationships between control and target variables is challenging since the mostly non-linear interrelationships require extensive modelling effort. Building on the existing analogy, further studies comparing the control panel of PPC and the project management office of MPM are feasible for the future. The cause-effect relationships could also be examined more closely for the targeted control of the portfolio to improve the achievement of the target variables.

Acknowledgements

The authors kindly thank the German Research Foundation (DFG) for the financial support to accomplish the research project "Entwicklung eines Prozessmodells der Multiprojektplanung und -steuerung in der Fabrik (MPPS-Fabrik)" (project number 439916044).

References

[1] Lanza, G., Nyhuis, P., Fisel, J., Jacob, A., Nielsen, L., Schmidt, M., Stricker, N., 2018. Wandlungsfähige, menschzentrierte Strukturen in Fabriken und Netzwerken der Industrie 4.0 (acatech Studie). Herbert Utz Verlage, München.

[2] Mack, O., Khare, A., 2016. Perspectives on a VUCA World, in: Mack, O., Khare, A., Krämer, A., Burgartz, T. (Eds.), Managing in a VUCA World. Springer International Publishing, Cham, pp. 3–19.

[3] 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, Heidelberg, 832 pp.

[4] 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.

[5] Aurich, J.C., Barbian, P., Naab, C., 2005. Multiprojektmanagement in der projektorientierten Produktion: Gestaltung und Lenkung der Projektlandschaft in der Produktion. wt Werkstattstechnik online 95 (1/2), 19–24.

[6] Hiller, M., Klusch, M., Monjé, M., 2001. Multiprojektmanagement als Führungsinstrument der Zukunft. ZWF 96 (6), 317–321.

[7] DIN, 2013. Multiprojektmanagement – Management von Projektportfolios, Programmen und Projekten - Teil 1: Grundlagen. Beuth Verlag, Berlin.

[8] Kunz, C., 2007. Strategisches Multiprojektmanagement: Konzeption, Methoden und Strukturen, 2nd ed. Deutscher Universitäts-Verlag GWV Fachverlage GmbH, Wiesbaden, 312 pp.

[9] Rabl, W., 2013. Projektmanagement, in: Kleinaltenkamp, M., Plinke, W., Geiger, I. (Eds.), Auftrags- und Projektmanagement. Mastering Business Markets, 2., vollständig überarbeitete Auflage 2013 ed. Springer Gabler, Wiesbaden, pp. 301–381.

[10] DIN, 2009. Projektmanagement – Projektmanagementsysteme - Teil 5: Begriffe. Beuth Verlag, Berlin.

[11] Kuster, J., Huber, E., Lippmann, R., Schmid, A., Schneider, E., Witschi, U., Wüst, R., 2011. Handbuch Projektmanagement, 3. Auflage ed. Springer-Verlag Berlin Heidelberg, Heidelberg, Dordrecht, London, New York, 460 pp.

[12] Berge, F., Seidl, J., 2009. Programmorientierung, in: Gessler, M. (Ed.), Kompetenzbasiertes Projektmanagement (PM 3). Handbuch für die Projektarbeit, Qualifizierung und Zertifizierung auf Basis der IPMA Competence Baseline Version 3.0, vol. 4, 1. Auflage ed. GPM Deutsche Gesellschaft für Projektmanagement e.V, Nürnberg, pp. 2181–2204.

[13] Seidl, J., 2011. Multiprojektmanagement: Übergreifende Steuerung von Mehrprojektsituationen durch Projektportfolio- und Programmmanagement. Springer-Verlag, Berlin, Heidelberg.

[14] DIN, 2013. Multiprojektmanagement – Management von Projektportfolios, Programmen und Projekten - Teil 2: Prozesse, Prozessmodell. Beuth Verlag, Berlin.

[15] Nielsen, L., Klausing, P., Nyhuis, P., 2021. Towards a Target System to Incorporate Sustainability in Multi-project Management in Factories., in: , Research on project, programme and portfolio management. Integrating sustainability into project management. Springer International Publishing, pp. 9–23.

[16] Nielsen, L., 2020. Prozessmodell für Multiprojektmanagement in der Fabrik. Dissertation, 231 pp.

[17] Hook, J., Nielsen, L., Nyhuis, P., 2021. Introduction Of A Concept For Planning And Controlling Multi-Project Environments In Factories.

[18] Schmidt, M., 2018. Beeinflussung logistischer Zielgrößen in der unternehmensinternen Lieferkette durch die Produktionsplanung und -steuerung und das Produktionscontrolling. Habilitationsschrift, Hannover.

[19] Lödding, H., 2016. Verfahren der Fertigungssteuerung: Grundlagen, Beschreibung, Konfiguration, 3. Auflage ed. Springer Vieweg, Berlin, Heidelberg, 664 pp.

[20] Hook, J., Nyhuis, P., Nielsen, L., 2022. Einfluss des Multiprojektmanagements auf Fabrikziele/Influence of multi-project management on factory goals – Developing a process model for planning and controlling multi-project environments in factories. wt 112 (04), 216–220.

[21] Hook, J., Nielsen, L., Nyhuis, P., 2022. Introducing a Fast Lane to Multi-Project Environments in Factories to Focus on Digital Transformation, in: Kim, D.Y., Cieminski, G. von, Romero, D. (Eds.), Advances in production management systems. Smart manufacturing amd logistics systems : turning ideas into action : IFIP WG 5.7 International Conference, APMS 2022, Gyeongju, South Korea, September 25-29, 2022, proceedings, vol. 664. Springer, Cham, Switzerland, pp. 157–164.

Biography

Justin Hook (*1994) studied industrial engineering with a focus on production technology at Leibniz University Hannover and University of Southern Denmark. He works as a research associate in the field of factory planning at the Institute of Production Systems and Logistics (IFA) at the Leibniz University Hannover since 2020.

Dr.-Ing. Lars Nielsen (*1986) studied industrial engineering and management at the University of Bremen, University of Cape Town and Technical University of Berlin. After working for two years as specialist for multi-project planning and control he started as a research associate at the Institute of Production Systems and Logistics (IFA) at the Leibniz University Hannover. After finishing his doctorate in engineering he worked as senior project leader in the FMCG industry as well as a team leader for project portfolio management at a leading reinsurer.

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 is heading the IFA since 2003.

5th Conference on Production Systems and Logistics

Testing The Limits: A Robustness Analysis Of Logistic Growth Models For Life Cycle Estimation During The COVID-19 Pandemic

Louis Steinmeister[1,2,4], Burim Ramosaj[1], Leo Schröter[4], Markus Pauly[1,3]

[1]*Department of Statistics, TU Dortmund University, Dortmund, Germany*
[2]*Graduate School of Logistics, Dortmund, Germany*
[3]*Research Center Trustworthy Data Science and Security, UA Ruhr, Dortmund, Germany*
[4]*Infineon Technologies AG, Neubiberg, Germany*

Abstract

The semiconductor industry operates in a dynamic environment characterized by rapid technological advancements, extensive research and development investments, long planning horizons, and cyclical market behavior. Consequently, staying vigilant to technological disruptions and shifting trends is crucial. This is especially challenging when external shocks seriously affect supply chain processes and demand patterns. Particularly, recent events, such as the COVID-19 pandemic, the ongoing Russian invasion of Ukraine, and high consumer price inflation impacting the semiconductor cycle emphasize the need to account for these influences.

In this context, we analyze growth patterns and life cycles of various technologies within the semiconductor industry by estimating logistic growth models. The logistic growth model was originally formulated to describe population dynamics. However, many processes outside the discipline of ecology share the fundamental characteristics of natural growth: self-proportionality and a self-regulating mechanism. Out of the different applications, two are of particular interest in the context of strategic business decisions: (1) modeling innovation diffusion and technological change to predict the mid- to long-term growth of a market, and (2) modeling of product life cycles. To obtain market growth and life cycle predictions, we apply the logistic growth model to forecast cumulative revenues by technology over time.

This model treats the analyzed technology as a closed system. However, in practice, external shocks are the norm. To analyze the robustness to such external shocks, we compare technology life cycle estimates derived from logistic growth models before and after the effects of COVID-19 became evident for a wide array of semiconductor technologies. We find that the impact of COVID-19 on these life cycle estimates is mixed, but the median change is low. Our findings have implications for the application of logistic growth models in strategic decision-making, helping stakeholders navigate the complexities of technological innovation, diffusion, and market growth.

Keywords

Innovation Management; Business Strategy; Technology; Forecasting; S-Curve; Sigmoidal Growth; Robustness; External Shocks; Supply-Chain Disruption; Semiconductor; Trustworthiness

DOI: https://doi.org/10.15488/15265
ISSN: 2701-6277

1. The semiconductor industry

The semiconductor industry is characterized by long lead times for expanding fabrication capacity, shortening life cycles, and rapid technological advances [1–3]. Consequently, strategic decisions are often long range and high impact, especially when involving R&D and fabrication capacities. Missing out on an important development can cost months or years to catch up market share. Capital-intensive investments in fabrication and high R&D costs raise the stakes further [4,5]. This highlights the need for forecasting methods that provide support to managers [4–6]. Life cycle modelling can give an indication of technologies prone to stagnation and disruption [7], providing managers with important information.

Apart from its importance to the wider economy [8], the semiconductor industry is a great test case for forecasting methods, which include technology diffusion and life cycle models [7,9,10], due to the challenges involved. Rapid technological advancements and shortening product life cycles imply that demand is volatile and difficult to predict [4,11,12]. Furthermore, the semiconductor industry does not only have complicated supply chains but also lies upstream in the supply chain for many consumer products. Consequently, it is exposed to the bullwhip effect. This effect refers to the phenomenon where small fluctuations in consumer demand can result in amplified variations in ordering patterns along the supply chain [13,14].

The above-mentioned challenges suggest that a closed-system view might be simplistic. In fact, the semiconductor industry has experienced several external shocks with severe consequences over the last few years: From geographic risks, such as earth quakes damaging sensitive fabrication equipment [15], to the impact of the COVID-19 pandemic, including subsequent government responses, and trade frictions on the global semiconductor supply chain [16] or the ongoing Russian invasion of Ukraine with its effects on inflation and consumer sentiment [17]. Therefore, the consideration of external disruptions in forecasts and technology life cycle analysis is particularly relevant in this industry, which motivates this study.

The main objective of this paper is the assessment of the trustworthiness of technology life cycle estimates derived from the logistic growth model under extreme events. Hence, a case study involving a significant external shock - the onset of the COVID-19 pandemic – is presented and its effects on these life cycle estimates are examined.

Structure: the next section provides an overview of the history of the logistic growth model and its application to innovation management and technology life cycle analysis. The methodology of this paper is presented in Section 3 with an emphasis on the estimation of the logistic curve and the derivation of technology life cycles. Section 4 completes the paper by applying the methodology to a technology portfolio of a leading semiconductor company and discussing the findings of this case study.

2. The logistic growth model

The logistic growth model, also referred to as S-shaped or sigmoidal curves, is characterized by the logistic differential equation $\frac{\mathrm{dN}}{\mathrm{dt}} = \mathrm{rN}\left(1 - \frac{\mathrm{N}}{\mathrm{K}}\right)$. Here, N represents the population size, K the carrying capacity, and r the growth rate. It was first derived by Verhulst in the early to mid-nineteenth century to describe population dynamics [18,19] and plays an important role in the Lotka-Volterra equations [20,21]. Since then, they have become popular to quantify natural growth more broadly. Growth patterns outside the discipline of ecology resemble a similar dynamic and their application across diverse disciplines has been studied by several authors [7,22–24]. For example, logistic growth models have been employed in studying the adoption of renewable energies [25], the development of prostatic hyperplasia [26], production forecasting in extremely low permeability oil and gas reservoirs [27], performance analysis of technologies [28], modelling bacterial growth [29], forecasting long-term country GDP development [30,31], and more recently, modelling the development of COVID-19 cases [32–34]. Furthermore, S-curves are popular in corporate strategic decision-making revolving around innovation, such as anticipating disruptive attacks on one's business [35] or life cycles and investments in the adoption of new technologies as they diffuse through the marketplace [7,36,37]. This technological progression is exemplified by the evolution of mobile phones in Figure 1. The lower left logistic curve represents classical cell phones, starting from their introduction in the 1970's. Despite their vast technological improvements over the decades, their design was a limiting factor to the value they could offer to consumers: the small screen and buttons meant that they were primarily used for voice calls, messaging, and short emails. The utility of the mobile phone was radically redefined with the introduction of the iPhone, the first commercially viable smart phone. This marked the launch of the second logistic curve, which subsequently disrupted the classical cell phone market (including the decline of its former champions, Nokia and Blackberry).

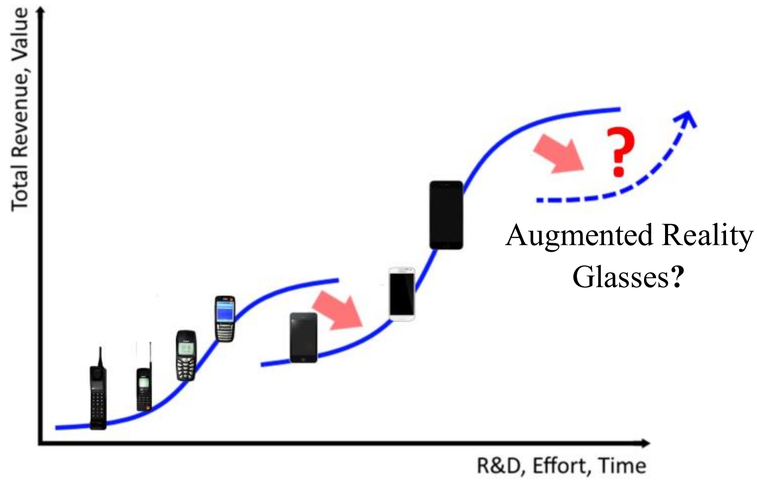


Figure 1: Technological progression exemplified by the evolution of mobile phones.

This motivates the application of logistic curves in the context of technological progress and life cycle analysis. To study the impact of the technology life cycle on strategic business decisions and corporate structure, the S-curve is often partitioned into 5 phases, as illustrated in Figure 2 [23,38,39]:

1. Birth /winter (1.4% - 6.3%): the technology is barely known or explored. Growth is slow and a large degree of effort is needed to progress. Entrepreneurship and a decentralized company structure are common.
2. Growth / spring (6.3%-30%): the technology is slowly getting adopted as "the next big thing". Growth remains nearly exponential. This phase is characterized by learning, product innovation, and continuous improvement.
3. Maturity / summer (30%-70%): the technology is being adopted and growing at its maximum rate. However, there are first signs of costs of complexity as the rate is approximately constant and departs from earlier near-exponential growth. Processes are driven by vertical integration, refinement, and bureaucratization.
4. Decline / autumn (70%-92.7%): the technology nears its limit. The growth rate remains positive but accelerates its decline. Managers should be on the lookout for the next "next big thing". This is the ear of process innovations and face lifts.
5. Death / winter (92.7%-98.6%): the technology has nearly reached its peak. There is little growth left to achieve, which requires increasingly higher investments. This means that technological progress stalls and the technology becomes prone to disruptions. Managers are looking to transition to alternative technologies while the current one phases out (compare the transition from cell to smartphones in Figure 1).

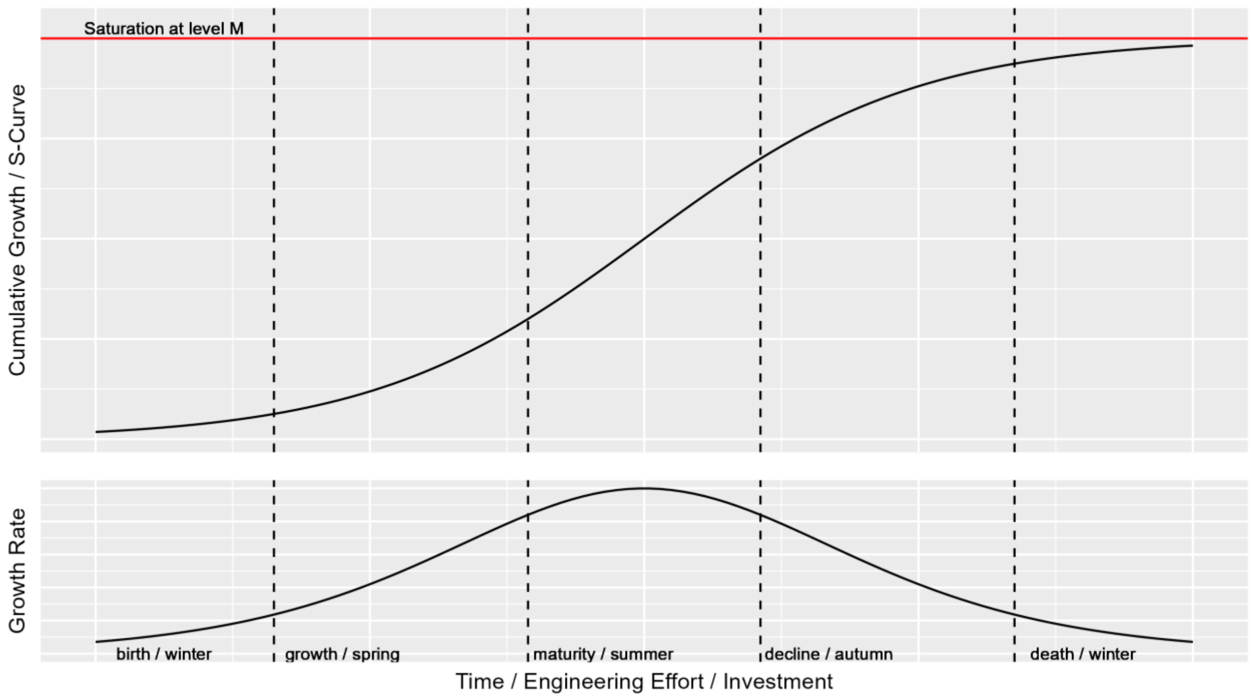


Figure 2: Partitioning the S-curve into life cycle stages.

This highlights the interpretability and usability of the simple logistic model, which played a pivotal role in formalizing the study of life cycles, on a business level. However, various extensions and generalizations of the simple logistic curve have been proposed [10, 19,40–44], such as the Richards' curve [45] or Gompertz curve. Ex post, these extended models may yield better fits [29]. However, the generalized models usually require more parameters. This can lead to identifiability issues [46,47]. Furthermore, the trajectory is seldomly observed completely, which can exacerbate the issue. Therefore, we focus on the simple logistic model in our analysis.

3. Methodology

We introduce the notation and explain the interpretation and meaning of the different parameters of the logistic growth model in 3.1. Subsection 3.2 provides details of the assumed data generating process and the estimation of model parameters.

3.1 Notation

As described in Section 2, the logistic growth model is described by the differential equation $\frac{\mathrm{dN}}{\mathrm{dt}} = \mathrm{rN}\left(1-\frac{\mathrm{N}}{\mathrm{K}}\right)$. For consistency with common statistical notation, we rewrite the solution of this differential equation as

$$Y = \frac{M}{1+e^{aX+b}} + C, \tag{1}$$

where Y is the response variable (in place of N), M is the carrying capacity or maximum cumulative market size, a corresponds to the growth rate (the maximum growth rate of $aM/4$ is reached at the inflection point), b determines the location of the inflection point (at $x = -b/a$), C is introduced to allow for vertical offsets of the logistic curve, and X denotes the dependent variable. The logistic curve with its parameters and their

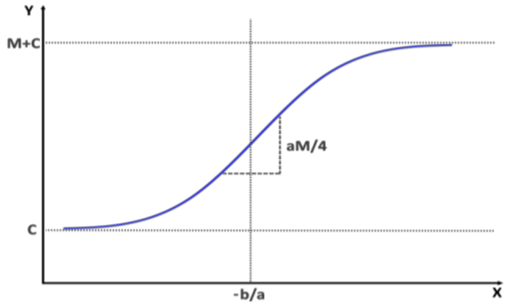


Figure 3: Parametrization and interpretation of parameters of the logistic curve.

respective interpretations is illustrated in Figure 3. This parametrization implies that the life cycle stage can be estimated as $(max(Y) - C)/(M - C)$.

3.2 Estimation

We assume the data generating process

$$Y = \frac{M}{1+e^{aX+b+\varepsilon}} + C, \tag{2}$$

where ε is an identically and independently distributed error variable with existing first and second moments. This model formulation allows us to estimate the parameters M, C, a, b in an iterative two-step process:

i. Estimate M and C. At initialization, start with two reasonable first guesses $\widehat{M} > max(Y)$, $\hat{C} < min(Y)$. For later iterations minimize the mean squared error of the step ii. regression with regard to M and C.

ii. Given M and C, the remaining parameters can be obtained via a simple linear regression

$$log\left(\frac{\widehat{M} - Y + \hat{C}}{Y - \hat{C}}\right) = aX + b + \varepsilon. \tag{3}$$

The mean squared error is given by $\frac{1}{N}\sum_{i=1}^{N}\left[log\left(\frac{\widehat{M}-Y_i+\hat{C}}{Y_i-\hat{C}}\right) - \hat{a}X_i - \hat{b}\right]^2$, where N is the sample size.

The optimization in step i. can be performed with any conventional optimization routine, such as Nelder and Mead's Simplex algorithm [48] or quasi-Newton methods such as BFGS or L-BFGS-B [49]. However, these local optimization methods tend to struggle with local optima [50]. This is particularly problematic when the error surface is rough. We used Generalized Simulated Annealing, which is implemented in the "GenSA" R package [51], as this yielded the most reliable results.

4. Empirical Analysis

Subsection 4.1 covers the introduction to the data and includes all pre-processing steps in. Subsection 4.2 presents the results of the analysis and discusses the implications.

4.1 Data

We obtained revenues for a diverse portfolio of products ranging from October 2006 to January 2023 from a leading semiconductor company. However, it is not reasonable to assume that one Euro today has the same value it had 17 years ago. Therefore, it is important to adjust for the general price level. This was done with the Harmonized Index of Consumer Inflation, which is published by the European Central Bank[1] [52]. These revenues were mapped to technology categorizations on the aggregation levels: Level 1, containing 18 technologies and Level 2, containing 10. Here, Level 1 (component) technology groups are more granular than Level 2 technology groups, see Figure 4 (the technologies and their corresponding technology groups, which are covered in this paper, can be seen in Table 1 in the appendix).

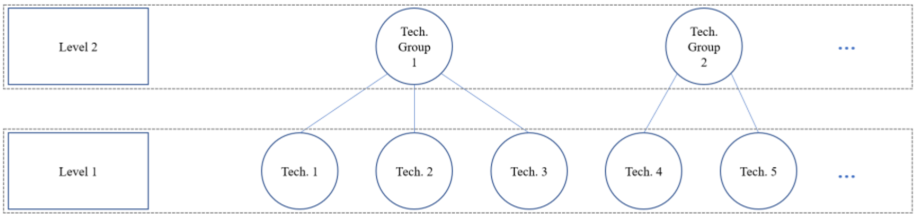


Figure 4: Example of a technology hierarchy.

We consider both, Level 1 and Level 2 technologies, because Level 1 technologies are more homogeneous but Level 2 technologies include more sub-technologies that would need to be excluded due to lack of data history. By aggregating several similar technologies, we further hope to reduce the effects of substitution and similar interactions. Furthermore, the logistic model should be applicable on either level because of its fractal property.

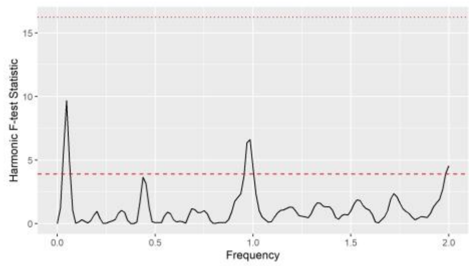


Figure 5: Harmonic F-test statistic over the frequency domain. The dashed red line corresponds to a point wise 95% confidence threshold, the dotted red line to a global 95% confidence threshold.

Further, we analyzed cyclicality by means of spectral analysis, particularly using a periodogram [53]. However, no frequency surpassed the significance threshold of the harmonic F-test [54] provided in the "multitaper" R package. As Figure 5 shows, there is no statistically significant cyclicality at any frequency when adjusting for multiple testing.

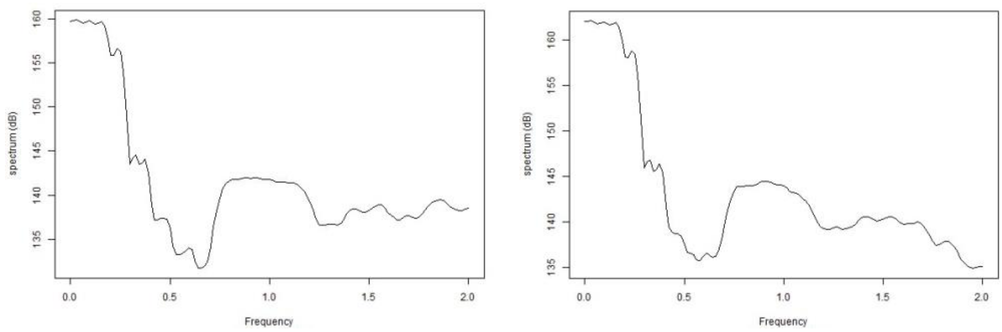


Figure 6: Periodograms before (left) and after (right) seasonal adjustment.

[1] Information on the Harmonized Index of Consumer Inflation and the corresponding time series can be found at www.ecb.europa.eu/stats/macroeconomic_and_sectoral/hicp

Additionally, we performed a time series decomposition into trend, seasonal effects, and a random component [55] using the "decompose" function in R. However, the time series post seasonal adjustment was not noticeably less noisy than the original time series, nor did the periodogram change much (see Figure 6). Therefore, we proceeded with the original data without seasonal adjustments.

4.2 Result

Logistic growth models were fit to cumulative technology revenues using the algorithm described in Section 3.2**.** We visually checked the models for consistency with the logistic curve by observing the quality of the fit and producing residual plots. These residual plots were helpful in checking if the models converged as expected and to identify residual patterns, which indicate a poor model fit.

Figure 7: Example residual plots

Figure 7 indicates a residual plot of a good logistic fit for Tech. 14, whereas the residual plot for Tech. 17 raises questions. Residuals are indicated by red circles. The drawn blue line represents the linear fit of the data in step ii. of section 3.2. If this line differs from the horizontal line at $Y = 0$, it indicates that the algorithm did not converge as expected. The dashed and dotted blue lines represent point-wise confidence intervals and confidence bands at 95%, respectively. Hence, a residual lying outside the 95% point-wise confidence interval would be expected to be observed every 20 data points, whereas a residual lying outside the 95% confidence band would be expected every 20 residual plots. These plots can help identify external shocks or patterns that are not captured by the model. In case of the left plot, the residuals are well dispersed and no clear trend is identifiable. This indicates a good fit. On the right, there is a clear pattern, which indicates a poor model fit.

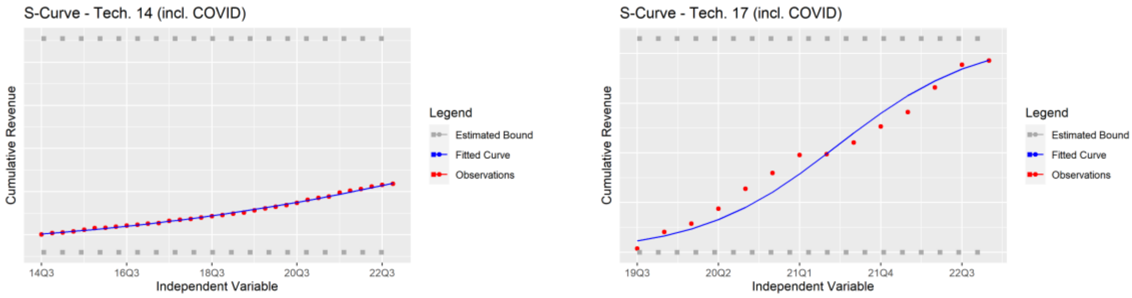


Figure 8: Example logistic fits. Tech. 14 (left) is an example of a good fit, Tech. 17 (right) one of a questionable one.

Additionally, we validated the logistic life cycle estimates by expert opinion. We excluded poor fits and technologies that were clearly driven by external structural effects (the semiconductor industry is largely a B2B business, where sales are often conducted through direct relationships – in segments where revenues are overwhelmingly driven by a few large customers, patterns in the data may be dominated by individual decisions at the level of a single customer and not always be reflective of the technological potential of the product). Overall, we excluded seven of the eighteen Level 1 technologies and four Level 2 technology from further analysis (see Table 1 in the Appendix).

Figure 8 illustrates logistic fits for Tech. 14 (left), which fits well, and Tech. 17 (right), which does not. Tech. 17 is an example of a technology that is driven by individual projects (also observe that the data in the right plot appears to be consisting of two logistic curves, not one). The blue curve indicates the estimated logistic model, the red dots correspond to the observed cumulative revenues, and the grey dotted lines correspond to the estimated lower bound, C, and the estimated upper bound, $M + C$. Generally, we did not estimate lower bounds unless we had reason to believe that we were missing previous revenues.

These logistic curves were estimated based on the complete history (from October 2006 to January 2023) and on the basis of the historical data preceding the COVID-19 Pandemic. After the curves were obtained and validated for the various Level 1 and Level 2 Technologies, we compared the life cycle estimates of the pre- and post-COVID models.

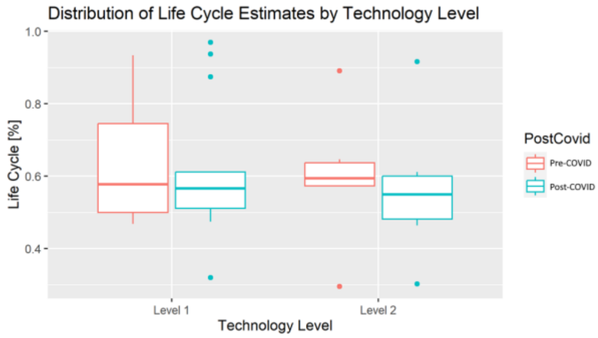


Figure 9: Boxplots of life cycle estimates before and after COVID.

Figure 9 illustrates the distributions of the Pre- (red) and Post- (cyan) COVID life cycle estimates on technology Level 1 (left) and 2 (right), respectively. Given the strong demand for consumer electronics and the subsequent rejuvenation of sales numbers, we expected lower life cycle estimates as an impact of the pandemic. Meanwhile, a moderate increase is expected without the interference of external shocks, given that two years elapsed and the technology has aged. On Level 1, the median life cycle estimate remained relatively stable, though more concentrated in the lower range. Thus, the logistic fits for the Level 1 technologies seem relatively unaffected by the pandemic. This is confirmed by Figure 10, which shows that the median life cycle estimate has increased slightly after COVID, which is consistent with our expectation. This result is slightly different for Level 2 technologies. As Figure 9 indicates, the distribution of life cycle estimates has noticeably shifted downwards. This observation is confirmed by Figure 10, which indicates that the median life cycle estimates have decreased by 2% after the revenues during the pandemic are included. This seems to confirm our hypothesis that COVID has had an impact on the logistic growth models. On the other hand, this decrease could be due to the inclusion of new emerging sub-technologies in the broader technology group. These would have been omitted during the analysis of the Level 1 technologies, due to small volumes and an insufficient amount of historical data.

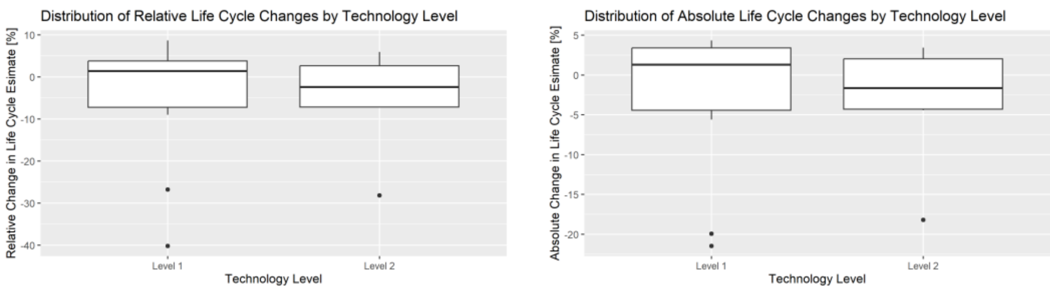


Figure 10: Boxplots of the change in life cycle estimates before and after COVID.

We conclude that logistic growth models are a valuable tool for managers in assessing product life cycles if the model is applicable. This is particularly useful in understanding technological limitations and guarding against the risk of disruption. The robustness to external effects could be further improved by incorporating them into the logistic growth model. For example, researchers have modelled the upper bound dynamically [56,57]. Given the dynamic nature of the semiconductor industry, the complexity of supply chain dependencies, and the exposure to other external factors, this highlights a potential for future research in the field.

Acknowledgements

This paper was supported by a research cooperation between Infineon Technologies AG and TU Dortmund University through the Graduate School of Logistics.

Appendix

Table 1: Technology table of technology groups and the corresponding technologies. Technologies marked with an (X) were excluded from further analysis.

Technology Group (Level 2)	Technology (Level 1)
Tech. Group 1	Tech. 7, Tech. 3 (X), Tech. 1 (X)
Tech. Group 2	Tech. 2, Tech. 4
Tech. Group 3	Tech. 17 (X), Tech. 14, Tech. 5
Tech. Group 4 (X)	Tech. 11, Tech. 9 (X), Tech. 6
Tech. Group 5 (X)	Tech. 12, Tech. 10 (X)
Tech. Group 6	Tech. 8
Tech. Group 7	Tech. 13
Tech. Group 8	Tech. 15
Tech. Group 9 (X)	Tech. 16 (X)
Tech. Group 10 (X)	Tech. 18 (X)

References

[1] Macher, J. T., 2006. Technological development and the boundaries of the firm:a knowledge-based examination in semiconductor manufacturing. Management Science, 52 (6), 826–843.

[2] Wu, J. Z., Chien, C. F., 2008. Modeling strategic semiconductor assembly outsourcing decisions based on empirical settings. OR Spectrum, 30 (3), 401–430.

[3] Lv, S., Kim, H., Zheng, B., Jin, H., 2018. A review of data mining with big data towards its applications in the electronics industry. Applied Sciences, 8 (4), 582.

[4] Chien, C.-F., Chen, Y.-J., Peng, J.-T., 2010. Manufacturing intelligence for semiconductor demand forecast based on technology diffusion and product life cycle. International Journal Of Production Economics, 128 (2), 496–509.

[5] Aubry, M., Renou-Maissant, P., 2014. Semiconductor industry cycles: explanatory factors and forecasting. Economic Modelling, 39, 221–231.

[6] Cakanyildirim, M., Roundy, R. O., 2002. SeDFAM: semiconductor demand forecast accuracy model. IIE Transactions, 34 (5), 449–465.

[7] Modis, T., 1994. Life cycles: forecasting the rise and fall of almost anything. Futurist, 28 (5), 20–25.

[8] Chow, H. K., Choy, K. M., 2006. Forecasting the global electronics cycle with leading indicators: a Bayesian VAR approach. International Journal of Forecasting, 22 (2), 301–315.

[9] Petropoulos, F., Apiletti, D., Assimakopoulos, V., Babai, M. Z., Barrow, D. K., et al., 2022. Forecasting: theory and practice. International Journal of Forecasting, 38 (3), 705–871.

[10] Meade, N., 1985. Forecasting using growth curves-an adaptive approach. The Journal of The Operational Research Society, 36 (12), 1103.

[11] Simchi-Levi, D., Kaminsky, P., Simchi-Levi, E., Ji, J., 2021. Designing and managing the supply chain, 4th ed. Irwin McGraw-Hill, New York.

[12] Chou, Y. C., Cheng, C. T., Yang, F. C., Liang, Y. Y., 2007. Evaluating alternative capacity strategies in semiconductor manufacturing under uncertain demand and price scenarios. International Journal of Production Economics, 105 (2), 591–606.

[13] Geary, S., Disney, S. M., Towill, D. R., 2006. On bullwhip in supply chains—historical review, present practice and expected future impact. International Journal of Production Economics, 101 (1), 2–18.

[14] Lee, H. L., Padmanabhan, V., Whang, S., 1997. The bullwhip effect in supply chains. MIT Sloan Management Review, 38 (3), 93–102.

[15] Matsuo, H., 2015. Implications of the Tohoku earthquake for Toyota′s coordination mechanism: supply chain disruption of automotive semiconductors. International Journal of Production Economics, 161, 217–227.

[16] Wu, X., Zhang, C., Du, W., 2021. An analysis on the crisis of “chips shortage” in automobile industry —— based on the double influence of COVID-19 and trade friction. Journal of Physics: Conference Series, 1971 (1), 012100.

[17] Caldara, D., Conlisk, S., Iacoviello, M., Penn, M., 2022. The effect of the war in Ukraine on global activity and inflation. Board of Governors of the Federal Reserve System, Washington.

[18] Verhulst, P.-F., 1838. Notice sur la loi que la population suit dans son accroissement. Correspondence Mathematique Et Physique, 10, 113–126.

[19] Tsoularis, A., Wallace, J., 2002. Analysis of logistic growth models. Mathematical Biosciences, 179 (1), 21–55.

[20] Lotka, A. J., 1910. Contribution to the theory of periodic reactions. The Journal of Physical Chemistry, 14 (3), 271–274.

[21] Berryman, A. A., 1992. The orgins and evolution of predator-prey theory. Ecology, 73 (5), 1530–1535.

[22] Bejan, A., Lorente, S., 2012. The S-curves are everywhere. Mechanical Engineering, 134 (5), 44–47.

[23] Kucharavy, D., De Guio, R., 2011. Application of S-shaped curves. Procedia Engineering, 9, 559–572.

[24] Kucharavy, D., De Guio, R., 2011. Logistic substitution model and technological forecasting. Procedia Engineering, 9, 402–416.

[25] Schilling, M. A., Esmundo, M., 2009. Technology S-curves in renewable energy alternatives: analysis and implications for industry and government. Energy Policy, 37 (5), 1767–1781.

[26] Berry, S. J., Coffey, D. S., Walsh, P. C., Ewing, L. L., 1984. The development of human benign prostatic hyperplasia with age. Journal Of Urology, 132 (3), 474–479.

[27] Clark, A. J., Lake, L. W., Patzek, T. W., 2011. Production forecasting with logistic growth models, in: SPE Annual Technical Conference and Exhibition. Society of Petroleum Engineers, Denver.

[28] Nieto, M., Lopéz, F., Cruz, F., 1998. Performance analysis of technology using the S curve model: the case of digital signal processing (DSP) technologies. Technovation, 18 (6–7), 439–457.

[29] Zwietering, M. H., Jongenburger, I., Rombouts, F. M., van ’t Riet, K., 1990. Modeling of the bacterial growth curve. Applied and Environmental Microbiology, 56 (6), 1875–1881.

[30] Kwasnicki, W., 2013. Logistic growth of the global economy and competitiveness of nations. Technological Forecasting and Social Change, 80 (1), 50–76.

[31] Modis, T., 2013. Long-term GDP forecasts and the prospects for growth. Technological Forecasting and Social Change, 80 (8), 1557–1562.

[32] Wu, K., Darcet, D., Wang, Q., Sornette, D., 2020. Generalized logistic growth modeling of the COVID-19 outbreak: comparing the dynamics in the 29 provinces in China and in the rest of the world. Nonlinear Dynamics, 101 (3), 1561–1581.

[33] Shen, C. Y., 2020. Logistic growth modelling of COVID-19 proliferation in China and its international implications. International Journal of Infectious Diseases, 96, 582–589.

[34] Aviv-Sharon, E., Aharoni, A., 2020. Generalized logistic growth modeling of the COVID-19 pandemic in Asia. Infectious Disease Modelling, 5, 502–509.

[35] Foster, R. N., 1986. Working the S-Curve: assessing technological threats. Research Management, 29 (4), 17–20.

[36] Christensen, C. M., 1992. Exploring the limits of the technology S-Curve. part I: component technologies. Production and Operations Management, 1 (4), 334–357.

[37] Rogers, E. M., 2014. Diffusion of innovations. Simon and Schuster, New York.

[38] Modis, T., 1999. A second lease on life for technological forecasting. Technological Forecasting and Social Change, 62 (1–2), 29–32.

[39] Modis, T., 1998. Conquering uncertainty: understanding corporate cycles and positioning your company to survive the changing environment. McGraw-Hill, New York.

[40] Banks, R. B., 1993. Growth and diffusion phenomena: mathematical frameworks and applications. Springer, Berlin.

[41] Oliver, F. R., 1969. Another generalisation of the logistic growth function. Econometrica, 37 (1), 144.

[42] Easingwood, C., Mahajan, V., Muller, E., 1981. A nonsymmetric responding logistic model for forecasting technological substitution. Technological Forecasting and Social Change, 20 (3), 199–213.

[43] Skiadas, C., 1985. Two generalized rational models for forecasting innovation diffusion. Technological Forecasting and Social Change, 27 (1), 39–61.

[44] Bewley, R., Fiebig, D. G., 1988. A flexible logistic growth model with applications in telecommunications. International Journal of Forecasting, 4 (2), 177–192.

[45] Richards, F. J., 1959. A flexible growth function for empirical use. Journal of Experimental Botany, 10 (2), 290–301.

[46] Simpson, M. J., Browning, A. P., Warne, D. J., Maclaren, O. J., Baker, R. E., 2022. Parameter identifiability and model selection for sigmoid population growth models. Journal of Theoretical Biology, 535, 110998.

[47] Benzekry, S., Lamont, C., Beheshti, A., Tracz, A., Ebos, J. M. L., et al., 2014. Classical mathematical models for description and prediction of experimental tumor growth. PLoS Computational Biology, 10 (8), e1003800.

[48] Nelder, J. A., Mead, R., 1965. A simplex method for function minimization. The Computer Journal, 7 (4), 308–313.

[49] Byrd, R. H., Lu, P., Nocedal, J., Zhu, C., 1995. A limited memory algorithm for bound constrained optimization. SIAM Journal on Scientific Computing, 16 (5), 1190–1208.

[50] Wright, S., Nocedal, J., 1999. Numerical optimization. Springer, New York.

[51] Xiang, Y., Gubian, S., Suomela, B., Hoeng, J., 2013. Generalized simulated annealing for global optimization: the GenSA package. The R Journal, 5 (1), 13.

[52] Diewert, W. E., 2002. Harmonized indexes of consumer prices: their conceptual foundations. SSRN Electronic Journal, 138 (4), 547–637.

[53] Shumway, R. H., Stoffer, D. S., 2017. Time series analysis and its applications. Springer, New York.

[54] Thomson, D. J., 1982. Spectrum estimation and harmonic analysis. Proceedings of the IEEE, 70 (9), 1055–1096.

[55] Kendall, M., Stuart, A., 1983. The advanced theory of statistics, 3rd ed. Griffin, London.

[56] Seidl, I., Tisdell, C. A., 1999. Carrying capacity reconsidered: from Malthus' population theory to cultural carrying capacity. Ecological Economics, 31 (3), 395–408.

[57] Calatayud, J., Cortés, J.-C., Dorini, F. A., Jornet, M., 2020. On a stochastic logistic population model with time-varying carrying capacity. Computational and Applied Mathematics, 39 (4), 288.

Biography

Louis Steinmeister was awarded his MS degree in applied mathematics from Missouri S&T, where he was a member of the Applied Computational Intelligence Lab. His research interests include machine learning, statistics, and their application to business and financial problems. Currently, he is pursuing a Ph.D. in Statistics through the Graduate School of Logistics at TU Dortmund University, Germany.

Burim Ramosaj (*1991) did his PhD on Statistical Inference Models using ML in 2019 and was a Post-Doc at TU Dortmund University. He researched significant feature selection using advanced ML-models with his own funding from the state of NRW through the KI-Starter Programme. Currently, he is working as a Data Scientist at Google in Zurich, Switzerland and continues research in his free time.

Leo Schröter (*1994) has been working as a Financial Controller at Infineon Technologies AG since 2021. Mr. Schroeter studied Industrial Engineering majoring in Finance and Communication Engineering at the University of Duisburg-Essen.

Markus Pauly received his diploma degree in mathematics from the Heinrich-Heine University Düsseldorf (2005), where he also completed his Ph.D (2008) and his habilitation (2013). From 2014 to 2019 he was full professor for Statistics at Ulm University. Since 2019 he is full professor at the Statistics Department at TU Dortmund University, where he investigates a wide range of statistical and machine learning topics.

CPSL

CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
CPSL 2023-2

5th Conference on Production Systems and Logistics

Product Development through Co-Creation Communities - General Measures For A Distributed And Agile Planning Preparation in Cross-Company Production

Dominik Saubke[1], Pascal Krenz[1], Tobias Redlich[1]
[1] *Helmut-Schmidt-University / University of the Federal Armed Forces Hamburg, 22043 Hamburg*

Abstract

The crises of recent years revealed the vulnerability of our global and linearly aligned value chains, and new concepts are being sought to meet ecological, economic and social demands. The possibility of producing locally at the place of need in adaptable and highly dynamic manufacturing networks is increasingly coming into focus. However, such structures would have to be built up laboriously, whereas an existing network of small and medium-sized enterprises is available in many industrial nations. Cross-Company Production (CCP) in such local networks could help to address the problems mentioned. Another recent phenomenon is the shift of development processes into the digital sphere and its simultaneous opening up to the public. Open development processes can offer considerable advantages by bundling the wisdom of the crowd across company boundaries, however the digital platforms for collaboration do not have their own product capacities. The interaction of Co-Creation Communities (CCC) and Cross-Company Production (CPP) networks could counter this shortcoming. To ensure cost-efficient production and success on the market, an early exchange of knowledge between development and production is targeted in every company through highly standardised processes in the field of Planning Preparation (PP) a subdivision of Operations Planning and Scheduling (OPS). In the new value creation constellation this exchange is limited, as high fluctuation, various developers and numerous companies involved lead to new challenges. In this approach, a meta synthesis of known innovation and product development processes was performed to gain a better understanding of their structure and to identify measures fulfilling the tasks of Planning Preparation (PP). Aligned with the principles of Cooper's Stage-Gate Process a basis of measures is built up. After that each measure is valued according to relevance and involvement for the introduced entities creating an overview of general measures. Finally, the need for a distributed and agile Planning Preparation (PP) is derived.

Keywords

Co-Creation; Open innovation; Planning Preparation; Producibility; Operation Planning and Scheduling

1. Introduction

Operations Planning and Scheduling (OPS) acts at the interface between product development and production, it takes on, among other things, the role of a knowledge mediator between these two [1]. In order to understand the motivation behind this research, the two entities of product development and production need to be contextualised by currently important influences. First of all, digitalisation in all areas of everyday life has greatly changed the way we collaborate [2,3]. This is also having an increasing impact in the field of innovation and product development. The software tools required are available to a broader mass, not least because there are also increasingly user-friendly open-source solutions [4]. People have the opportunity

DOI: https://doi.org/10.15488/15273
ISSN: 2701-6277

to participate more in this initial step of value creation and to implement their own ideas, either for private use or as a secondary occupation [5]. Platforms (e.g. Github, Instructabels, GrabCad etc.) have become established and enable participants to further develop or publish their own artefact related information and designs [6], whereas a decade ago studies only analysed less than a hundred open-source designs, simply because there were not more available [7]. Today, numerous of artefact related information and designs can be retrieved at various levels of complexity [8]. The ever-increasing emergence of co-creation is leading to the development of new values in the digital sphere [9]. In order to materialise the developed artefacts, appropriate production capabilities are needed. This introduces the second major issue that needs to be understood for this research, the production of goods. While there has been an accelerated change in the way digital product development works, production depends on physical capabilities and skills that cannot be easily modified. The multiple crises of recent years have exposed the vulnerability of today's primarily linear value creation [10,11]. The climate crisis, for example, has become one of the dominant issues in our way of life, politics and economy [12],[13]. Industrial CO_2 emissions [14], transport of goods and short product life cycles are directly connected to our value creation system [15]. Local, smaller and more flexible manufacturing units at the place of need could address these problems, increase sustainability in all three dimensions (social, ecological, economic) and strengthen the overall resilience of the production sector. It is evident that there is an extensive net of small and medium-sized enterprises (SMEs) [16,17], both in densely populated areas and in their periphery. A future professionalised local production of open and collaboratively developed artefacts is a rewarding target [18,19]. While there are already existing research approaches to harnessing co-creation approaches for single (industrial) companies [5] the further investigation focuses on Cross-Company Production (CCP) networks of small and medium-sized enterprises working together with Co-Creation Communities (CCC). The interaction of the two entities is already observable, but existing open source hardware (the result of co-creation communities) still shows major shortcomings in the technical documentation and consideration of manufacturing-relevant basic principles that are to be confronted by this approach.

2. Structure of the Approach

2.1 Research Objective

The interaction of CCP and CCC leads to new challenges in creating value [20]. Quite fundamentally, there is a lack of producibility due to the non-fulfilment of general technical documentation criteria within these openly developed artefacts. As a sub-discipline of OPS, Planning Preparation (PP) includes advising people involved in the development process with regard to producibility. In order to implement this, measures are carried out at various points in the development process, such as an engineering assessment or the creation of a functionality overview. These general measures for implementing the knowledge flow between product development and production require assessment. The following research question arises:

> ***Which general measures are necessary for fulfilling the tasks of planning preparation? Which entity of the value creation system is involved in the measures and what relevance does the measure have for the value creation task of this entity?***

The approach seeks an outcome that can be understood as a overview of general measures to fulfil the tasks of PP (stated in Chapter 3) in a new value creation environment. It is intended to provide a possible basis for the layout and optimisation of digital, collaborative and platform-oriented product development processes in terms of *producibility*. In the following the methodological approach is explained to the reader in more detail. Subsequently, all the theoretically relevant terminology is defined and the current interaction between production and product development in industry is explained, with a particular emphasis on why existing models for the organisation of the product development are inadequate. Finally, the measures found are displayed and an evaluation using the criteria of relevance and necessary involvement are presented (compare Chapter 5).

2.2 Applied Method

The basis for identifying the measures is an existing literature research on innovation and product development processes, which was expanded to include more current models in order to obtain a complete picture [21,22]. Subsequently, a meta synthesis was performed. The qualitative method [23] is an evaluation of existing research. The models aggregated from the literature research were examined for statements on possible operational measures, which were selected and categorised [24]. The aim is to integrate and deepen findings from analyses and studies already conducted in a specific field of research. In this way, new insights are gained. A crucial aspect of meta-synthesis is the extraction of content from the texts of the selected studies without necessarily considering the original contexts of the studies [25,26]. During the content analysis, the process steps and their respective measures have been transferred. Based on the principles of *Cooper's Stage-Gate* Process the steps were transferred into stages. In addition, a further subdivision of the process steps into further phases could be found in some of the models. These were also transferred. The result was numerous phases and measures that could be combined and solidified. The evaluation of the identified measures was carried out through expert workshops, the used criteria are presented later on (Chapter 5).

3. Theoretical Background and Current Concepts

The Product Development Process (PDP) is the systematised sequence of work steps to think through an initial idea and make it available for production. Following these steps within a chosen context makes it become a product development project [27]. The outcome of this process is an unmitigated image of an artefact, the artefact on the other hand is the result of the value creation activities of the stakeholders in the value creation system [28]. The artefact consists of tangible and intangible components [28]. Product development and the subsequent materialisation can be assigned to the product creation process following the Product Life Cycle (PLC) according to DIN ISO 15226 [29]. In a company, many product development processes and product creation processes can run in parallel; at system level, numerous systemic processes also run on top of these individual processes. At the interface between product development and production, one of the tasks of PP as a sub-discipline of OPS is to ensure a sufficient flow of information in the development process. Currently, the PDP is designed according to the principle of integrated product development (compare Concurrent Engineering and Simultaneous Engineering). Information is exchanged between the production department and the development environment at an early stage. At the interface between development and production OPS acts as a knowledge aggregator and mediator between the two sub-disciplines of product development and production.

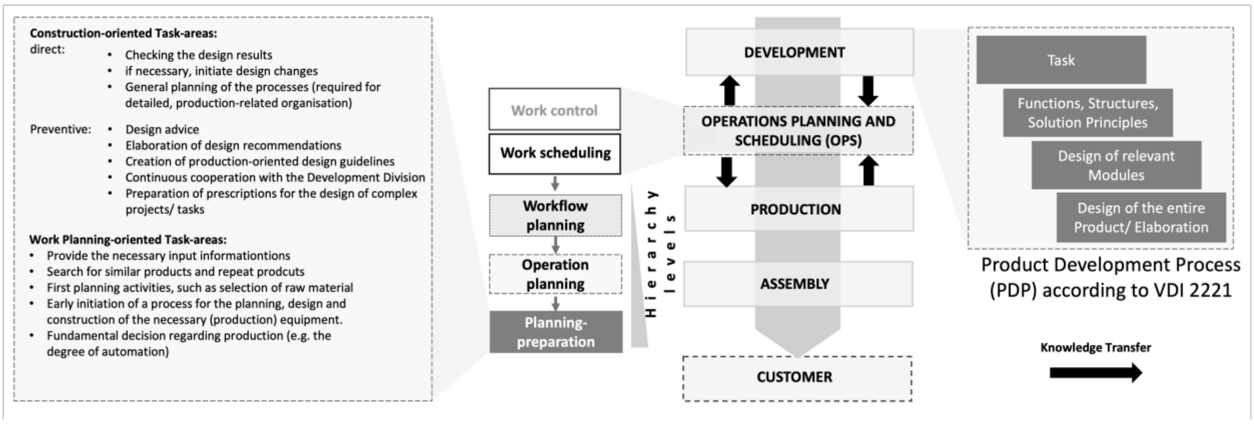


Figure 1: The roles of development, OPS and production in a company [30].

As shown in Figure 1., knowledge transfer occurs in the process. OPS essentially describes all organisational functions that must be fulfilled in order to bring a product design into production and thus ultimately to the customer. PP is a sub-area of OPS that is divided into the two sub-areas of design-oriented tasks and planning-oriented tasks. In classic literature, the consultation of the development department is always placed in the foreground, while the measures that fall under this are not further specified. Other tasks are stated rather vaguely as *"checking the design results"* or (giving) *"design advice"* (compare Figure 1.) [30]. Nevertheless, the improvement of the overall *producibility* of an artefact can be seen as a major goal of PP. In this context, the definition of *producibility* must be mentioned; it includes influencing factors such as materials management, production, assembly and testing, the associated logistics and the control mechanisms and support measures used for this purpose [31].

There are many standards in the field of product development, but these often refer to interaction within companies or company networks dominated by a single company. For example, modern concepts of product development presuppose the interaction of all relevant knowledge and information carriers of a company at the earliest possible point in time; this full integration should enable a holistic product development [32].First mentioned by OLSSON in the late 1960s [33] the term *Integrated Product Development* was introduced by EHRLENSPIEL [34]. These processes can be referred to as *Concurrent Engineering* or *Simultaneous Engineering* as a working methodology [34,35]. In all these concepts parallelisation of activities is the common approach to reduce development times and ensure cost-efficient production at an early stage. A possible strategy for a more detailed separation of the development process was introduced by COOPER [36].The stage-gate process follows a division of the development steps into so-called stages and gates that follow a temporal horizon. Each stage is associated with several measures which help to complete the objective of the gate. This can be an "*internal resolution"*, a "*successful test"* or "*the creation of a concrete technical document"*. In his latest update COOPER points out that rigid adherence to gates and stages is no longer appropriate for the complex development tasks prevalent today and that there must be iterations and feedback loops [37].

4. Challenges in the interaction of Co-Creation Communities and Cross Company Production

It was already predicted that the introduced concepts only work inadequately. The value co-creation scenario outlined in Chapter 1 assumes numerous companies and a variety of developers to be involved [20]. Furthermore, the development projects in such an environment show different degrees of professionalism and are characterised by phases of varying activity and changing project management. SAUBKE et al. (in press) showed that the interaction of CCP and CCC inevitably leads to new challenges due to the diversity of network members, the systematics of network governance and the network maxims [20]. In addition, it must be assumed that the means of production and the competencies of the employees are diverse. The network members are autonomously operating enterprises with a high degree of specialisation. They are horizontally and vertically disintegrated [38]. Governance follows decentralised structures and requires a higher coordination effort. There is a need for coordination between the individual companies with regard to the overarching value creation task. Productivity and optimisation can be cited as the maxims of the entrepreneurial actors. It becomes clear that the interaction of a multitude of different companies with an unknown mass of digitally collaborating developers, however, leads to further challenges in fulfilling the task of PP. The usual knowledge carriers are distributed and are no longer directly accessible or easy to bring together. But precisely all the details about production capabilities and the functionality of production systems have an high influence on the *producibility* of an artefact [38]. In the value creation constellation of CCC and CCP there will be no department that can take care of the tasks of PP or orchestrate the measures associated with them. For example, the motivation of an entrepreneur to spend resources on consulting tasks for an artefact that she or he may never produce or only produce in small quantities can only be assumed to a limited extent. The requirement is therefore no longer to carry out as many measures as possible to complete the task, and to do so in parallel, but its is rather to examine which tasks are of particular relevance for the participating entities and to clarify who is involved in the execution of a measure and to what extent.

5. Findings of the Analysis

5.1 Collection and Classification of Measures according to the Stage-Gate-Process

Aiming at the alignment of the systematics of general measures for Planning Preparation PP, the Product Life Cycle PLC according to DIN ISO 15226 [29] was used as a basis. The PLC is a well-established concept in marketing and product management that describes the stages a product goes through from its introduction to the market until its eventual decline and discontinuation. It systematises the product related value creation process into ten phases, of which four can be assigned to product development. These four phases are Planning, Knowledge, Development and Production. These four phases build the baseline in the new structure of stages and activities. The basis of the research was a summary of all PDPs and innovation processes that had been subjected to a published literature review by EVELEENS [21]. The literature research has a clear focus on innovation processes, but there is a lack of clarity in many concepts. In general a clear distinction between the innovation process and product development process is only possible to a limited extent. Therefore, recognised process models of product development were added from a published overview in a scientific publication by LENDERS [22]. In total 14 concepts were integrated in the meta synthesis.

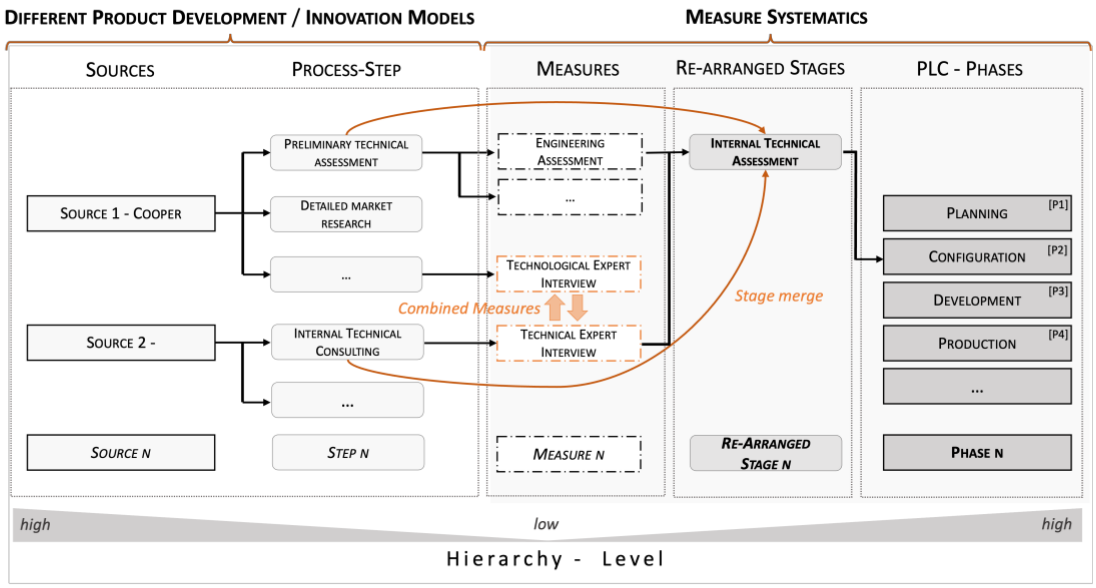


Figure 2: Procedure of identifying measures and stages.

In order to obtain a comprehensive overview of the possible stages and activities within the PLC, the above-mentioned sources were systematically examined for phases, stages or steps of the individual process structure, hereinafter referred to as process-steps. The procedure of the re-arrangement of the identified measures and process-steps is shown in Figure 2. Moreover, possible measures that can be assigned to the process-steps were selected through the analysis. The target was to unify the process-steps and finally transfer them into stages. According to the same principle, the identified measures were combined. The measures represent the lowest hierarchical level and can be associated with operational activities.

The grouping of these measures takes place in stages and several stages can in turn be assigned to the phases of the PLC. In 35 of 55 stages relevant measures could be identified. This led to a total of 103 measures, of which 30 were selected (displayed in Table 2., Chapter 5.2. The complete model can be requested through the corresponding author.

Table 1: List of innovation and product development models

No.	Related Models	Author	Reference
1.	Diffusion Of Innovations	Rogers (1962)	[39]
2.	An Investigation Into The New Product Process Step	Cooper (1986)	[36]
3.	Towards The Fifth-Generation Innovation Process	Rothwell (1994)	[40]
4.	Organizational Innovation - Review Critique And Suggested Research Directions	Wolfe (1994)	[41]
5.	World-Class New Product Development Benchmarking Best Practices Of Agile Manufacturers	Dimancescu (1996)	[42]
6.	Trends And Drivers Of Success In NDP Practices: Results Of The PDMA Best Practices Study	Griffin (1997)	[43]
7.	A Multidimensional Approach To The Adoption Of Innovation	Cooper J. (1998)	[37]
8.	Auditing Best Practice For Effective Product Innovation Management	Cormican (2004)	[44]
9.	Managing Innovation	Tidd & Bessant (2005)	[45]
10.	The Innovation Value Chain	Hansen (2007)	[46]
11.	Concept Development And Design	Ponn (2011)	[47]
12.	Design Theory [Konstruktionslehre]	Pahl/Beitz (2013)	[48]
13.	Integrated Design Engineering An Interdisciplinary Model For Holistic Product Development	Vajna (2014)	[31]
14.	Design Of Technical Products And Systems Configuration Of Individual Product Design Processes	VDI (2019)	[49]

5.2 Introduction of the Relevant Measures and Assessment

In an **initial step** all identified measures were valued with regard to their conformity with the tasks of PP introduced before (compare Chapter 3). Measures such as *"Engineering Assessment"* were assigned to the PP systematics, although they might include logistics or assembly aspects. All measures with a high level of consistency regarding the tasks performed by PP are listed in Table 2. In some models, measures were mentioned which have a technical aspect, but which is not associated with PP's overall target to increase the artefacts *producibility*. Furthermore, in some of the models examined, measures were identified that could not already be assigned to any of the four phases of the PLC considered and also have no technical reference. From today's perspective, these would not be implemented at such an early stage of the process. These measures were excluded. With the emergence of new technologies since the 1990, for various reasons some measures are no longer adequate. The following measures are examples of this: *„Structuring And Planning The Market Launch"* or *"Provide An Effective User Education"*. As already indicated in the beginning, in a **second step** an assessment was made. The resulting list was evaluated:

- EVALUATION CRITERIA I. - WHAT IS THE RELEVANCE OF THIS MEASURE TO THE ENTITY?
  (*The outcome of the measure e.g. knowledge inflow is required)*
- EVALUATION CRITERIA II. - TO WHAT EXTENT IS THE ENTITY INVOLVED IN THE EXECUTION?
  (e.g. knowledge carrier).

In the evaluation, a differentiation must be made between the shared value creation activity (successful cooperation of the CCC and CCP) and the domain-specific value creation task (production and development). When assessing relevance, it is therefore important to consider the extent to which the measure affects one's own value creation task and whether the measure also has a particularly positive influence on the PP's tasks (increase in *producibility*). The evaluation follows the scheme **low**, **medium** and **high**, because limiting resources (time, costs) make prioritisation necessary. Nevertheless, it is a basic premise that all stakeholder have an interest in the success of the shared value creation activity. For example, the measure *"(Technical) Review Of Competing Products To Improve Manufacturing Decisions"* was rated with a high relevance for the producer. The argumentation that such a decision could be less important to the producer because otherwise he could simply take on another value creation task (producing of another artefact) loses its validity against this background. The evaluation has shown that a measure can have a high relevance for one entity, but the implementation of the measure depends fundamentally on another entity. Under certain circumstances, this leads to conflicts. In addition, it must be assumed that the effort of the measures is not the same - this could not be considered. For a better understanding, some of the measures mentioned are explained in more detail. The measure *„Knowledge About Innovation In The Considered Field"* is assigned to the stage *"Needs"*. As outlined at the beginning, a focus was placed on PLC steps one to four, i.e. this is an Initial Stage which is a measure to support the developer within the framework of the idea exception. To be well informed about your own field of innovation is highly relevant for the developer, on top of that he is highly involved completing the measure. In contrast, the producer is confronted from the outset with many different artefacts. He cannot use his scarce resources for the agglomeration of knowledge in diverse disciplines, this measure has therefore less relevance for him. The measure no. 2 prescribes the *"Creation Of A Technological Solution System To Overcome A Problem"*. The evaluation of this measure is particularly interesting, the introduction of technical support systems has a high relevance for both entities. However, shaping and introducing the system itself can only be done to a limited extent through the involvement of the two entities. The sponsorship would have to be taken over by another entity.

In summary, the assessment helps to prioritise tasks and assign a corresponding entity, which can be of high importance for a system architecture or the selection of suitable support technologies to achieve the overall objective of increasing the producibility of openly and collaboratively developed artefacts.

Table 2: Selection of the 30 Measures most important for PP and their Evaluation.

medium = ■	high = ■■	very high = ■■■	RELEVANCE CCC	INVOLVE. CCC	RELEVANCE CCP	INVOLVE. CCP
NO.	**IDENTIFIED MEASURES**	**STAGE**				
1.	*Knowledge About Innovation In The Considered Field*	Needs	■■■	■■	■	■
2.	*Creation Of A Technological Solution System To Overcome A Problem*	Research	■■■	■	■■■	■
3.	*Advice On Hardware Components (Material, Etc.)*	Research	■	■	■	■■■
4.	*Performance Input And Estimation Of The Idea*	Development	■■	■■	■■■	■■
5.	*Transfer Of The Development Results Into Information Required For Production*	Development	■■■	■	■■■	■
6.	*Consideration Of (Product) Logistics*	Development	■	■■■	■■■	■
7.	*(Technical) Support For A Decision-Making Process (If An Idea Should Be Pursued)*	Initial Screening	■	■■■	■■	■■■
8.	*(Technical-) Review Of Competitors Products To Improve Manufacturing Decisions*	Pre. Market Assessment	■■■	■	■■■	■
9.	*Engineering Assessment*	Pre. Tech. Assessment	■■	■■	■■■	■■
10.	*Identify And Define Product Specifications*	Pre. Tech. Assessment	■	■■	■■■	■■■
11.	*Conducting A Capability/Feasibility Analysis*	Pre. Tech. Assessment	■■■	■■■	■	■■■
12.	*Generic Development Of A Product Design-Model*	Pre. Tech. Assessment	■■	■■	■■■	■■
13.	*Costs And Sales Forecast (Technical Perspective)*	Business Analysis	■■■	■■■	■	■
14.	*Pooling Of Technical Expertise*	Product Development	■■■	■	■	■
15.	*Identification Of Missing Knowhow (in the development process)*	Product Development	■■■	■■■	■■■	■■■
16.	*Detailed And Transparent Presentation Of Technical Issues/Problems/Questions*	Product Development	■■	■	■■	■
17.	*Production Trial/ Testing Of The Production Processes*	Trial Production	■■■	■■■	■■■	■■■
18.	*Emphasis On Satisfying User Needs*	Idea Generation	■	■■	■■■	■■■
19.	*Attaining Cross-Project Synergies And Inter-Project Learning*	Research, Design, Dev.	■■■	■■	■■■	■■
20.	*Development Emphasis On Creating User Value*	Research, Design, Dev	■	■	■■■	■■
21.	*Checking The Solution Path (Product Design/Structure)*	Projecting / Specifying	■■■	■■■	■	■
22.	*Determination Of A Manufacturing Strategy*	Conceptualise /Design	■	■	■■■	■■■
23.	*Support For Simulating Production At An Early Stage (Predictive Engineering)*	Construction	■	■	■■■	■■■
24.	*Peer - Review On Decisions*	Configuration	■■■	■■■	■■■	■■■
25.	*Clarification And Itemisation Of The Assignment, Task Or Problem*	Clarification	■■	■■	■	■
26.	*Collecting Available Information On The Product Context*	Clarification	■■	■■	■	■
27.	*The Identification Of Information Gaps*	Clarification	■■	■	■	■
28.	*(Technological) Support For The Search For Innovative Solutions*	Search For Solution	■■■	■	■	■
29.	*Solution Mapping*	Search For Solution	■■	■■	■	■
30.	*(Technological) support for the definition of the overall function*	Search For Solution	■■■	■	■	■

5.3 Conclusions and evaluation of the results

After the evaluation, two conclusions can be drawn. First, the planning preparation environment changes drastically. Since many developers and numerous companies are involved in this new value-creation constellation, one can speak of the distributed character of PP. It must be assumed that there are dislocated knowledge carriers that extend the distribution by the aspects of spatial and temporal separation. Distribution may make it necessary to make knowledge more accessible through storage and generalisation. This distribution makes knowledge aggregation necessary to a higher degree and also has a concrete effect on the necessary technical systems that are referred to in the measures. In order to meet the requirements of this value-creation environment while at the same time keeping development time low and producibility high, PP has to be agile to a high degree. Following the use of the term in software development (achieving executable software as early as possible in the development process), the use of the term 'agility' in the hardware context is intended to meet the overriding goal of creating producible hardware as quickly as possible while at the same time maintaining a transparent source of knowledge. For example, decisions can be positively influenced at an early stage with a *"peer review on decisions"* (c. Table 2, No. 24), but for this to happen, knowledge carriers must be linked to knowledge needs short term. At the same time, there must be a high degree of transparency regarding knowledge creation in order to create credibility, which also must be tracked and made accessible for both entities. The evaluation of the measures in terms of relevance and the degree of involvement in the fulfilment of the tasks is widespread. Some of the measures focus on positively influencing the development process at an early stage in terms of producibility. Other measures provide producers with sufficient assistance. Overall, the participation of both entities is necessary. Furthermore, according to the evaluation scheme, some measures cannot be fulfilled by the two entities. Another party is needed to moderate between the two. An intermediary could function as the needed knowledge aggregator stated before and could provide a suitable digital infrastructure for the process.

6. Critical Analysis and Outlook

The overarching goal of this approach is to increase the *producibility* of artefacts developed in Co-Creation Communities (CCC) for the production in Cross-Company Production (CCP) Networks. Following the classical organisational structure of Operations Planning and Scheduling (OPS), this is a task of the subdivision of Planning Preparation (PP). In contrast to the approaches of integrated product development, where the shortening of the development time and the parallelisation of tasks are in the foreground, it is now more important to examine which tasks are of relevance for the participating entities and to clarify who is involved in the execution of a measure and to what extent. This product development process may require a more sequential orientation again in this value-creation constellation. It was deduced why existing concepts only function insufficiently. In order to take all approaches into account, a fundamental analysis of existing concepts for innovation and product process design was performed and numerous measures were identified to achieve the overarching goal: The increase of *producibility*. Fourteen theoretical and published process models were analysed during the processes to identify possible stages and related measures. These were then ordered in the sense of the stage-gate process. Based on the challenges in the interaction of Cross-Company Production (CCP) and Co-Creation Communities (CCC) described in Chapter 4 the measures identified were evaluated. It shows whether a measure is relevant for an entity and through whose involvement it can be fulfilled. Therefore, the research question of identifying and evaluating suitable measures could be adequately answered. Furthermore, it has been shown that the Planning Preparation (PP) tasks can only be fulfilled through an additional entity. This intermediary must mediate between production and development, take responsibility for fulfilling tasks and monitor them. This is only possible through technological support. In this regard, the temporal and spatial separation must be further observed. Even if the basis for the development measure systematics consisted of fourteen different models, each of which is based on an extensive and contemporary case study, it may have improved the expressiveness to conduct a direct survey in the companies and within the developer community. Another topic for further research is which measures can be supported technologically. On top of that, the technological feasibility needs to be assessed and concrete technologies must be detected. Therefore, the systematics found so far provide initial assistance in optimizing and designing digital platforms for the organisation of value creation systems. In general, the approach to improve the outcome of product development processes in Co-Creation Communities (CCC) by achieving higher *producibility* bears great potential to impact future value creation systems positively.

Acknowledgements

The Project *'Production Next Door'* at the Helmut-Schmidt-University, University of the Federal Armed Forces Hamburg is funded by the Center for Digitization and Technology Research of the Federal Armed Forces (dtec.bw) - dtec.bw is funded by the European Union - NextGenerationEU.

References

[1] Arndt, K.-D., 2016. Arbeitsvorbereitung und Arbeitsplanung, in: Böge, A., Böge, W. (Eds.), Handbuch Maschinenbau. Grundlagen und Anwendungen der Maschinenbau-Technik, 23., überarbeitete Auflage ed. Springer Vieweg, Wiesbaden, pp. 1735–1772.

[2] Almeida, F., Duarte Santos, J., Augusto Monteiro, J., 2020. The Challenges and Opportunities in the Digitalization of Companies in a Post-COVID-19 World. IEEE Eng. Manag. Rev. 48 (3), 97–103.

[3] Reiffer, A., Magdolen, M., Ecke, L., Vortisch, P., 2022. Effects of COVID-19 on Telework and Commuting Behavior: Evidence from 3 Years of Panel Data. Transportation Research Record, 036119812210899.

[4] Castro, H., Putnik, G., Castro, A., Bosco Fontana, R.D., 2019. Open Design initiatives: an evaluation of CAD Open Source Software. Procedia CIRP 84, 1116–1119.

[5] Chesbrough, H.W., 2003. Open innovation: The new imperative for creating and profiting from technology, [Nachdr.] ed. Harvard Business School Press, Boston, Mass., 227 pp.

[6] Hippel, E. von, 2005. Democratizing innovation: The evolving phenomenon of user innovation. JfB 55 (1), 63–78.

[7] Mies, R., Bonvoisin, J., Stark, R., 2020. Development Of Open Source Hardware In Online Communities: Investigating Requirements For Groupware. Proc. Des. Soc.: Des. Conf. 1, 997–1006.

[8] Antoniou, R., Bonvoisin, J., Hsing, P.-Y., Dekoninck, E., Defazio, D., 2022. Defining success in open source hardware development projects: a survey of practitioners. Des. Sci. 8.

[9] Adam, F., Hertwig, M., Barwasser, A., Lentes, J., Zimmermann, N., Siee, M., 2019. Crowd Engineering – Approach for Smart and Agile Product Development in Networks. Procedia Manufacturing 39, 1317–1326.

[10] Kohtala, C., 2015. Addressing sustainability in research on distributed production: an integrated literature review. Journal of Cleaner Production 106, 654–668.

[11] Larsson, M., 2018. Circular business models: Developing a sustainable future. Palgrave Macmillan, Cham, 303 pp.

[12] No Author Given., (2020, 05. März). Wie der Bundestag über Klimapolitik spricht. Süddeutsche Zeitung, URL https://www.sueddeutsche.de/projekte/artikel/politik/wie-der-bundestag-ueber-klimapolitik-spricht-e704090/

[13] No Author Given., (2022, 01. November). Trends der Lufttemperatur. Umweltbundesamt. URL https://www.umweltbundesamt.de/daten/klima/trends-der-lufttemperatur#fruhling-und-sommer-signifikant-warmer.

[14] No Author Given., (2022, 01. November). Für eine Welt ohne Hunger und Armut 2022 in Klimawandel – Folgen & Ursachen. Welthungerhilfe. URL https://www.welthungerhilfe.de/informieren/themen/klimawandel.

[15] No Author Given., (2022, 01. November). Klima und Handel - Warum der Klimawandel zu einer Reform des Welthandels zwingt. Heinrich-Böll-Stiftung. URL https://www.boell.de/de/navigation/oekologische-marktwirtschaft-7043.html.

[16] Antonioli, D., Mazzanti, M., Pini, P., 2010. Productivity, innovation strategies and industrial relations in SMEs. Empirical evidence for a local production system in northern Italy. International Review of Applied Economics 24 (4), 453–482.

[17] Mariale Moreno, Charnley, F., Tiwari, A., 2018. Network on consumer goods, big data and re-distributed Manufacturing - RECODE Network.

[18] Menichinelli, M., Cangiano, S., 2021. Open Design as an approach for the commoning of design. The collaborative experience of openly defining Open Design with an open source process, in: .

[19] Redlich, T., Moritz, M., Wulfsberg, J.P., 2019. Co-Creation. Springer International Publishing, Cham.

[20] Moritz, M., Redlich, T., Buxbaum-Conradi, S., Wulfsberg, J.P., 2023. Global collaboration, local production - how Fab Cities enable a circular economy (In print).: Verteile Produktentwicklung für eine lokale unternehmensübergreifende Produktion – Herausforderungen in der Zusammenarbeit, 1. (In print). ed. Springer-Verlag Berlin Heidelberg, Wiesbaden. (In print).

[21] Eveleens, C., 2010. Innovation management; a literature review of innovation process models and their implications.

[22] Lenders, M., 2009. Beschleunigung der Produktentwicklung durch Lösungsraum-Management. Apprimus-Verl., Aachen, 267 pp.

[23] Döring, N., Bortz, J., 2016. Forschungsmethoden und Evaluation in den Sozial- und Humanwissenschaften. Springer Berlin Heidelberg, Berlin, Heidelberg.

[24] Böhm, A., 2017. Theoretisches Kodieren. Textanalyse in der Grounded Theory, in: Flick, U., Karrdorf, E. von, Steinke (Eds.), Qualitative Forschung, ein Handbuch, 12. Auflage ed. Rowohlt Taschenbuch Verlag, Reinbek bei Hamburg, pp. 475–485.

[25] Hoon, C., 2013. Meta-Synthesis of Qualitative Case Studies. Organizational Research Methods 16 (4), 522

[26] Kornmeier, M., 2007. Wissenschaftstheorie und wissenschaftliches Arbeiten: Eine Einführung für Wirtschaftswissenschaftler. Physica-Verlag Heidelberg, Heidelberg.

[27] Deutsches Institut für Normung e.V., 2009. DIN 69901: Projektmanagementsysteme. Beuth Verlag GmbH, 10772 Berlin 03.100.40.

[28] Redlich, T., Wulfsberg, J.P., 2011. Wertschöpfung in der Bottom-up-Ökonomie. Springer-Verlag Berlin Heidelberg, Berlin, Heidelberg.

[29] Deutsches Institut für Normung e.V., 2017. DIN ISO 15226 - Technische Produktdokumentation - Lebenszyklusmodell und Zuordnung von Dokumenten. Beuth Verlag GmbH, 10772 Berlin 01.110.

[30] Eversheim, W., 2002. Organisation in der Produktionstechnik 3: Arbeitsvorbereitung, 4., bearbeitete und korrigierte Auflage ed. Springer, Berlin, Heidelberg, 295 pp.

[31] Vajna, S., 2014. Integrated Design Engineering. Springer Berlin Heidelberg, Berlin, Heidelberg, 621 pp.

[32] Gerwin, D., Barrowman, N.J., 2002. An Evaluation of Research on Integrated Product Development. Management Science 48 (7), 938–953.

[33] Olsson, F. Machine design procedure related to product development procedure., in: , Hubka, V. (Hrsg.) Review of Design Methodology, Schriftenreihe WDK, Bd. 5,, S. 229–238.

[34] Ehrlenspiel, K., Meerkamm, H., 2017. Integrierte Produktentwicklung: Denkabläufe, Methodeneinsatz, Zusammenarbeit, 6., vollständig überarbeitete und erweiterte Auflage ed. Hanser, Müchen, Wien, 991 pp.

[35] Vajna, S., 2014. Integrated Design Engineering. Springer Berlin Heidelberg, Berlin, Heidelberg.

[36] Cooper, R., 1986. An investigation into the new product process: Steps, deficiencies, and impact. Journal of Product Innovation Management 3 (2), 71–85.

[37] Cooper, J.R., 1998. A multidimensional approach to the adoption of innovation. Management Decision 36 (8), 493–502.

[38] Krenz, P., 2020. Formen der Wissensarbeit in einer vernetzten Wertschöpfung: Formen der Wissensarbeit in einer vernetzten Wertschöpfung.

[39] Rogers, E.M., 2012. Diffusion of Innovations. SSRN, S.l., 1 p.

[40] Rothwell, R., 1994. Towards the Fifth-generation Innovation Process. International Marketing Review, 7–31.

[41] Wolfe, R.A. Organizational Innovation - Review Critique And Suggested Research Directions_DS, in: , Journal of Management Studies, 31:3 1994.

[42] Dimancescu, D., Dwenger, K., 1996. World-class new product development: Benchmarking best practices of agile manufacturers. AMACOM, New York, 239 pp.

[43] Barczak, G., Griffin, A., Kahn, K.B., 2009. PERSPECTIVE: trends and drivers of success in NPD practices: results of the 2003 PDMA best practice study. The journal of product innovation management.

[44] Cormican, K., O'Sullivan, D., 2004. Auditing best practice for effective product innovation management. Technovation 24 (10), 819–829.

[45] Joe Tidd, J.B. MANAGING INNOVATION: Integrating Technological, Market and Organizational Change.

[46] Hansen, M.T., Birkinshaw, J., 2007. The innovation value chain. Harvard Business Review 85 (6), 121-30

[47] Ponn, J., Lindemann, U., 2011. Konzeptentwicklung und Gestaltung technischer Produkte. Springer Berlin Heidelberg, Berlin, Heidelberg, 471 pp.

[48] Bender, B., Gericke, K., 2021. Pahl/Beitz Konstruktionslehre. Springer Berlin Heidelberg, Berlin, Heidelberg.

[49] Verein Deutscher Ingenieure e.V., 2019. VDI 2221 - Entwicklung technischer Produkte und Systeme: Modell der Produktentwicklung, 2021st ed. Beuth Verlag GmbH, 10772 Berlin 03.100.40.

Biography

Dominik Saubke, M.Sc. (*1989) has been a research assistant at the Institute of Production Engineering (LaFT) of Helmut-Schmidt-University in Hamburg since 2021. With several years of industrial experience in Product Development his current research is on increasing the producibility of value creation artefacts.

Pascal Krenz, Dr.-Ing. (*1983) has been a research assistant at the Institute of Production Engineering (LaFT) within the Department of Mechanical Engineering of Helmut-Schmidt-University in Hamburg since 2011. He leads the research area on local production at the Institute and related research projects.

Tobias Redlich, Dr.-Ing., MBA (*1981), is the senior engineer at the Institute of Production Engineering (LaFT) in the Department of Mechanical Engineering at Helmut-Schmidt-University in Hamburg since 2013. His research focuses on value creation systematics and the impact of new value creation patterns on production engineering and production management.

CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
CPSL 2023-2

5th Conference on Production Systems and Logistics

Design Elements Of Corporate Functions In The Trade-Off Between Efficient Goal Achievement And Prevention Of Disturbance Impacts

Michael Riesener[1], Maximilian Kuhn[1], Jonas Tittel[1], Pawan Singh[1], Günther Schuh[1, 2]
[1]Laboratory for Machine Tools and Production Engineering (WZL), RWTH Aachen University, Aachen, Germany
[2]Fraunhofer Institute for Production Technology IPT, Aachen, Germany

Abstract

In the context of sustainable management, organizational resilience is gaining importance. Manufacturing companies are increasingly exposed to external disturbances. At the same time, corporate functions today are usually geared towards efficient execution. A positioning in this trade-off between efficient achievement of goals and the prevention of impacts of disturbances is necessary. Crisis-resistant product development is of particular importance, as innovative products offer a promising opportunity to create competitive advantages and thus secure the company's existence or even enable a company to increase its market share in the event of a crisis. Based on a literature review and its structured consolidation, this paper presents design elements of product development for positioning in this trade-off. The overall dimensions of the design elements are strategy, organization, resources, product, as well as project management. The approach is transferable to other corporate functions.

Keywords

Design Elements; Resilience; Efficiency; Manufacturing Companies; Product Development

1. Introduction

The topic of sustainability has risen in importance and popularity, with manufacturing companies increasingly incorporating sustainable management and sustainable product development into their operational practices [1–3]. The recent COVID-19 pandemic has shown that organizational resilience is also crucial, highlighting its contribution to sustainable management [4]. However, businesses frequently overlook resilience in favour of efficiency. General management heuristics do not recognize creating transparency regarding uncertainties and related risks as a top concern. As a result, businesses struggle to strike a sensible balance between risk and return while making development decisions. [5] Therefore, it is vital for an organization to position itself and its corporate functions appropriately in this trade-off between efficient goal achievement and mitigating the effects of disturbances. Accordingly, the question arises: How can a company position itself in this trade-off between efficiency and resilience?

The corporate function of product development is essential to increase organizational resilience in manufacturing companies because it opens the doors to new innovative products and enables product-side adaptation to changing circumstances. This helps a company to create an edge over its competitors and increase its market share or even capture a new market segment. [6] Product development is a complex corporate function and thus can best be described using a variety of meaningful design elements. With the help of these design elements and their characteristics, organizations can perform evaluations to better position themselves in the conflicting goals. However, there is currently no comprehensive overview of the

DOI: https://doi.org/10.15488/15307
ISSN: 2701-6277
publish-Ing.

design elements that can be referred to. Hence, this paper aims to provide an overview of the design elements that make up product development.

As part of this work, a thorough systematic literature review and consolidation have been conducted to find the design elements as well as their superordinate dimensions. The design elements are clustered and assigned to one of the following dimensions: Strategy, organization, resources, product, and project management.

This introduction is followed by the fundamentals relevant for the paper in the second section. The steps of the methodology employed for this paper are described in the third section. An overview of the results is presented in the fourth section. The extracted design elements are listed with a brief description and an allocation to the respective dimension. Finally, the conclusion with the scope of further research is presented.

2. Fundamentals

This section presents the relevant basic concepts for this paper. It includes brief descriptions of product development, systematic literature review, Design Structure Matrix (DSM), and Idicula-Gutierrez-Thebeau-Algorithm-plus (IGTA-plus).

2.1 Product Development

Product development is an interdisciplinary process within a company that aims to create an innovative product for the market. The process starts by defining the initial objectives and requirements for the product, which are continuously improved and constantly adjusted. [7] Product development is a significant corporate function because the design and creation of products help organizations potentially gain an advantage over their competitors. Moreover, it helps corporations to diversify, adapt, and even reinvent themselves according to the changing markets and technological conditions. [8]

Product development can be explained in two ways. On the one hand, it is a process that controls the operations of development projects as well as how the individuals and teams engaged behave. It is possible to distinguish between sequential, iterative, and hybrid processes. [7] On the other hand, product development is defined as an organizational division that outlines the layout of the required workplaces. It consists of dividing product development into subsystems and assigning tasks to each of the subsystems [9]. [10,2] Furthermore, the product development process can be divided into different phases, such as the concept phase, the development and verification phase, as well as the planning and development of production processes phase [11].

2.2 Systematic Literature Review

A systematic literature review (SLR) is required to make the process of finding relevant articles, papers, and books organized and efficient. Figure 1 shows the most common steps for conducting a SLR despite the differences in various procedures. Literature reviews are categorized into four sections based on the main objective of the review: describe, test, extend, and critique. This paper falls into the extend category as the current literature has been reviewed to extract information and derive design elements of product development. There are different methodologies to conduct a SLR developed by various authors. [12] Therefore, a systematic approach based on [12] is developed to proceed with the literature review in this research project. The approach is described in the third section of this paper.

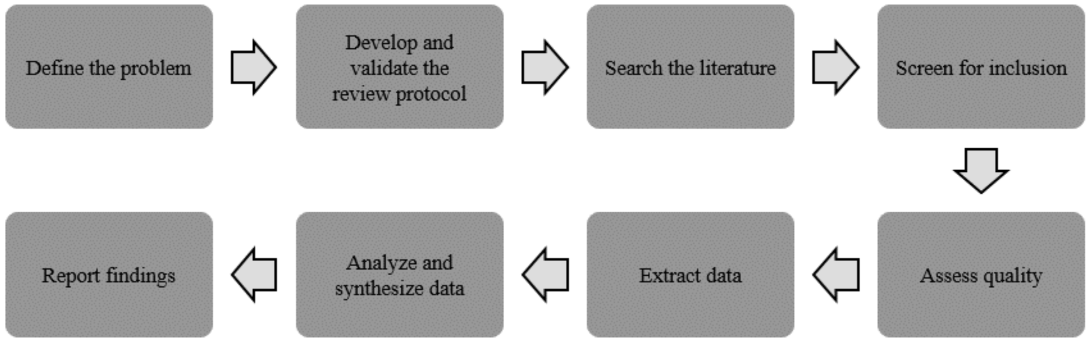


Figure 1: Process of systematic literature review [12]

2.3 DSM and IGTA-plus

As shown in Figure 1, one of the necessary steps of a literature review is the analysis and synthesis, which, in the context of this work, is the consolidation of the extracted data. This also requires a systematic approach, whereby DSM and IGTA-plus are the methodical procedures applied to facilitate this consolidation process.

DSM is a widely used tool for modelling, offering a straightforward, consolidated, and visual representation of a complex framework that encourages innovative solutions to challenges involving decomposition and integration. [13] A DSM is essentially a square matrix where the system elements are listed along the horizontal as well as the vertical axis. The off-diagonal cells of a DSM demonstrate relationships between the system elements, such as dependencies, interactions, interfaces, etc. [14]

[13] lists different types of DSMs. For the purpose of this work, an efficient representation of product development is necessary. Therefore, component-based DSM is the most suitable. A component-based DSM is particularly useful when system architectures are modelled based on the components and/or the subsystems and their relationships [13]. This kind of DSM is filled using the binary system in which a cell is marked if there is a relationship or an interaction between the elements. However, the binary system does not provide any information about the extent as well as the direction of the relation. [15]

With the help of a DSM, the components can be clustered into multiple categories. Although manual clustering can be performed, it is inconvenient for bigger problems. Consequently, computer algorithms are developed to fulfil this task. One such algorithm is the IGTA-plus [16], which is built upon the foundations of the IGTA [18,17,19]. IGTA is designed to find optimal groups by minimizing the overall interactions between clusters while simultaneously maximizing the interactions within clusters. This is achieved by shifting the individual components from one cluster to another. The algorithm assigns costs to all the interactions. The costs of the interactions within a cluster are weighted lower than the costs of the interactions between different clusters. As a result, the algorithm finds an optimal cluster for a component by minimizing the total cost. IGTA-plus is a significant improvement over the original algorithm in terms of the computational speed and the quality of the solutions. [16]

3. Methodology

The objective of this paper is to identify the design elements that describe the corporate function of product development. Figure 2 shows the procedure adopted in this project, which includes conducting a SLR based on [12].

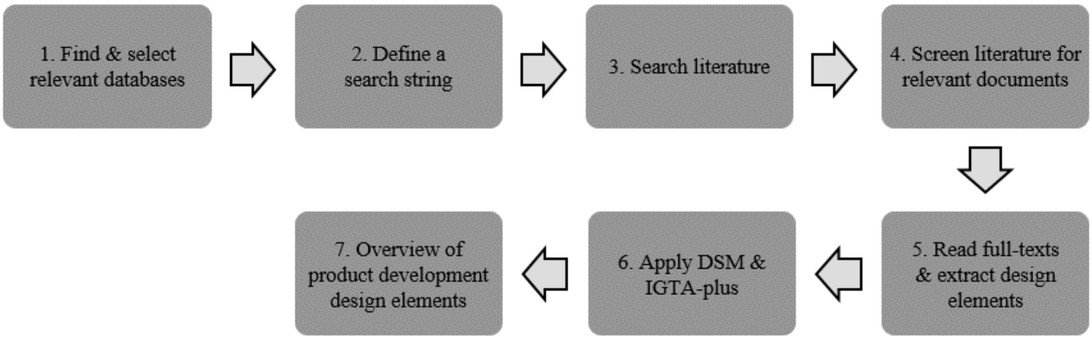


Figure 2: Methodological procedure for deriving design elements of product development

The first step is to find the relevant databases to search the literature. As a part of this project, a list of well-known databases is compiled, taking the database-information system of RWTH Aachen University into consideration [20]. The databases are then inspected based on the volume of literature, the availability of engineering literature in English or German, and the possibility of applying filters on the results. After looking at all the databases, Scopus and Web of Science are deemed relevant for the purpose of this work because of their unique capacity to aggregate results from various other databases, thereby enhancing the comprehensiveness of the data acquisition process, and their user-friendly interfaces. In order to find significant publications, it is necessary to define a search string for the literature search in the second stage of the methodology (see Figure 3). The defined search string includes terms in both English and German. Additionally, Boolean operators (i.e., “AND” and “OR”), as well as the wildcard (i.e., “*”), are used to formulate an appropriate string. The operator “AND” finds the documents that contain all terms connected by it, whereas “OR” finds documents that contain at least one of the connected terms. Therefore, it is often used for synonyms in a search string. The wildcard “*” is used to include the different forms of a word. For instance, “strateg*” would provide results containing words such as strategy, strategize, strategic, etc.

(produktentwicklung OR "product development") AND (gestalt* OR design* OR innovat* OR faktor* OR factor* OR konfigur* OR configur* OR organis* OR organiz* OR manag* OR steuer* OR regel* OR control* OR strateg* OR einstell* OR align* OR adjust* OR orient* OR optim*)

Figure 3: Search string for literature search

The results from both databases are sorted by relevance and citations, and the top results are taken into consideration for screening. Screening starts by removing all the duplicates in the results. A team of researchers independently executes parallel analyses of the titles and abstracts to filter out irrelevant publications. Subsequently, the full texts of the relevant publications are collected. However, it is imperative to note that not all full-texts are accessible or available, rendering them ineligible for inclusion in the ensuing review. Furthermore, the book [21] is included for the full-text evaluation, given its status as a foundational resource for teaching product development at RWTH Aachen University. Figure 4 illustrates the important steps of the systematic literature review, which constitute the third, fourth, and fifth steps of the overall methodology.

Scopus and Web of Science deliver 2881 and 1550 results, respectively, which contain the terms from the defined search string in their title. Given the practical constraints and time limitations associated with examining the entire pool of results, only the top 200 publications sorted by relevance and citation are selected from each database. Therefore, 800 of the total generated results are considered for screening. In the subsequent phase, a rigorous screening and assessment process is undertaken, encompassing the examination of the titles, abstracts, and full texts of the results, and those that do not align with the research objectives are systematically excluded from consideration. Consequently, a refined selection of 57 publications is deemed suitable to extract design elements of product development.

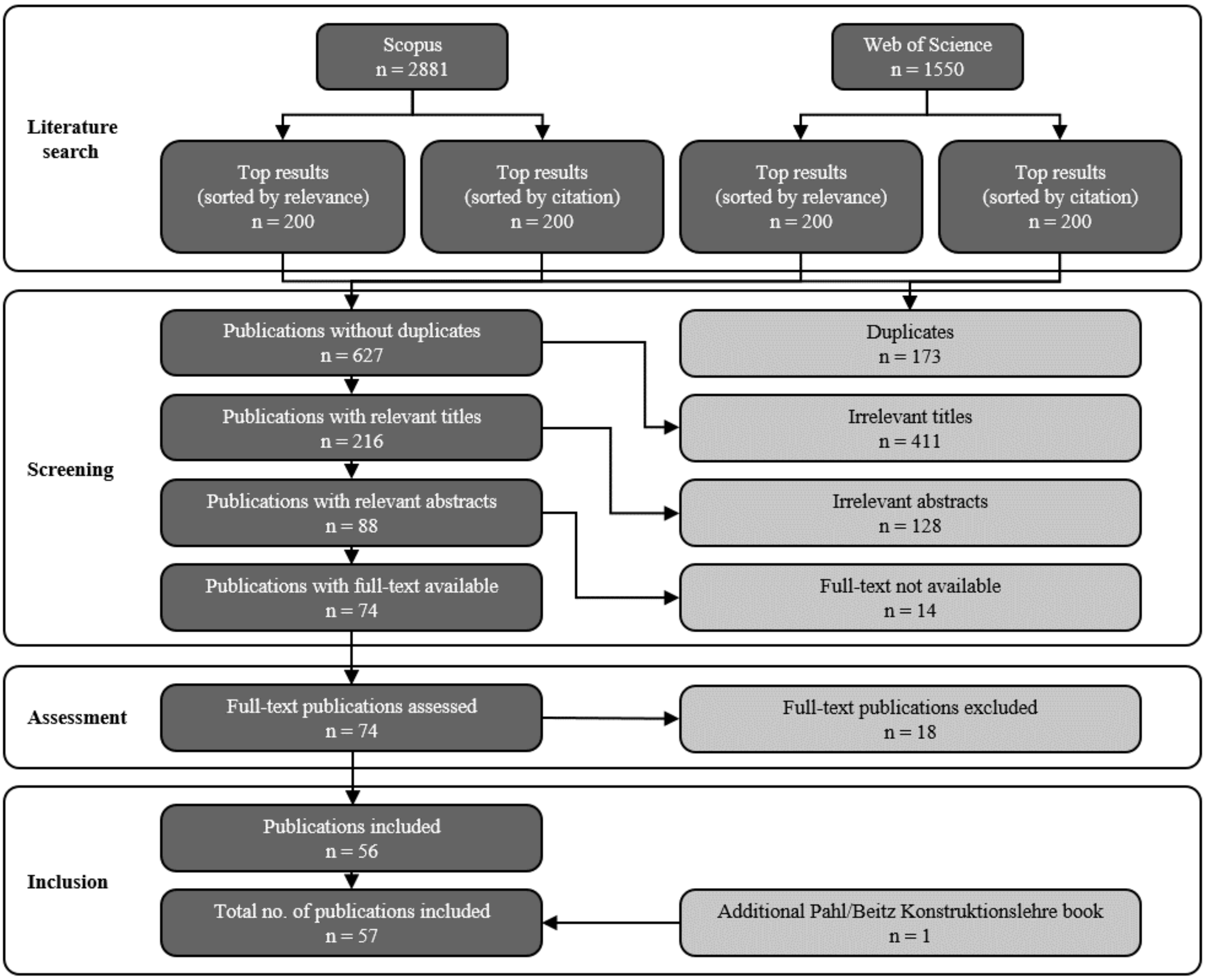


Figure 4: Systematic literature review based on [12]

After the first evaluation of the relevant publications, 195 design elements of product development are extracted from the available literature. Subsequently, all the duplicates and the design elements that are aspects of other design elements are excluded. As a result, 157 of the initial 195 design elements are removed. Further consolidation is essential to remove design elements that, though not blatantly identical, exhibit significant overlaps with other design elements. Both DSM and IGTA-plus are used to assist with this consolidation in the sixth step of the methodological procedure. DSM plays a pivotal role in streamlining the process of establishing linkages among the design elements. The IGTA-plus algorithm is subsequently used to group the design elements by utilising these links inside the DSM, which leads to the establishment of numerous distinct clusters. The remaining 38 design elements are inserted into a DSM, and the cells are filled based on the similarity between the design elements. IGTA-plus uses this DSM to analyse and group the design elements with the most similarity. The algorithm offers various adjustable parameters that influence the outcomes. Notably, one of the most decisive parameters is denoted as "pow_cc," which plays a significant role in determining the cost allocation associated with the size of clusters during the computation of the "Total Cost." A higher value assigned to this parameter corresponds to an increased cost attributed to larger clusters, consequently favouring the formation of numerous smaller clusters comprised of fewer design elements. In the present work, the parameter is set to “2” because it delivers an appropriate number of clusters in comparison to other values. As a result, nine design elements are taken out of further consideration based on their similarity to other design elements within the same cluster.

In the next step, the remaining 29 design elements are to be clustered into multiple dimensions. A new DSM is generated using these final design elements and is evaluated with a focus on content relatedness rather than mere similarity. IGTA-plus is applied again to determine the optimal groups by clustering the design elements. The groups of design elements are discussed and named by the group of researchers. Each group of design elements is known as a dimension of product development.

4. Results

This section presents the results that are obtained by conducting the described systematic literature review, and represents the final step of the overall methodology. Table 1 displays the design elements as well as the dimensions they are assigned to. A brief description of the design elements is also provided.

Table 1: Dimensions and design elements of product development

Dimension	Design Element	Description
Strategy	Innovation type	Addresses whether gradual improvements of an existing product are made or a completely new product is developed [22]
	Trigger of product development	Addresses the alignment to market pull or technology push [23]
	Design flexibility	Addresses the company's openness to new technologies and product development risks [24,25]
	Innovation openness	Addresses the extent to which a company applies open innovation [26]
	Sourcing strategy	Addresses the extent to which the company outsources tasks and resources [27]
	Portfolio management risk aversion	Addresses whether a company has a lot of large and high-risk projects or smaller and lower-risk projects [28]
Organization	Decision making	Addresses the degree of centrality of decision making [29]
	Development process	Addresses the structure and flexibility of the development process [22]
	Degree of cross-functionality	Addresses the degree of cross-functionality of teams in product development [30]
	Specialization of the employees	Addresses the balance between generalists and specialists in product development [31]
	Customer and supplier integration	Addresses the integration of customer requirements and suppliers into product development [30]
	Senior management involvement	Addresses the extent to which a company's managers are involved in projects and bear personal responsibility [28,32]
	Internal control system	Addresses the internal evaluation of employees and managers in product development [33]
	Training of employees	Addresses the methods used for further training of the employees [21,31]

Dimension	Design Element	Description
Organization	Global presence	Addresses the international diversification of product development [34]
Resources	Knowledge structure	Addresses the structure and storage of knowledge [21,31]
	Resources allocation	Addresses the allocation of personnel, materials and monetary resources in product development [28]
	Resources flexibility	Addresses the sharing or relocating of resources when necessary due to changing circumstances [35]
Product	Product category	Addresses whether the product is developed as an investment product or a consumer product [36]
	Product variety	Addresses the planned number of product variants [37]
	Product modularity	Addresses the degree of modularity of a product [30]
	Design for X	Addresses the determination of the favoured Design for X approach [38]
	No. of units	Addresses the planned number of units to be produced [21]
	Product durability	Addresses the planned durability of a product [21]
	Updateability	Addresses the updateability of products after manufacturing [21]
Project management	Project duration	Addresses the duration of a product development project [28]
	Project selection	Addresses the factors based on which a project is selected [39]
	Upfront feasibility	Addresses the steps that take place before the actual product development begins [40]
	Focus on simulation and testing	Addresses the use of simulations or rapid prototyping methods to test the products [32]

5. Conclusion

Many companies give high significance to efficient performance. However, focusing just on efficient execution makes a company vulnerable to disturbances. Manufacturing companies are realizing the importance of introducing organizational resilience. Therefore, in the context of sustainable management, a company must be prepared for external as well as internal disturbances and position itself effectively in this trade-off between being efficient and being resilient. One of the key aspects to increase organizational resilience is the corporate function of product development.

Since product development is a complex corporate function, it can be described meaningfully using design elements. Design elements provide an overview of the scope of a corporate function that can be aligned by management. Companies can use the design elements to position themselves in the trade-off between conflicting goals. As part of this work, 29 design elements are derived by conducting an extensive literature review. Subsequently, the design elements are clustered into the five major dimensions of strategy, organization, resources, product, and project management. Furthermore, the methodology introduced in this paper for deriving product development design elements holds wider applicability. It can be easily adapted to extract design elements of other corporate functions.

The presented topic is currently being researched as part of a doctoral thesis at the Chair of Production Engineering of the Laboratory for Machine Tools and Production Engineering WZL at RWTH Aachen University. The results of this paper will be applied in industry working groups and consulting projects to ensure their feasibility in industrial applications. The next step is assuring the comprehensiveness of the formulated design elements. For this purpose, interviews are being conducted with experts in the field of product development. In addition, it is essential to operationalize each design element by specifying its key characteristics. In the broader context of enhancing organizational resilience within manufacturing companies, the identification of corporate function goals and the recognition of internal and external disturbances are of paramount significance for strategic orientations. As an integral component of this research endeavour, methodologies are being developed to facilitate the identification of corporate function goals, as well as both internal and external disturbances. Additionally, an approach is under development to determine the interdependencies among corporate function design elements, goals, and disturbances. This holistic framework aims to empower companies with the strategic insights necessary to enhance their resilience while concurrently achieving their corporate goals efficiently.

Acknowledgements

Funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy – EXC-2023 Internet of Production – 390621612.

References

[1] McAloone, T.C., Pigosso, D.C.A., 2017. From Ecodesign to Sustainable Product/Service-Systems: A Journey Through Research Contributions over Recent Decades, in: Stark, R., Seliger, G., Bonvoisin, J. (Eds.), Sustainable manufacturing. Challenges, solutions and implementation perspectives. Springer, Cham, pp. 99–111.

[2] Riesener, M., Kuhn, M., Tittel, J., Schuh, G., 2021. Concept for Enhancing the Contribution of Product Development to Organizational Resilience of Manufacturing Companies, in: 2021 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM). IEEE, Singapore, pp. 1303–1307.

[3] Rodrigues, M., Franco, M., 2023. Green Innovation in Small and Medium-Sized Enterprises (SMEs): A Qualitative Approach. Sustainability 15 (5), 4510.

[4] Corrales-Estrada, A.M., Gómez-Santos, L.L., Bernal-Torres, C.A., Rodriguez-López, J.E., 2021. Sustainability and Resilience Organizational Capabilities to Enhance Business Continuity Management: A Literature Review. Sustainability 13 (15), 8196.

[5] Birkhofer, H. (Ed.), 2011. The Future of Design Methodology. Springer, London.

[6] Shafqat, A., Welo, T., Oehmen, J., Willumsen, P., Wied, M., 2019. Resilience in Product Design and Development Processes: A Risk Management Viewpoint. Procedia CIRP 84, 412–418.

[7] VDI, 2019. VDI 2221 - Part 1. Design of technical products and systems: Model of product design.

[8] Brown, S.L., Eisenhardt, K.M., 1995. Product Development: Past Research, Present Findings, and Future Directions. The Academy of Management Review 20 (2), 343.

[9] Kosiol, E., 1976. Organisation der Unternehmung. Gabler Verlag, 251 pp.

[10] Ponn, J., Lindemann, U., 2011. Konzeptentwicklung und Gestaltung technischer Produkte. Springer, Berlin, 466 pp.

[11] Zrim, G., Maletz, M., Lossack, R., 2006. Experience based cost management in the early stages of product development. DS 36: Proceedings DESIGN 2006, the 9th International Design Conference, Dubrovnik, Croatia, 1569–1576.

[12] Xiao, Y., Watson, M., 2019. Guidance on Conducting a Systematic Literature Review. Journal of Planning Education and Research 39 (1), 93–112.

[13] Browning, T.R., 2001. Applying the design structure matrix to system decomposition and integration problems: a review and new directions. IEEE Transactions on Engineering Management 48 (3), 292–306.

[14] Browning, T.R., 2016. Design Structure Matrix Extensions and Innovations: A Survey and New Opportunities. IEEE Transactions on Engineering Management; 63 (1), 27–52.

[15] Eppinger, S.D., Browning, T.R., 2012. Design structure matrix methods and applications. MIT Press, Cambridge, Mass., 334 pp.

[16] Borjesson, F., Hölttä-Otto, K., 2012. Improved Clustering Algorithm for Design Structure Matrix, in: Proceedings of the ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference - 2012, New York, NY, pp. 921–930.

[17] Idicula, J., 1995. Planning for concurrent engineering, Singapore.

[18] Gutierrez, C.I., 1998. Integration analysis of product architecture to support effective team co-location.

[19] Thebeau, R.E., 2001. Knowledge management of system interfaces and interactions from product development processes, Cambridge.

[20] Universitätsbibliothek der RWTH Aachen, 2023. Datenbank-Infosystem (DBIS): Fachübersicht. https://dbis.ur.de/dbinfo/fachliste.php?bib_id=bthac&lett=l&colors=&ocolors=. Accessed 4 September 2023.

[21] Bender, B., Gericke, K. (Eds.), 2021. Pahl/Beitz Konstruktionslehre: Methoden und Anwendung erfolgreicher Produktentwicklung, 9th ed. Springer, Berlin.

[22] Veryzer, R.W., 1998. Discontinuous Innovation and the New Product Development Process. Journal of Product Innovation Management 15 (4), 304–321.

[23] Mu, J., Thomas, E., Peng, G., Di Benedetto, A., 2017. Strategic orientation and new product development performance: The role of networking capability and networking ability. Industrial Marketing Management 64, 187–201.

[24] Krishnan, V., Bhattacharya, S., 2002. Technology Selection and Commitment in New Product Development: The Role of Uncertainty and Design Flexibility. Management Science 48 (3), 313–327.

[25] Song, M., Noh, J., 2006. Best new product development and management practices in the Korean high-tech industry. Industrial Marketing Management 35 (3), 262–278.

[26] Bahemia, H., Squire, B., 2010. A contingent perspective of open innovation in new product development projects. International Journal of Innovation Management 14 (04), 603–627.

[27] Jiao, J., Simpson, T.W., Siddique, Z., 2007. Product family design and platform-based product development: a state-of-the-art review. J Intell Manuf 18 (1), 5–29.

[28] Cooper, R.G., Kleinschmidt, E.J., 2007. Winning Businesses in Product Development: The Critical Success Factors. Research-Technology Management 50 (3), 52–66.

[29] Muffatto, M., 1999. Introducing a platform strategy in product development. International Journal of Production Economics 60-61, 145–153.

[30] Koufteros, X., Vonderembse, M., Jayaram, J., 2005. Internal and External Integration for Product Development: The Contingency Effects of Uncertainty, Equivocality, and Platform Strategy. Decision Sciences 36 (1), 97–133.

[31] Leonard-Barton, D., 1992. Core Capabilities and Core Rigidities: A Paradox in Managing New Product Development. Strategic Management Journal 13, 111–125.

[32] Hoppmann, J., Rebentisch, E., Dombrowski, U., Zahn, T., 2011. A Framework for Organizing Lean Product Development. Engineering Management Journal 23 (1), 3–15.

[33] Li, Y., Liu, Y., Zhao, Y., 2006. The role of market and entrepreneurship orientation and internal control in the new product development activities of Chinese firms. Industrial Marketing Management 35 (3), 336–347.

[34] Brentani, U. de, Kleinschmidt, E.J., Salomo, S., 2010. Success in Global New Product Development: Impact of Strategy and the Behavioral Environment of the Firm. Journal of Product Innovation Management 27 (2), 143–160.

[35] Tatikonda, M.V., Rosenthal, S.R., 2000. Successful execution of product development projects: Balancing firmness and flexibility in the innovation process. Journal of Operations Management 18 (4), 401–425.

[36] Meißner, M., Gericke, K., Gries, B., Blessing, L., 2005. Eine adaptive Produktentwicklungsmethodik als Beitrag zur Prozessgestaltung in der Produktentwicklung. DFX 2005: Proceedings of the 16th Symposium on Design for X, Neukirchen, Germany, 67–76.

[37] Pero, M., Abdelkafi, N., Sianesi, A., Blecker, T., 2010. A framework for the alignment of new product development and supply chains. Supply Chain Management: An International Journal 15 (2), 115–128.

[38] Lu, B., Zhang, J., Xue, D., Gu, P., 2011. Systematic Lifecycle Design for Sustainable Product Development. Concurrent Engineering 19 (4), 307–324.

[39] Schilling, M.A., Hill, C.W.L., 1998. Managing the new product development process: Strategic imperatives. AMP 12 (3), 67–81.

[40] Pujari, D., 2006. Eco-innovation and new product development: understanding the influences on market performance. Technovation 26 (1), 76–85.

Biography

Dr.-Ing. Michael Riesener (*1986) has been Managing Chief Engineer at the Chair of Production Engineering at the Laboratory for Machine Tools and Production Engineering (WZL) of RWTH Aachen University since 2017. Furthermore, he holds several positions in various entities at RWTH Aachen Campus connecting science and industry.

Dr.-Ing. Maximilian Kuhn (*1991) has been Chief Engineer in the Innovation Management Department at the Chair of Production Engineering at the Laboratory for Machine Tools and Production Engineering (WZL) of RWTH Aachen University since 2021. He is also Managing Director of the Complexity Management Academy and the Innovation Factory Aachen.

Jonas Tittel (*1991) has been Research Associate in the Innovation Management Department at the Chair of Production Engineering at the Laboratory for Machine Tools and Production Engineering (WZL) of RWTH Aachen University since 2018. He is also Group Leader for Complexity Management.

Pawan Singh (*1999) is currently pursuing his M.Sc. in Production Engineering at RWTH Aachen University. He has been working as a Student Research Assistant in the Innovation Management Department at the Chair of Production Engineering at the Laboratory for Machine Tools and Production Engineering (WZL) of RWTH Aachen since 2022.

Prof. Dr.-Ing. Günther Schuh (*1958) has been head of the Chair of Production Engineering at the Laboratory for Machine Tools and Production Engineering (WZL) of RWTH Aachen University since 2002. He is Director of FIR e.V. as well as a Member of the Board of WZL and Fraunhofer IPT. He is also a member of numerous technical-scientific committees and founder and CEO of several start-ups in the field of electro mobility.

5th Conference on Production Systems and Logistics

Towards Enabling Human-Robot Collaboration In Industry: Identification Of Current Implementation Barriers

Johannes C. Bauer[1*], Mohammed-Amine Abdous[2*], Sebastian Kurscheid[1*], Flavien Lucas[2], Guillaume Lozenguez[2], Rüdiger Daub[1]

[1]*Institute for Machine Tools and Industrial Management (iwb), Technical University of Munich, Garching near Munich, Germany*
[2]*IMT Nord Europe, Institut Mines-Télécom, Univ Lille, Center for Digital Systems, Lille, France*
*Authors contributed equally.

Abstract

Human-robot collaboration (HRC) is designed to combine the repeatability and precision of robots with the flexibility and adaptability of human workers. However, despite being researched for several years, HRC applications are still not broadly adopted in the industry. This study aims to identify current barriers to HRC adoption in the industry from a practical perspective. Therefore, a qualitative explorative approach based on semi-structured interviews with knowledgeable industry experts was chosen. The study was conducted in cooperation between IMT Nord Europe and the Technical University of Munich in France and Germany. Thereby, several experts from various backgrounds in areas such as robot manufacturing, system integration, and robot application in manufacturing were interviewed. These interviews are inductively analysed, and the findings are compared to the state-of-the-art in scientific HRC research. The study offers insights into the practical barriers to HRC adoption resulting from the technical, economic, social, and normative dimensions as well as the trade-offs between them. Based on these insights, opportunities for future research are identified.

Keywords

Robotics; Human-robot collaboration; Implementation barriers; Industry survey

1. Introduction

The increasing complexity and rapidly changing demands in the industrial sector have emphasised the need for more efficient and flexible manufacturing systems. The term human-robot collaboration (HRC) describes approaches that combine the strengths of human workers, such as adaptability, flexibility, experience, and problem-solving skills, with the precision and repeatability of robots [1,2]. These systems can support humans when performing physically challenging tasks and simultaneously allow automation in scenarios considered unfeasible previously [3]. Resulting work environments can be more efficient, safer, and more productive [4]. Another motivation for the use of HRC is the opportunity it offers to address skilled labour shortages, e.g., [5].

Generally, HRC applications are divided into three categories based on the spatial delineation of humans and robots [2,6]. In coexistence scenarios, robots and humans may share the same workspace, but not simultaneously. In cooperation scenarios, they stay in the shared workspace at the same time but do not work on the same workpiece. Finally, in collaborative HRC applications, humans and robots also execute tasks on the same workpiece. In this context, the term cobot refers to lightweight robots equipped with additional

DOI: https://doi.org/10.15488/15254
ISSN: 2701-6277

force-torque sensors that are specifically designed to reduce risks of injury. In this work, the term HRC may also involve deploying classical industrial robots in HRC applications or use cases involving mobile robots deployed in presence of humans.

Despite the numerous potentials of HRC, its adoption in the industry is still slow. Various barriers, including technical, economic, social, safety, and organisational factors, have prevented or slowed the implementation of HRC in real-world applications [7]. To help overcome these barriers, this study deploys a qualitative research approach based on semi-structured interviews with experts from industry, to understand existing practical barriers and their underlying causes in more detail and propose directions for further research.

To illustrate our findings, the study is organized as follows. Section 2 discusses related works on the challenges of HRC. The study's methodology is described in Section 3, including data collection and analysis. The derived results are presented in Section 4, including a discussion of their implications. Finally, Section 5 summarises and concludes the paper.

2. Related works

Different challenges to implementing HRC applications have already been identified in scientific literature. In the following, findings of works summarising these challenges are presented at first. Afterwards, studies that already involve industry experts are highlighted.

Authors in [8] conducted a semi-structured literature review to analyse the challenges of HRC implementation, identifying twenty challenges, including initial investment costs, flexibility concerns, scalability issues, and operator training. The identified challenges were then validated by an expert panel. In contrast, [9] review HRC solutions proposed in the literature and summarise open challenges for HRC in five categories. They identify the handling of the systems' overall complexity (1) as essential for adopting HRC in the industry. Due to HRC's safety requirements (2), the technical complexity is further increased. Furthermore, they emphasise that safety does not only have a technical or normative aspect but that the operators' confidence (3) in the system's safety must be considered, too. Finally, the accessibility (4) and flexibility (5) of HRC should be improved, keeping industrial use cases in mind. The emphasis on safety is shared by [10], including the distinction between technical safety and perceived safety by the operator. Standards governing technical safety are continuously evolving. In this context, the high complexity of the environment is a major challenge, especially since it is more difficult for humans to predict the industrial robots' movements, e.g., compared to vacuum cleaner robots with fewer degrees of freedom. Communicating the motions to the operator can improve and increase the operator's confidence in the system's safety. On the other hand, human motion prediction is also a challenge to HRC applications' safety [11]. Moreover, human motion prediction is essential for effective function distribution between humans and robots. Therefore, [11] name safety, effectiveness, and complexity as the main challenges for HRC solutions. In contrast to the previous studies, [12] specifically investigated the challenges of HRC in the shipbuilding industry. Among other things, human unpredictability is highlighted as a challenge. However, industry-specific challenges, such as high load capacity, and general challenges, such as ergonomics, e.g., workers' posture and part weights, during execution, are also identified. Authors in [13] examine the challenges associated with processing and analysing the large volumes of data produced by cyber-physical systems, including those in HRC, underlining the complexity of scheduling tasks within Industry 4.0 contexts. To encapsulate the broader context, [14,3] discuss the application of HRC in various manufacturing processes, noting that the balance of task distribution between humans and robots often depends on specific contexts such as part weight, size, ergonomic considerations, and visibility. This introduces an additional layer of complexity when addressing the challenges in one-way and two-way human-robot collaboration [14].

Shifting the focus to specific aspects of HRC, [15] investigate the economic aspects of HRC line balancing along the dimensions of assembly line characteristics, collaborative assumptions, and methodology. Authors claim that research has focused on linear assembly lines where humans and robots collaborate sequentially rather than in parallel. As mentioned, human unpredictability is a major challenge, resulting in non-deterministic task execution times. One way to counter human unpredictability is to use real-time data acquired via Industry 4.0 networks. It is further pointed out that ergonomic aspects should be considered in an economic analysis. According to [16], identifying universal economic challenges for HRC is particularly difficult due to the significantly varying applications. [17] point out that learning processes used by robots for interacting with humans and different environments may pose a critical aspect to consider when designing and implementing HRC applications. [18] investigate the effect of HRC applications on the involved human workers within a scoping literature review. Considering the categories ergonomics, safety, and productivity, the inseparability of the actual and perceived properties could be shown from a psychological perspective. Therefore, stress, workload, acceptance, trust, and usability should be considered when analysing an application's psychological effects. [19] add the robot's behaviour, the user's self-efficacy, and the operator's experience working in HRC systems as criteria, which were identified via a systematic literature review. In turn, integrating the operator experience into HRC application design and testing is described as the main challenge.

While the previously mentioned studies are mainly based on scientific literature, others already specifically include industry perspectives and therefore focus more on the practical challenges of implementing HRC in industry. In [20] such challenges are identified based on a questionnaire, supplemented by five expert interviews. Challenges are categorized into safety-related, organisational- and process-related, and technical aspects. [21] focus on challenges for small and medium enterprises, incorporating interviews with practitioners from five companies. The main challenges identified are related to safety, performance, strategy, involvement, and training aspects. A case study in a Swedish heavy vehicle manufacturing company using the actor-analysis method is performed by [22]. During this process eleven employees with different roles in the company were interviewed concerning their experience with HRC implementation. Authors conclude that safety-related issues and under-development standardization are the key challenges for HRC adoption. [23] on the other hand focus on risk assessment challenges, conducting multiple expert interviews, followed by a questionnaire. Their fragmentation, complexity, and a lack of validation are listed as the main shortcomings of existing approaches for HRC risk assessment.

To facilitate the practical adoption of HRC, developed methods and solutions must be based on a profound understanding of current implementation barriers. This understanding can only benefit from the inclusion of practical insights. Works like [20,23,21,22] already contribute to this goal. Nevertheless, further studies are necessary to validate and extend previous findings and gather a holistic understanding of underlying phenomena.

3. Methodological approach for identification of barriers to HRC adoption

To investigate what barriers to HRC adoption exist in the industry, an explorative qualitative research design was chosen based on a multiple case study. Semi-structured, in-depth expert interviews served as the primary data source. These interviews were afterwards inductively analysed to yield new insights. Since HRC is not yet broadly adopted in industry and the reasons for this are not fully understood so far, qualitative research is adequate to assess underlying phenomena holistically [24]. Additionally, these phenomena may span a wide range of aspects that are not only technical but may also be economically, socially, or organisationally caused. Case studies are well suited to generate new knowledge about novel topics [25] and answer questions such as *what is happening?*, *how is it happening?*, and *why is it happening?* [26,27]. Multiple case studies usually produce more robust results in this context than a single case study [28].

3.1 Data collection

As mentioned above, we chose to use semi-structured, in-depth interviews with multiple knowledgeable experts from the industry as our primary source of data. Such interviews are a popular technique in qualitative case studies and are used as such in this study [26]. Members of organisations experience occurring phenomena directly and can provide first-hand insights [29]. The experts usually have long and diverse backgrounds in their specific fields. Since it is unlikely that the interviewers will influence multiple experts in the same way, the danger of introducing bias into the study is reduced [28]. Experts from different companies were selected based on their experience and their position. These companies operate in various business fields as robot manufacturers, system integrators, or application users. Furthermore, we did not only focus on scenarios involving stationary robots but also explicitly included experts in the fields of mobile robotics. This allows for an assessment of discrepancies and similarities between these applications. The interviews were conducted in German and French language, and anonymity was assured to all experts. Subsequently, all the recorded contents were accurately translated into English for analysis, maintaining the authenticity and essence of the interviewee's responses. We used an interview guideline to give the interview process a standardised structure. This guideline was iteratively reviewed and improved before the first interview, to avoid leading the witness questions and anticipate related questions that may come up during the interviews [29]. However, following the principles of flexibility and openness, we deviated from it, if appropriate, to react to the experts' interests and knowledge [29]. The full interview guideline can be found in Appendix A.

3.2 Data analysis

The interview analysis was conducted following the systematic approach to inductive analysis developed by [29]. The methodology is based on summarising the content step-by-step into a data structure [29]. First, the interview recordings were systematically assessed and the core messages, hereafter referred to as first-order concepts, were filtered out. In doing so, the semantics used by the informant were retained as far as possible, and a certain distance from the literature was kept to avoid confirmation bias [29]. In the second step, the first-order concepts were grouped into categories. These categories are hereafter referred to as second-order themes. The concepts were compared, examined for similarities and differences, and thus progressively categorised. This process was highly iterative. In the third step, the second-order themes were further grouped into so-called aggregated dimensions. We repeatedly involved feedback from external but knowledgeable colleagues to discover potential misinterpretations and contradictions and to validate our interpretations [30].

4. Results

In the following section, we first give an overview of the expert sample. Afterwards, the findings of the study are presented and discussed.

4.1 Sample characterisation

The sample for this study comprises eleven experts with diverse backgrounds and experiences in the field of HRC. An overview of different aspects describing the sample is provided in Figure 1. Experts' years of experience in the industry range from one to over 25 years, offering a wide variety of perspectives. The companies they represent generate revenue between one and several thousand mil. EUR, emphasising the sample's diversity in terms of company size and financial results. The participants specialise in various focus areas, such as robot manufacturing, system integration, and application usage. This diversity allows for a comprehensive understanding of the barriers to HRC adoption in manufacturing systems. It should be noted, however, that the sample in this case does not claim to be a representative sample of the population, as is the case with quantitative studies. To measure the current importance of HRC in their organisations, the interviewees were asked to rate its relevance on a scale from one (very low) to five (very high). The current relevance of HRC among interviewees varies, with scores ranging from one to five and an average score of 3.6. The experts anticipate a higher relevance of HRC in the future, with scores ranging from three to five and an average score of 4.4, indicating some sort of familiarity with the subject.

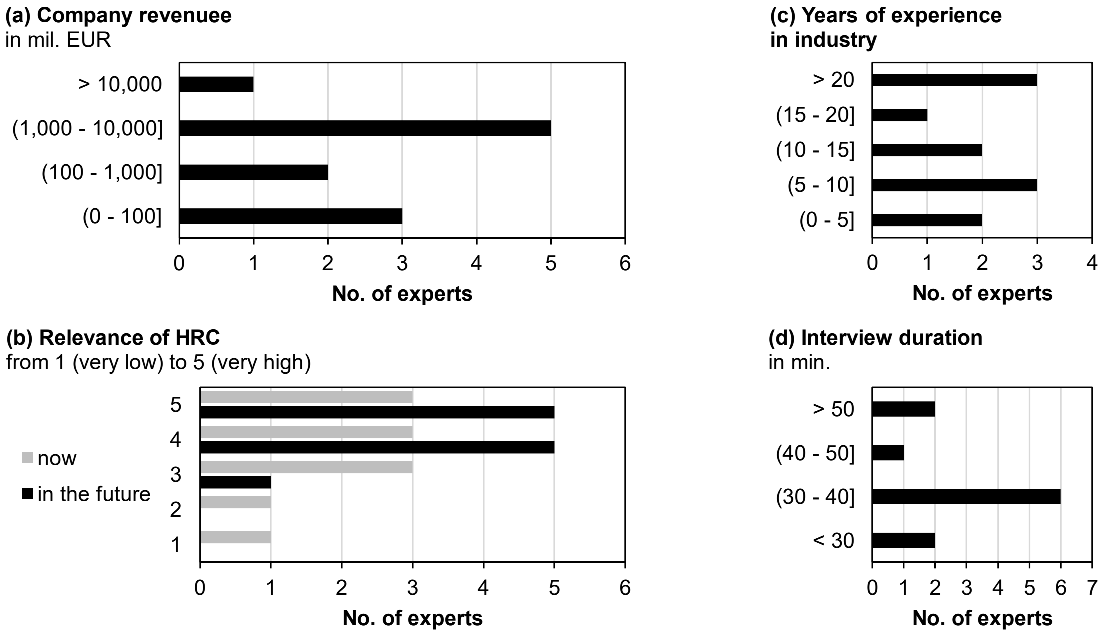


Figure 1: Characterisation of the sample, including company revenue (a), years of experience in industry (b), the duration of the interviews (c), and the perceived relevance of HRC now and in the future (d)

4.2 Presentation of results

In total, 240 first-order concepts were extracted from the interviews and grouped into 23 second-order themes. Based on these 23 second-order themes, four aggregated dimensions could be identified: *1) technical*, *2) economic*, *3) social*, and *4) norms and safety*. All of the second-order themes either specifically address a single dimension or address a relationship between two of the dimensions. No differences could be observed between Germany and France when merging the second-order themes into the four aggregated dimensions. Therefore, the results presented are valid for both countries. In the following, we first report on findings regarding individual dimensions before focusing on their interrelations. A full list of second-order themes and their associated aggregated dimensions is provided in Appendix B.

4.2.1 Aggregated dimensions

Regarding the *technical* dimension, multiple experts reported on the need for HRC applications to be capable of handling complex environments. This requires sensor systems to perceive the environment and adapt the robots' behaviour accordingly.

Second-order themes addressing the *economic* dimension focus on the profitability of HRC applications. While on the one hand, the flexible integration of HRC systems into assembly lines allows for an increase in overall profitability. On the other hand, HRC's higher development costs and efforts, combined with non-deterministic processes during production, often result in an insufficient cost-performance ratio of HRC systems.

“I believe that the foundations have been laid regarding the robots, but now we need an overall view of how to achieve a productive system quickly.” (interview no. 3)

When exploring the *social* dimension, several experts emphasise the importance of acceptance and interaction between human workers and robots. As the robot's autonomy increases, so does the need for appropriate social behaviour since the success of the application may also depend on the workers' perceptions and willingness to collaborate. This includes respecting personal space, using non-verbal cues, and being predictable in its movements. In turn, workers may need additional training to efficiently interact with collaborative robots.

Regarding *norms and safety*, experts perceived the normative landscape as complex and ambiguous, which poses a challenge during the development of HRC applications. Different stakeholders interpret the guidelines differently, and a strict interpretation makes realising HRC applications difficult.

“There are no clean standards here [in Germany] that you can use to develop well and reach your goal quickly.” (interview no. 1)

4.2.2 Interrelations between aggregated dimensions

Most of the second-order themes (14 out of 23) addressed two aggregated dimensions, describing some sort of relationship between them. The following section will focus on these relationships between dimensions.

Technical and *economic* aspects were addressed by four themes. One barrier in this context is that competitive HRC applications are usually technically complex. Required sensors and safety features result in high development efforts, rendering HRC applications less attractive economically. Different experts also stressed the importance of assessing potential use cases’ suitability for an HRC solution. For several use cases, classical industrial robots are better suited, e.g., when short cycle times are necessary or ensuring safety is technically very difficult, e.g., when collaboratively handling objects with sharp edges. This is caused by the robot being stopped when a collision potential between a robot and a human worker is detected and results in non-deterministic cycle times. Therefore, more focus should be put on approaches that specifically avoid collisions rather than reduce their impact. Overall, HRC solutions may benefit from new application and development paradigms.

“The wish was to design the solution as before and then just add HRC to get rid of the protective fences, and that just doesn't work. In fact, you have to look at it holistically [...]. Otherwise, you create facts through the application realisation, which you cannot handle from the HRC point of view.” (interview no. 2)

One of the main reasons for the *technical* complexity of HRC applications was found in *safety* requirements. A coexistence scenario is considered more technically feasible and economically more reasonable than full collaboration. It was also mentioned that safety-certified hardware is usually less powerful, and system intelligence functions are separated from safety functions. This leads to conservative behaviour and frequent stops of the robot.

That cobots often come with intuitive graphical user interfaces is a *technical* aspect that also affects the *social* dimension. That easier programming interfaces make robots more accessible for non-experts is viewed as a benefit.

Two themes have been identified that show the interaction between *safety* and *economic* aspects like performance, adaptability, and flexibility of applications. Safety requirements affect an application’s performance by effectively limiting payload and movement speed and, respectively, cycle times. Consequently, HRC applications cannot always execute a process step profitably. In addition, conservative safety systems ensure worker safety by changing the robot’s trajectory, reducing its speed, or stopping it. The resulting unpredictable cycle times impair the production flow and, consequently, the production line’s economic efficiency.

“The topic of speed also came up with many who had originally planned [an HRC application]. You eventually realise: I can't calculate with the usual accelerations or cycle times if I want to realise HRC.” (interview no. 4)

While the discussed effects may lead a company to decide not to use an HRC application, aspects like adaptability and flexibility may also complicate the development of an HRC application as they increase the system complexity. In turn, it is necessary to unify two complex systems, i.e., the automation of an assembly step and the safety devices. As a result, HRC applications are usually only transferable to another task to a limited extent.

The relationship between the *social* and *economic* dimensions highlights the benefits of improved working conditions for workers in HRC applications. Ergonomic conditions can be improved, and workers may be relieved of strenuous tasks and assigned to higher-value tasks. However, experts also pointed out the current lack of consideration for these aspects in economic evaluation. This may also be due to the fact that there are few metrics to include improved working conditions in economic evaluation.

"We have noticed that these ergonomic aspects are usually not directly taken into account economically. Many companies do not include such aspects in their calculations but instead focus directly on the ROI." (interview no. 2)

The complex *norms* for HRC affect the *social* aspects since the development of such applications depends heavily on specialised experts. Furthermore, it is important to critically evaluate the intersection of *safety* requirements and *social* interaction potential. Although, seamless interaction between humans and cobots is desired, prioritising human worker safety entails strict adherence to established safety regulations to mitigate workplace accidents and injuries. Constructing a secure operating system and adequate human-robot interactions requires considering various parameters, such as risk assessments, safety protocols, user training, and intuitive interfaces.

"The safety aspect is also a stumbling block, as customers want a mobile robot to be very close to humans (for example, at 10 cm), whereas this distance does not comply with the norms and safety standards for this type of solution." (interview no. 10)

In conclusion, the interrelations between the identified dimensions are manifold, and a clear assignment to two individual dimensions is often difficult. Furthermore, a large portion of barriers is due to some kind of trade-off between two or more dimensions, describing features that cannot be completely fulfilled simultaneously.

4.3 Discussion of results

The findings of our study underline aspects presented in the existing literature. These include the high level of technical complexity in HRC applications due to required safety functions and the complexity of the environment [11,10,9]. Barriers in the economic dimension also match those identified in previous studies, like high investment costs for HRC systems, reduced productivity, and non-deterministic cycle times [8,15] or insufficient flexibility and scalability of HRC applications [8,9]. Regarding social aspects, interviewed experts also pointed out the need for training and early integration of users into development processes to increase system acceptance, as mentioned by [19,18]. In the eyes of some experts, however, user acceptance did not represent a significant barrier but rather an aspect that can be well addressed through the mentioned measures. Apart from confirming and extending already identified barriers in the literature, our study also sheds light on the interrelations between different aspects and their trade-offs. Understanding these trade-offs in more detail may play a crucial role in overcoming current implementation barriers for HRC.

We conclude that one of the main barriers to industry application is the insufficient cost-performance ratio of HRC systems, which makes them economically unattractive. The safety requirements can be fulfilled by technical solutions, like integrating sensors or lightweight structures. Still, these increase the system complexity and, therefore, development costs or lead to reduced process speed and payload and therefore reduce a system's productivity. A company's decision is usually based on monetary aspects, and the gained advantages, like the fenceless operation of the robot, may not be enough to compensate for these disadvantages. Furthermore, ergonomic advantages of HRC approaches are usually not included in such monetary calculations [31]. Based on this conclusion, several starting points for research are suggested:

Use case assessment: As individual experts pointed out, HRC solutions are often not competitive when simply substituting a classic robot application. Additionally, in collaborative scenarios, a cobot will not substitute a human worker completely at a particular station. If the automation goal is to actually reduce the required number of human workers for a task, multiple workstations must be addressed. Therefore, the assessment of a use case regarding its suitability for HRC plays a crucial role for successful implementation, as also mentioned by [20]. This also concerns the non-deterministic cycle times of HRC applications.

Collision avoidance: As different experts pointed out, past solutions may have focused too much on reducing the impact of collisions rather than avoiding it. Such active collision avoidance may enable increased robot speeds and payloads. Active collision avoidance strategies can be employed, leveraging advanced technologies such as computer vision and human movement anticipation.

Scalable safety systems: Safety systems that can be easily transferred to another robot application may reduce system complexity and therefore development costs. Such systems should be easy to integrate with the robot and other peripherals. This may also increase the flexibility of an existing system to handle different tasks.

Reduce development efforts: Since a current drawback of HRC solutions is their high development cost, reducing these costs is of great importance. During the study, different approaches were identified. On the one hand, a higher degree of modularisation of components is desirable, e.g., by combining sensors with preconfigured software for analysis. On the other hand, experts also suggested methodical approaches, that may help to structure the development process and reduce the dependency on the experience of HRC experts. Easy programming interfaces and methodologies can contribute to the reduction of development efforts.

5. Conclusion and outlook

To shed light on current barriers to adopting HRC in the industry, a multiple case study based on semi-structured expert interviews was performed. Eleven interviews with experts from France and Germany were conducted and analysed. The identified barriers could be associated with the technical, economic, social, and safety dimensions. We found that many aspects brought up by the experts address interrelations and trade-offs between these dimensions, such as between safety and technical or technical and economic aspects. To advance the adoption of HRC and overcome these barriers, several research and development questions were proposed. These include exploring technical innovations for collision avoidance and safety systems or developing more cost-effective strategies.

By addressing these research directions, future studies and applications can contribute to the effective implementation of HRC in industrial settings. This may unlock the benefits of increased productivity, improved working conditions, and optimised performance. It is crucial to take a holistic approach and consider the multidimensional nature of HRC to realise its full potential.

Acknowledgements

The study presented was carried out as part of the ENABLE-I research project. This project aims to identify the obstacles to the use of HRC applications in industry and to point out new research and development questions for HRC applications in the future. ENABLE-I is funded by the German-French Academy for the Industry of the Future (GFA). Researchers from the IMT Nord-Europe, MINES Paris PSL, and the Technical University of Munich cooperate on the project. The authors thank the GFA for the funding that made the collaboration and this study possible. Furthermore, the authors would like to thank all experts for their participation.

Appendix

A. Interview guideline

---

1. **Professional background**
   - What is your current job or position in your company?
   - Please explain your role and responsibilities.
   - Please report on your professional career (incl. training, apprenticeship etc.).
   - How long have you worked in your current position?
2. **Clarifying the term human-robot collaboration (HRC)**
3. **Experience with HRC applications in past, current, or planned projects**

   3.1. Importance
   - How important is HRC for your company, rated on a scale from 1 to 5 (1 = very low; 5 = very high)?
   - How important will HRC be for your company in the future, rated on a scale from 1 to 5 (1 = very low; 5 = very high)?

   3.2. Specific for HRC users
   - Did you or are you currently planning to realise an HRC application?
   - Which use cases for HRC applications do you know or can imagine?

   3.3. Specific for system integrators
   - Could you report on your typical HRC implementation projects, including workflows?
   - What are the most common HRC applications of your customers?

   3.4. Challenges of HRC implementation
   - Do you have an example of a project where an HRC application was considered, but another solution was selected?
   - If yes: Why did you choose another option?
   - If yes: Which technology/application was selected instead?
   - If yes: Would you decide differently with today's technical and business constraints?
   - If yes: At which point does the current situation differ from the situation of the past?

   3.5. Social factors and staff opinion (planning and workshop staff)
   - What is the attitude of the workforce towards HRC?
   - Did the staff's attitude towards HRC change over the curse of the HRC project execution?
   - Is there a difference in the attitude towards HRC between planning and workshop staff?
   - Is there a difference in the attitude towards HRC in the groups which do work with HRC solutions and those that don't?
4. **Identification of HRC barriers/inhibitors**
   - What barriers to HRC exist?
   - Could you please order the aspects according to their relevance?
5. **Identification of potential future enablers and innovations**
   - Which of the mentioned obstacles or problems must be overcome to use HRC more extensively?
   - Which technologies can be helpful or are a prerequisite?
   - What could be the next innovation leap or game changer, in your opinion?

B. Second-order themes and associated aggregated dimensions

Second-order themes	Technical	Economic	Social	Norms & safety
– Use case suitability assessment	X	X		
– Competitive HRC applications are technically complex	X	X		
– New application and development paradigms required to reach full potential	X	X		
– Increased productivity by collision avoidance	X	X		
– HRC lowers the burden for robot usage	X		X	
– Decreased performance of certified hardware	X			X
– Trade-off between system capability (intelligence) and safety	X			X
– Distinguish coexistence and collaboration	X			X
– Safety as a system complexity driver	X			X
– Capabilities to handle complex environments	X			
– Advantages beyond monetary aspects		X	X	
– Trade-off between performance (speed and payload) and safety		X		X
– Trade-off between adaptability/flexibility and safety		X		X
– Flexible integration into shopfloor		X		
– Higher development costs and efforts		X		
– Cost-performance-ratio insufficient		X		
– Non-deterministic processes (e.g., cycle times and ROI)		X		
– Specific know-how during development required			X	X
– Human safety is imperative for interaction			X	X
– Training for HRC application user			X	
– Data privacy concerns			X	
– No lack of technology enthusiasm			X	
– Complex and ambiguous norms and regulations				X

References

[1] Abdous, M.-A., Delorme, X., Battini, D., 2020. Cobotic assembly line design problem with ergonomics, in: 21st IFIP WG 5.5 Working Conference on Virtual Enterprises Boosting Collaborative Networks 4.0, Valencia, Spain, pp. 573–582.

[2] KUKA, 2023. Human-robot collaboration: Welcome, fellow robot! https://www.kuka.com/en-de/future-production/human-robot-collaboration. Accessed 26 June 2023.

[3] Matheson, E., Minto, R., Zampieri, E.G.G., Faccio, M., Rosati, G., 2019. Human–robot collaboration in manufacturing applications: A review. Robotics 8 (4), 100.

[4] Abdous, M.-A., Delorme, X., Battini, D., Sgarbossa, F., Berger-Douce, S., 2022. Assembly line balancing problem with ergonomics: A new fatigue and recovery model. International Journal of Production Research, 1–14.

[5] Inamura, K., Iwasaki, K., Kunimura, R., Hamasaki, S., Osumi, H., 2023. Investigation of Screw Fastening by Human-Robot Cooperation, in: 2023 IEEE/SICE International Symposium on System Integration (SII). 17-20 Jan. 2023. 2023 IEEE/SICE International Symposium on System Integration (SII), Atlanta, GA, USA. 1/17/2023 - 1/20/2023. IEEE, Piscataway, NJ, pp. 1–6.

[6] Müller, R., Vette, M., Mailahn, O., 2016. Process-oriented task assignment for assembly processes with human-robot interaction. Procedia CIRP 44, 210–215.

[7] Zanchettin, A.M., Ceriani, N.M., Rocco, P., Ding, H., Matthias, B., 2016. Safety in human-robot collaborative manufacturing environments: Metrics and control. IEEE Transactions on Automation Science and Engineering 13 (2), 882–893.

[8] Karuppiah, K., Sankaranarayanan, B., Ali, S.M., Bhalaji, R.K.A., 2022. Decision modeling of the challenges to human-robot collaboration in industrial environment: A real world example of an emerging economy. Flexible Services and Manufacturing Journal.

[9] Othman, U., Yang, E., 2022. An overview of human-robot collaboration in smart manufacturing, in: 27th International Conference on Automation and Computing (ICAC), Bristol, United Kingdom, pp. 1–6.

[10] Kaiser, L., Schlotzhauer, A., Brandstötter, M., 2018. Safety-related risks and opportunities of key design-aspects for industrial human-robot collaboration, in: 3rd International Conference of Interactive Collaborative Robotics (ICR), Leipzig, Germany, pp. 95–104.

[11] Galin, R., Meshcheryakov, R., 2019. Review on human-robot interaction during collaboration in a shared workspace, in: 4th International Conference on Interactive Collaborative Robotics (ICR), Istanbul, Turkey, pp. 63–74.

[12] Zacharaki, N., Dimitropoulos, N., Makris, S., 2022. Challenges in human-robot collaborative assembly in shipbuilding and ship maintenance, repair and conversion (SMRC) industry. Procedia CIRP 106, 120–125.

[13] Parente, M., Figueira, G., Amorim, P., Marques, A., 2020. Production scheduling in the context of Industry 4.0: Review and trends. International Journal of Production Research 58 (17), 5401–5431.

[14] Inkulu, A.K., Bahubalendruni, M.R., Dara, A., K., S., 2022. Challenges and opportunities in human robot collaboration context of Industry 4.0: A state of the art review. Industrial Robot 49 (2), 226–239.

[15] Kheirabadi, M., Keivanpour, S., Chinniah, Y., Frayret, J.M., 2022. A review on collaborative robot assembly line balancing problems. IFAC-PapersOnLine 55 (10), 2779–2784.

[16] Peifer, Y., Weber, M.-A., Jeske, T., Stowasser, S., 2020. Human-robot-collaboration in the context of productivity development and the challenges of its implementation: A case study, in: Conference on Human Factors and Systems Interaction, virtual, pp. 38–44.

[17] Chandrasekaran, B., Conrad, J.M., 2015. Human-robot collaboration: A survey, in: SoutheastCon, Fort Lauderdale, USA, pp. 1–8.

[18] Simone, V. de, Di Pasquale, V., Giubileo, V., Miranda, S., 2022. Human-robot collaboration: An analysis of worker's performance. Procedia Computer Science 200, 1540–1549.

[19] Prati, E., Borsci, S., Peruzzini, M., Pellicciari, M., 2022. A systematic literature review of user experience evaluation scales for human-robot collaboration, in: 29th Global Conference of the International Society of Transdisciplinary Engineering, Cambridge, USA.

[20] Gaede, C., Ranz, F., Hummel, V., Echelmeyer, W., 2018. A study on challenges in the implementation of human-robot collaboration. Journal of engineering, management and operations (1), 29–39.

[21] Schnell, M., Holm, M., 2022. Challenges for Manufacturing SMEs in the Introduction of Collaborative Robots, in: Ng, A.H.C. (Ed.), Sps2022. Proceedings of the 10th Swedish Production Symposium, 1st ed. ed. IOS Press Incorporated, Amsterdam.
[22] Wang, Q., Liu, H., Ore, F., Wang, L., Hauge, J.B., Meijer, S., 2022. Multi-actor perspectives on human robotic collaboration implementation in the heavy automotive manufacturing industry - A Swedish case study. Technology in Society 72, 102165.
[23] Huck, T.P., Münch, N., Hornung, L., Ledermann, C., Wurll, C., 2021. Risk assessment tools for industrial human-robot collaboration: Novel approaches and practical needs. Safety Science 141, 105288.
[24] Morgan, G., Smircich, L., 1980. The case for qualitative research. The Academy of Management Review 5 (4), 491–500.
[25] Eisenhardt, K.M., 1989. Building theories from case study research. The Academy of Management Review 14 (4), 532–550.
[26] Lee, T.W., Mitchell, T.R., Sablynski, C.J., 1999. Qualitative research in organizational and vocational psychology, 1979–1999. Journal of Vocational Behavior 55 (2), 161–187.
[27] Yin, R.K., 1994. Case study research: Design and methods, 2nd ed. Sage, Thousand Oaks, USA.
[28] Eisenhardt, K.M., Graebner, M.E., 2007. Theory building from cases: Opportunities and challenges. Academy of Management Journal 50 (1), 25–32.
[29] Gioia, D.A., Corley, K.G., Hamilton, A.L., 2013. Seeking qualitative rigor in inductive research: Notes on the gioia methodology. Organizational Research Methods 16 (1), 15–31.
[30] Edmondson, A.C., Mcmanus, S.E., 2007. Methodological fit in management field research. Academy of Management Review 32 (4), 1246–1264.
[31] Goggins, R.W., Spielholz, P., Nothstein, G.L., 2008. Estimating the effectiveness of ergonomics interventions through case studies: Implications for predictive cost-benefit analysis. Journal of safety research 39 (3), 339–344.

Biographies

Johannes C. Bauer (*1995) is a research associate at the Institute for Machine Tools and Industrial Management (*iwb*) at the Technical University of Munich. He works in the department Assembly Technologies and Robotics focussing on computer vision methods for industrial robotics and quality monitoring applications.

Mohammed-Amine Abdous (*1992) is an associate professor at the Center for Digital Systems, IMT Nord Europe. A PhD holder in Industrial Engineering from Mines Saint-Etienne and the University of Padova, his primary research interest lies in industrial and manufacturing system design, human factors in manufacturing, and Industry 4.0.

Sebastian Kurscheid (*1997) is a research associate at the Institute for Machine Tools and Industrial Management (*iwb*) at the Technical University of Munich. He works in the department Assembly Technologies and Robotics focusing on the manufacturing industry's sustainability and robot applications in particular.

Flavien Lucas (*1993) is an associate professor at the Center for Digital Systems, IMT Nord Europe. His main research projects focus on combinatorial optimization, explainable AI and logistics.

Guillaume Lozenguez (*1984) got his PhD from the University of Caen Basse-Normandie in 2019 on Distributed Planning Under Uncertainty. His research focuses on applied Decision-Making Processes in Multi-Agent Systems, mainly with approaches based on Markov Chain formalisms. He is Assistant Professor at IMT Nord Europe since 2014.

Rüdiger Daub (*1979) is the holder of the Chair of Production Engineering and Energy Storage Systems at the Technical University of Munich since June 2021. Prof. Dr.-Ing. Rüdiger Daub is also head of the Institute for Machine Tools and Industrial Management (iwb) and of the Fraunhofer Institute for Casting, Composite and Processing Technology (IGCV).

5th Conference on Production Systems and Logistics

A systematic literature review of communications standards in discrete manufacturing

Furkan Ercan[1], Maximilian Bega[1], Bernd Kuhlenkötter[1]
[1]*Chair of Production Systems / Ruhr-University Bochum, Bochum, Germany*

Abstract

Industry 4.0 has a particular emphasis on the data landscape of production facilities. Data is needed to gain essential insights from the production machinery to support operations management in better decision-making or indirectly by feeding decision support systems. Such data is encapsulated in an industrial communication standard to organize in a higher-level ontology. It is challenging for operation technology specialists to have an overview of all those standards because they are numerous. This work contributes a solution to this problem by systematically approaching the literature to give an overview of the industrial communication standards landscape. The method used is a systematic literature review with a backward and forward search consisting of three main phases: 1. keyword-based search on different platforms, 2. abstract screening, and 3. full-text screening. Over 2,100 article abstracts have been parsed systematically to condense it to the most relevant 309 full-text articles. This work presents an overview of the most significant industrial communication standards mentioned in these articles. Several use cases and some brief IT-security-relevant aspects are presented as well.

Keywords: Industry 4.0; communication standards; systematic literature review; ProfiNet; Modbus; MQTT; OPC UA; MTConnect

1. Introduction

Industrial communication standards have seen significant advancements in recent years, with the emergence of Industry 4.0 and the (Industrial) Internet of Things (IIoT). As a result, many communication standards are available for use in industrial manufacturing settings, each with its strengths and weaknesses. This paper aims to compare the most common industrial communication standards comprehensively. By examining each standard's practical applicability and popularity, valuable insights to researchers and practitioners in data-driven manufacturing are offered. The technical details and the distribution of the chosen standard are essential criteria for selection from the plethora of industrial communication standards.

The Open System Interconnection (OSI) reference model provides an essential structure for classifying communication systems. It defines seven different layers. Starting with the physical layer, where electromechanical properties of the interface are described, and ending with the application layer, where the interface to the software application is defined. All standards mentioned in this paper operate at the highest level of abstraction, the application layer. The underlying layers are outside the scope of the industrial communication standards.

2. Related Work

Several other authors have reviewed industrial communication standards. Hasnain and Awais [1] classified wireless IoT protocols and proposed a three-dimensional network design space with battery life, gateway

DOI: https://doi.org/10.15488/15260
ISSN: 2701-6277 publish-Ing.

range, and the device data rate as parameters as a decision aid. They focus their work on wireless protocols. Lata and Kumar [2] classified protocols for an IoT environment based on a five-layer structure from the Internet Protocol for Smart Objects Alliance (IPSO). Additionally, they have provided several examples of IoT-based applications. They conclude their work by stating that several intervening protocols are required to form a holistic IoT architecture. Gericke et al. [3] reviewed communication protocols within a cloud manufacturing environment and sorted protocols into different layers. They analyzed a cloud-based manufacturing system consisting of three communication layers: The first is between a cloud and a server, the second between server and manufacturing units, and the third between the manufacturing units. They provide examples of communication protocols for each of the three layers.

Pliatsios et al. [4] examine protocols in their survey with an extensive focus on security. They give an overview of Supervisory Control and Data Acquisition (SCADA) systems' general architecture, describe communication protocols, discuss security incidents, and review security proposals for critical infrastructure.

The main shortcoming of the above mentioned works is that they do not describe a systematic approach to filter the relevant protocols from the literature corpus. This shortcoming motivated this review.

3. Methodology

For pointing out relevant literature regarding industrial communication standards, the systematic literature research (SLR) approach introduced by Brunton and Thomas [5] was used. Figure 1 shows the search query and illustrates the quantitative results of the literature search (only scientific publications, other sources (e.g. norms) are omitted).

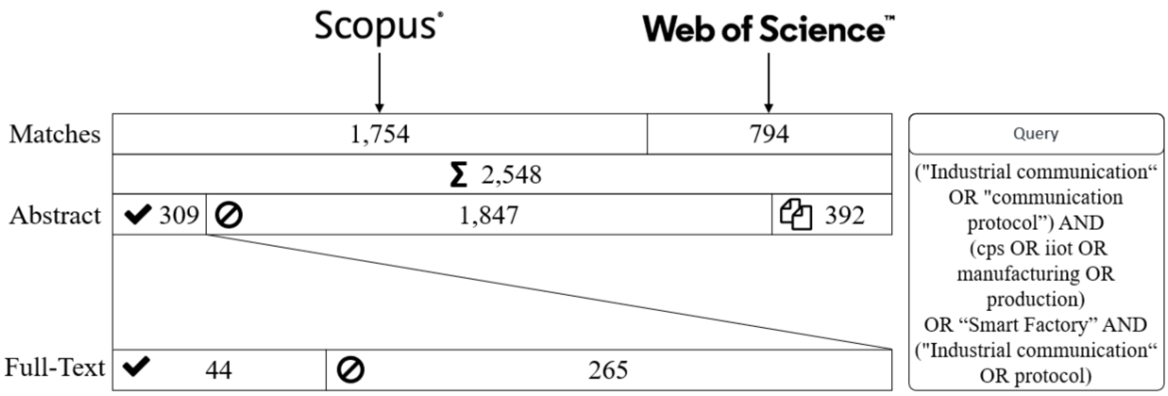


Figure 1: Results of the literature search and the search query

First, broad search queries were defined to gather all publications that treat the application of communication standards within the production environment.

Two scientific databases, Scopus and Web of Science, were searched without any limitations on publication date. All publications up to March 2023 were taken into consideration. Furthermore, only publications in English and German were included. Overall, 2,156 publications were gathered, and double abstract screening for each publication was performed, meaning a publication is only suitable for subsequent full-text review when both reviewers agreed. After directly eliminating 1,847 publications and solving 467 reviewer derivations, 309 publications were included in the full-text review. Finally, the publications were categorized into five standards: MTConnect, MQTT, OPC UA, Modbus, and ProfiNet.

4. Results

In this Chapter, the results of the literature search are shown. Each protocol is introduced, and related use cases are presented.

4.1 MTConnect

MTConnect is a royalty-free, read-only, open-source standard that unifies over 250,000 devices across multiple industries [6]. Its goal is to provide structured, contextual data without a proprietary format by defining a semantic data model and an extensible data dictionary. The standard employs the Hypertext Transfer Protocol (HTTP) as a means of transportation and Extensible Markup Language (XML) as the encoding mechanism. There are three basic building blocks defined in the standard: The device that generates the Data, an agent that provides a representational state transfer (REST) interface, and a client software application [5]. MTConnect is typically used for machine monitoring since it is a read-only protocol.
Numerous use cases of MTConnect are discussed in scientific literature. Lee et al. [7] developed a monitoring system to track the axis positions of a virtual milling machine. This system is similar to the event-based real-time control architecture for tool-tip temperature control of a small-scale CNC prototype machine demonstrated in the work of Subhasish Malik et al. [8], Edrington et al. [9] built a web-based application for general-purpose machine monitoring.

4.2 MQTT

In contrast to MTConnect, MQTT is bi-directional, lightweight, stateful, and standardized by ISO 20922 [10]. By default, it uses the Transmission Control Protocol (TCP) for transmission but can be configured to use non-TCP protocols such as Zigbee, User Datagram Protocol (UDP), or Bluetooth. The architecture of MQTT is based on a client-server and publish-subscribe paradigm (see Figure 2). The MQTT broker is the central access point between clients. The broker is a central node that forwards all messages; clients cannot communicate directly. Several open-source MQTT broker implementations on different platforms exist (for a comparison, see [10]). The communication architecture is shown in Figure 2 Clients subscribe to a specific topic structure, similar to a path in a file system, e.g. "productionfacility/shopfloor/millingmachine/cuttingvelocity/"; a publisher sends the values to the topic, and a subscriber receives the values. A unique feature is that MQTT guarantees a particular quality of service (QoS), which can be chosen between three levels: At level 0, the publisher sends the message once, and no confirmation from the subscriber is expected. At levels 1 and 2, the subscriber must confirm with a 2-part or a 4-part handshake that the message arrived successfully.

Since MQTT lacks a systematic way to represent data, the Eclipse Foundation developed an extension specification to address this issue: SparkPlug [11]. The Eclipse SparkPlug Working Group unified the topic name scheme, data, message types, session management and introduced command messages.

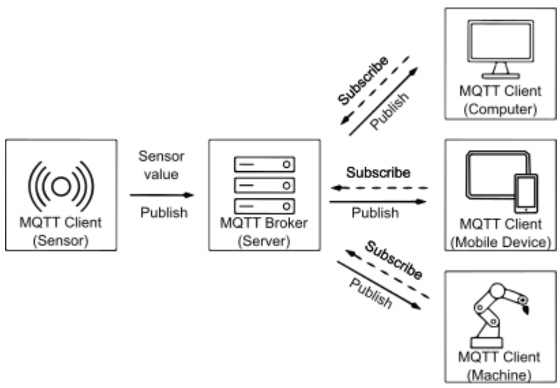


Figure 2: Network architecture of MQTT [7]

The scientific literature highlights various use cases for MQTT. For instance, Salvatierra et al. [12] and Ahmad et al. [13] designed a condition monitoring system for a milling machine. Breuning et al. [14] presented a model-driven approach to aggregate data in production networks with a heterogeneous protocol landscape. Aliev et al. [15] implemented real-time monitoring of critical metrics customized to collaborative and mobile robotics. Bartholet et al. [16] built a multi-protocol bridge that unifies OPC UA and MQTT through a REST Interface. Yeh et al. [17] made a gesture recognition application that employed edge computing to classify gestures and send appropriate requests to a machine via MQTT. Luchian et al. [18] utilized the collaborative IoT framework Coaty to implement field devices and controllers.

4.3 OPC UA

Open Platform Communications Unified Architecture (OPC UA) is an open standard focusing on interoperability, security, extensibility, and reliability [19]. The Reference Architecture Model Industry 4.0 (RAMI 4.0) recommends OPC UA as the only recommended standard in the communication layer [20].

OPC UA provides three different security modes to meet industry standards: "None" for no security, "Sign" for providing authenticity, and "SignAndEncrypt," which provides authenticity and encrypts the data so that it can only be read by the certificate owner [21].

OPC UA provides two communication mechanisms: client-server and publish-subscribe (PubSub) [22]. In the PubSub model, the clients are not directly connected. In both mechanisms, the network type can either be a brokerless model with UDP broadcasts or a broker-based model. The underlying message protocol can be Advanced Message Queuing Protocol (AMQP) or MQTT.

In a client-server structure, a server implements a set of services and exposes them to a client. The client can then invoke these services. The services are organized into several sets [23]. In addition to services, servers have objects accessible from the address space in various formats. Address spaces structure data systematically so that information models can be used. The data itself can be defined in different encodings (binary, Extensible Markup Language (XML), or JavaScript Object Notation (JSON)). Information models are extending OPC from a communication standard to a shared infrastructure model that facilitates information exchange in a standardized way across all industrial domains and information hierarchies.

The OPC specifications define a basic information model, which is extended by domain-specific information models (e.g. [24]) and standard mappings (e.g. [25]) in the Companion Specifications.

OPC UA consists of an information model that defines the structure and organization of data, a communication model between endpoints, and an extensible conformance model for semantic interoperability.

Numerous OPC use cases are outlined in the literature. For example, Wang et al. [26] proposed a versatile and integrated architecture for the Industrial Internet of Things. Steininger et al. [27] developed a data acquisition system for an experimental deep-drilling setup. Bennulf et al. [28] created a plug-and-produce system that automatically detects and configures the added resources and parts, utilizing OPC UA for communication between system parts. In the mold industry, Martins et al. [29] developed a standardized method for monitoring CNC data, and Kong et al. [30] utilized algorithms to evaluate machine statuses and improve machine utilization. Additionally, Cavalieri and colleagues [31] implemented a platform for accessing OPC UA Servers via the Internet, while Park et al. [32] designed a gateway for legacy equipment.

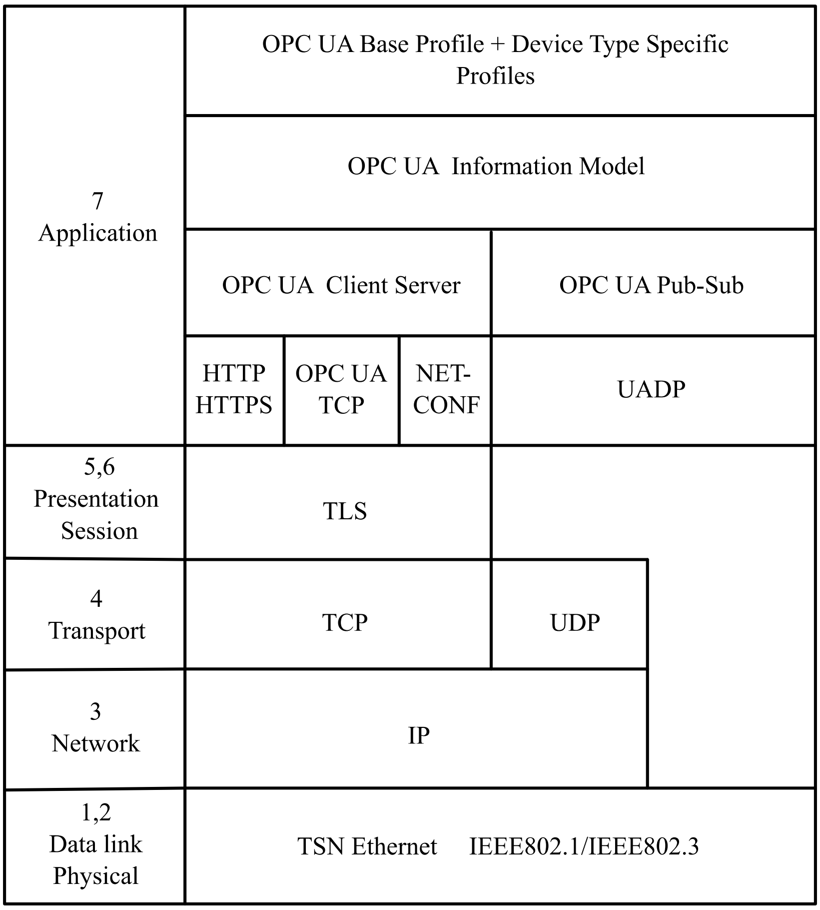


Figure 3: Mapping of OPC UA components to ISO/OSI layers. [33]

4.4 ProfiNet

ProfiNet is an industrial Ethernet standard from the German ProfiBus and ProfiNet International interest group. Devices are classified into three classes: an IO-controller (e.g. Programmable Logic Controller (PLC)), an IO device providing the in-output signals to the process, and an IO-supervisor for configuring the IO-Devices (e.g. a human-machine interface). [34]. A specific file called Generic Station Description (GSD) is provided to ease the configuration process. It is an XML file containing the properties and functions of ProfiNet devices. A GSD file is helpful for virtual facility planning and configuration [35]. An even easier way to configure ProfiNet Devices is described by Duerkop et al. [36], who developed an auto-configurable automation system.

ProfiNet offers several levels of performance. Component-based automation (ProfiNet CBA) provides bus cycle times of 50-100ms with off-the-shelf commercial equipment; for a performance analysis, see [37,38].

In the literature ProfiNet is used in different scenarios. Ionescu et al. designed an autonomous robotic system with a PLC. They use ProfiNet to control and connect the flexible cell to the manufacturing line [39]. A condition monitoring system for rotating machines using ProfiNet is presented by Dias et al. [40].

4.5 Modbus

Even though OPC UA is a modern industrial communication standard, it is not as widely implemented as Modbus [41]. Modbus was developed by Modicon (now Schneider Electric) in 1979 and is independent of the physical interface. Implementations via ZigBee [42], RS485 [43], and virtually in Matlab Simulink [44] are existing. The protocol structure consists of a 1-byte address field, a 1-byte function field, a variable data field, and a 2-byte error check field [45]. The possible function codes for the function field are defined by the Modbus Organization [41].

The most common variants are Modbus Remote Terminal Unit (RTU), Modbus American Standard Code for Information Interchange (ASCII), Modbus Transmission Control Protocol (TCP), and Modbus Plus. Modbus RTU is a binary serial protocol commonly utilized in legacy systems. On the other hand, Modbus ASCII is a serial communication protocol that uses ASCII characters to represent data and is less widely used than Modbus RTU. Meanwhile, Modbus TCP is a request/reply protocol that operates via Ethernet using the Transmission Control Protocol (TCP). It is the most recent variant of Modbus.

Within the scientific literature, Modbus is used for several application scenarios. For instance, Cheng et al. [43] successfully implemented condition monitoring for a wire drawing process using Modbus TCP. Cena et al. [44] developed a Modbus extension for distributed embedded systems by optimizing the protocol's address space size, bandwidth allocation, and handover between masters. Li and Zhong [45] created a gateway between Profibus and Modbus in an aluminum-roasting drought system. Zagan and Găitan [46] measured the performance of Modbus and designed an extension to improve the communication times and dataflow.

5. Discussion

5.1 IT-Security Aspects

Historically grown industrial communication infrastructure is still operated under the assumption that machine and shopfloor communication takes place in isolation from the internet. Due to the advancing networking of the IT- and operation technology infrastructure of a manufacturing company, cybersecurity in industrial networks is decreasing [46,47]. To achieve the full extent of capabilities that are provided by industry 4.0 technologies, the issues surrounding cybersecurity need to be addressed [48] - especially because IIoT devices in their default settings have a higher focus on usability and user experience than on security [49]. Because of its increasing relevance, this article also shortly addresses the topic of cybersecurity. In the following, a selection of different approaches is presented.

Wang et al. [46] described two possible approaches to increase the security of industrial communication standards. First, the addition of cryptographic security mechanisms to the standard itself. Second, the application of an additional encryption protocol such as Transport Layer Security (TLS) or Secure Sockets Layer (SSL). The authors applied this encryption protocol to the Modbus TCP communication standard on a computer platform.

Another Modbus TCP-focused approach used two gateway modules to realize bidirectional data transfer between PLCs and Servers. This concept can be used in legacy systems without a provider dependency [50].

Bienhaus et al. [51] mentioned the use of TLS in combination with MQTT and OPC UA. They integrated TLS and OPC UA in the Trusted Platform Module (TPM) 2.0 framework. Whereas TLS enabled authentication, authorization, cryptography, encryption, and integrity protection, TPM 2.0 was integrated to provide the secure management of cryptographic keys.

However, two contributions focusing on MQTT pointed out that TLS cannot be appropriately used in the Internet of Things due to the limited computing capacity and resources of IoT devices - more lightweight encryption standards are needed [49,52]. Boppana et al. [49] emphasized the danger of man-in-the-middle (MITM) and cross-site scripting (XSS) attacks on IoT devices that use MQTT under default settings. Generally, Kant [53] presented a comprehensive analysis of the cybersecurity of the MQTT communication standard.

Regarding the default security settings in IoT devices, Kohnhäuser et al. [54] addressed this issue in OPC UA – they provided a holistic assessment of existing OPC UA-related secure device provisioning solutions due to the high expected longevity of CPPS. Finally, Paul et al. [55] already consider the computational power of quantum computing and developing a corresponding mechanism in the context of OPC UA.

5.2 Conclusion

This paper describes current industrial communication standards with relevant use cases. It covers the broad landscape of the subject through the systematic approach to literature. The findings show that OPC UA is the most mentioned standard, which can be argued to be due to its complexity and the underlying (extensible) information model. Furthermore, it can be stated that all included standards are Ethernet-based. Ethernet-based standards can run on the same infrastructure as the already existing enterprise IT infrastructure. In most cases, off-the-shelf networking components can connect the operation technology (OT) architecture to the IT architecture. This makes them very popular.

The use cases mentioned can be considered as recommendations for standard usage. Generally, OPC UA is the most suitable standard for modern production infrastructure due to its flexibility and speed of configuration. For smaller setups, MQTT is well-suited. Its topic structure makes it easy to organize information, and multiple open-source implementations on different platforms simplify customization.

A table with decisive properties of the mentioned communication standards for use in an industrial environment with a manufacturing context is summarized in Table 1.

Table 1: Overview of the mentioned standards

Criteria	*MTConnect*	*MQTT*	*OPC UA*	*Modbus TCP*	*ProfiNet*
Application Layer Protocol	HTTP	HTTP, Zigbee, etc.	HTTP, UADP, custom	custom	TCP, UDP,
Realtime capable	yes	yes	yes (config dependent)	no	yes (config dependent)
Speed	high	high	high	low	high
Information model	no	yes (by extension)	yes	no	no
Secure Communication	yes	yes	yes	yes (optional)	yes
Encoding	XML	custom	XML, custom	ASCII, custom	custom

As an outlook for future work, comparing the distribution of protocols in the literature with their actual usage in the field is interesting. Although many organizations claim industrial use of their protocols, no independent organization provides usage data.

Acknowledgments

The project "WIN4KMU" (grant number EFO 0015B-E) is funded by the Ministry of Economics, Innovation, Digitalization, and Energy of the State of North Rhine-Westphalia (MWIDE).

References

[1] Kashif, H., Khan, M.N., Awais, Q. Selection of Network Protocols for Internet of Things Applications: A Review, 359–362.

[2] Lata, N., Kumar, R. Internet of Things: A Review of Architecture and Protocols, 1027–1031.

[3] Gericke, G.A., Vermaak, H., Kurakose, R.B. Communication Protocol Review for SMART Manufacturing Units within a Cloud Manufacturing Environment, 1–6.

[4] Pliatsios, D., Sarigiannidis, P., Lagkas, T., Sarigiannidis, A.G., 2020. A Survey on SCADA Systems: Secure Protocols, Incidents, Threats and Tactics. IEEE Commun. Surv. Tutorials 22 (3), 1942–1976.

[5] Gough, D., Oliver, S., Thomas, J., 2017. An introduction to systematic reviews, 2nd edition ed. Sage, Los Angeles, London, New Delhi, Singapore, Washington, DC, Melbourne, 331 pp.

[6] AMT - The Association for Manufacturing Technology. MTConnect Standard: Part 1.0 - Fundamentals.

[7] Lee, K.B., Song, E.Y., Gu, P.S., 2012. A Sensor Model for Enhancement of Manufacturing Equipment Data Interoperability. ASME International Mechanical Engineering Congress and Exposition.

[8] Malik, S., Bedillion, M.D. Event-Based Temperature Control for Machining Using MTConnect, 629–637.

[9] Edrington, B., Zhao, B., Hansel, A., Mori, M., Fujishima, M., 2014. Machine Monitoring System Based on MTConnect Technology. Procedia CIRP.

[10] ISO/IEC, 2016. Information technology — Message Queuing Telemetry Transport (MQTT) 35.100.70 Application layer.

[11] Eclipse Foundation. Sparkplug™ Specification.

[12] Salvatierra, N., 2021. Cloud Condition Monitoring Platform for Steel Rolling Mill Machines. IEEE Latin-American Conference on Communications.

[13] Ahmad, M.I., Saif, Y., Yusof, Y., Daud, M.E., Latif, K., Kadir, A.Z.A., 2022. A case study: monitoring and inspection based on IoT for milling process. Int J Adv Manuf Technol.

[14] Breunig, D.A., Schneider, M., 2019. Multi-protocol Data Aggregation and Acquisition for Distributed Control Systems. Procedia CIRP.

[15] Aliev, K., Antonelli, D., Awouda, A., Chiabert, P., 2019. Key Performance Indicators Integrating Collaborative and Mobile Robots in the Factory Networks.

[16] Bartholet, M., Überall, C., 2020. Multi-protocol bridge generation for M2M communication using MQTT. Journal of Physics: Conference Series.

[17] Yeh, C.-S.-L., 2021. Implementation of MQTT protocol based network architecture for smart factory. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture.

[18] Luchian, R.-A., Stamatescu, G., Stamatescu, I., Fagarasan, I., Popescu, D., 2021. IIoT Decentralized System Monitoring for Smart Industry Applications. 29th Mediterranean Conference on Control and Automation.

[19] IEC, 2015. OPC Unified Architecture, 1st ed. 25.040.40. doi:10.31030/2346272.

[20] VDI Verein Deutscher Ingenieure e.V., ZVEI – German Electrical and Electronic, 2015. Reference Architecture Model Industrie 4.0 (RAMI4.0).

[21] OPC Foundation. OPC 10000-2 UA Part 2: Security. https://reference.opcfoundation.org/Core/Part2/v104/docs/#4.8.

[22] OPC Foundation. OPC 10000-1: UA Part 1: Overview and Concepts: 5.2 General.

[23] OPC Foundation. OPC 10000-4: UA Part 4: Services: 4.1 Service Set model, 1st ed.

[24] OPC Foundation. OPC 30200 Commercial Kitchen Equipment. Accessed 27 July 2023.

[25] OPC Foundation. OPC 30140 Profinet. Accessed 27 July 2023.

[26] Wang, R., S.ShiZ.Meng, W., 2022. An interoperable and flat Industrial Internet of Things architecture for low latency data collection in manufacturing systems. Journal of Systems Architecture.

[27] Steininger, A., Bleicher, F., 2019. In-process monitoring and analysis of whirling motions in boring and trepanning association deep drilling. MM SCIENCE JOURNAL.

[28] Bennulf, M., Danielsson, F., Svensson, B., 2019. Identification of resources and parts in a Plug and Produce system using OPC UA. Procedia Manufacturing.

[29] Martins, A., Lucas, J., Costelha, H., Neves, C., 2021. Developing an OPC UA Server for CNC Machines. Procedia Computer Science.

[30] Kong, C., Liu, W., Niu, Q., Zhou, X., 2019. Research on Data Acquisition and Analysis of CNC Machine Tool in Smart Factory. Advances in Transdisciplinary Engineering.

[31] Cavalieri, S., Salafia, M.G., Scroppo, M.S., 2019. Integrating OPC UA with web technologies to enhance interoperability. Computer Standards & Interfaces.

[32] Park, H.M.J., 2019. OPC UA based universal edge gateway for legacy equipment. IEEE International Conference on Industrial Informatics (INDIN).

[33] Bruckner, D., Stanica, M.-P., Blair, R., Schriegel, S., Kehrer, S., Seewald, M., Sauter, T., 2019. An Introduction to OPC UA TSN for Industrial Communication Systems. Proc. IEEE 107 (6), 1121–1131.

[34] Neumann, P., Pöschmann, A., 2005. Ethernet-based real-time communications with PROFINET IO.

[35] Bogdan M. Wilamowski and J. David Irwin. The Industrial Electronics Handbook. Second Edition: Industrial Communication Systems.

[36] Duerkop, L., Trsek, H., Jasperneite, J., Wisniewski, L. Towards autoconfiguration of industrial automation systems: A case study using Profinet IO, 1–8.

[37] Dias, A.L., Sestito, G.S., Brandao, D., 2017. Performance Analysis of Profibus DP and Profinet in a Motion Control Application. J Control Autom Electr Syst 28 (1), 86–93.

[38] Ferrari, P., Flammini, A., Vitturi, S., 2006. Performance analysis of PROFINET networks. Computer Standards & Interfaces 28 (4), 369–385.

[39] Ionescu, D., Filipescu, A., Simion, G., Mincă, E., Cernega, D., Șolea, R., Filipescu, A., 2022. Communication and Control of an Assembly, Disassembly and Repair Flexible Manufacturing Technology on a Mechatronics Line Assisted by an Autonomous Robotic System. Inventions 7 (2), 43.

[40] Dias, A.L., Turcato, A.C., Sestito, G.S., Brandao, D., Nicoletti, R., 2021. A cloud-based condition monitoring system for fault detection in rotating machines using PROFINET process data. Computers in Industry 126, 103394.

[41] Modbus Organization Inc., 2012. Modbus Application Protocol Specification, 1st ed.

[42] Zheng, Y. An active transmission ModBus protocol based on Zigbee.

[43] Zhang, B., Hu, S. Design and Implementation of Intelligent Acquisition Terminal Based on Modbus.

[44] Chattha, H.A., G.KhanA. Q.Abid, M., 2021. Implementation of Cyber-Physical Systems with Modbus Communication for Security Studies. 2021 International Conference on Cyber Warfare and Security, ICCWS 2021 - Proceedings.

[45] Modbus Organization Inc., 24.10.06. MODBUS Messaging on TCP/IP Implementation Guide, 1st ed.

[46] Jingran, W., Mingzhe, L., Aidong, X., Bo, H., Xiaojia, H., Xiufang, Z., 2020. Research and Implementation of Secure Industrial Communication Protocols. Proceedings of 2020 IEEE International Conference on Artificial Intelligence and Information Systems, ICAIIS 2020.

[47] Pliatsios, D., 2020. A Survey on SCADA Systems: Secure Protocols, Incidents, Threats and Tactics. IEEE Communications Surveys and Tutorials.

[48] Mourtzis, D., 2019. Mapping vulnerabilities in the industrial internet of things landscape. Procedia CIRP.

[49] Boppana, T.K., 2022. Security risks in MQTT-based Industrial IoT Applications. 2022 IEEE International Conference on Omni-Layer Intelligent Systems, COINS 2022.

[50] Rajesh, L., 2020. Security vulnerabilities of scada communication protocols. International Journal of Scientific and Technology Research.

[51] Bienhaus, D., Jäger, L., Rieke, R., Krauß, C., 2020. Gateway for Industrial Cyber-Physical Systems with Hardware-Based Trust Anchors.

[52] Dinculeană, D., Cheng, X., 2019. Vulnerabilities and Limitations of MQTT Protocol Used between IoT Devices. Applied Sciences.

[53] Kant, D., 2021. Analysis of IoT security risks based on the exposure of the MQTT Protocol. IS and T International Symposium on Electronic Imaging Science and Technology.

[54] Kohnhauser, F., Meier, D., Patzer, F., Finster, S., 2021. On the Security of IIoT Deployments: An Investigation of Secure Provisioning Solutions for OPC UA. IEEE Access.

[55] Paul, S., 2020. Hybrid OPC UA: Enabling Post-Quantum Security for the Industrial Internet of Things. IEEE International Conference on Emerging Technologies and Factory Automation.

Biographies

Furkan Ercan (*1992) is a scientific associate at the Chair of Production Systems (LPS) at the Ruhr-Universität Bochum. His research interests include Industry 4.0, simulation, production planning, and machine learning.

Maximilian Bega (*1995) is a scientific associate at the Chair of Production Systems (LPS) at the Ruhr-Universität Bochum. His research interests include Industry 4.0, IT security, machining, and resilient production systems.

Bernd Kuhlenkötter (*1971) was responsible for product management and technology at ABB Robotics Germany until 2009. In 2009, Bernd Kuhlenkötter took over the professorship for "Industrial Robotics and Production Automation" at the Technical University of Dortmund. Univ. Prof. Dr.-Ing. Bernd Kuhlenkötter has held the professorship for "Production Systems" at the Ruhr University Bochum since 2015.

5th Conference on Production Systems and Logistics

Conceptualizing A Digital Twin Based On The Asset Administration Shell For The Implementation Of Use Case Specific Digital Services

Henry Himmelstoss[1], Roland Hall[1], Bernd Vojanec[2], Paul Thieme[1], Thomas Bauernhansl[1,3]

[1] *Fraunhofer Institute for Manufacturing Engineering and Automation IPA, Nobelstraße 12, 70569 Stuttgart, Germany*
[2] *Wittenstein SE, Walter-Wittenstein-Str. 1, 97999 Igersheim, Germany*
[3] *Institute of Industrial Manufacturing and Management, University of Stuttgart, Allmandring 35, 70569 Stuttgart, Germany*

Abstract

In the context of ongoing digitalization, manufacturing companies face new challenges and the need to expand their portfolios to include new digital services. Enriching their portfolio with digital services can be an opportunity for manufacturing companies to position themselves in emerging collaborative production networks and thus make their business model fit for the future. The paper ties in with the activities from the Product Lifecycle Enrichment as a Service (PLCEaaS) research project. Within this context, use cases for digital services have already been derived, modelled, and documented in various workshops. The respective digital services directly address external customers and internal stakeholders from development. The central enabler for the new digital services is the digital twin based on the asset administration shell, which makes the necessary data available and thus supports interoperability. The asset administration shell is enriched with use case-specific submodels. The procedure for structuring these submodels is shown in this paper using the research project as an example. This includes modelling the digital services with a standardized modelling language based on the semi-structured use cases described so far. As a result, we obtain an asset administration shell enriched with several submodels - some of which may be based on standardization activities already underway or represent proprietary submodels. Likewise, it is considered whether more submodels are required to implement the domain-specific use cases that are currently not yet addressed in standardization activities. The paper ends with an outlook on the further research activities that are necessary to prototype the planned project and describes which criteria can be used to evaluate the defined submodels in the later course of the project.

Keywords

Digital Twin; Asset Administration Shell; Smart Service; Digital Manufacturing; Industry 4.0

1. Introduction

The ongoing digital transformation is also changing the engineering industry and should be understood as a process that operates at different levels through the use of various technologies and concepts. New possibilities are now available for gathering product data along the life cycle of a product. The digital twin (DT) [1] supports this because it can integrate the physical and virtual data throughout the product lifecycle. The DT is increasingly emphasized by both academia and industry. The lifecycle data can be used for various types of analytical methods, for example, to optimize the performance of physical products or processes [2]. The DT can be used to tackle the challenges of information islands and duplicate data between different

DOI: https://doi.org/10.15488/15285
ISSN: 2701-6277
publish-Ing.

phases of the product lifecycle. Therefore it has high potential in product design, manufacturing, and product service [3]. Early definitions characterize DT as a set of virtual constructs that describe a product – actual or virtual – in different levels of detail. It includes the use of operational states from sensor data or from predicting models for a variety of purposes [4]. The DT therefore ties information of physical and virtual products together [5]. Since the project described in this paper relies on a digital twin based on the asset administration shell (AAS), the digital twin is defined as a digital representation sufficient to meet the requirements of a set of use cases. The AAS, in turn, is the standardized digital representation of an asset that enables interoperability between applications and the management of manufacturing systems. Assets represented by it are uniquely identifiable, contain various digital models – called submodels – and describe the functionality of the assets [6]. It characterizes the technological attributes of an asset, central to the Reference Architectural Model for Industry 4.0, often referred to as RAMI 4.0 [7].

This paper builds on a functional service model created without a standard modelling method. To obtain this functional model, we built on an abstract idea for servitising an existing business model of a component manufacturer. This abstract idea arose from a business opportunity addressed as part of a research project, which in turn, is exploring new manifestations of everything-as-a-service approaches. To sharpen the abstract idea of services, the component manufacturer's product life cycle was examined. Subsequently, user stories were created for the respective stakeholders, who could be external customers or internal employees, depending on the service. For the user stories, word templates were used for systematic elaboration. To prioritize the user needs expressed by the user stories and the service functionalities, the quality function deployment (QFD) method was applied. For this purpose, the user stories were first weighted in a pairwise comparison. The services' functionalities were defined as precisely as possible by various domain experts. Next, the correlation of the customer's voice in the form of the weighted user story was correlated with functionality by asking, for each comparison, what effect does the fulfilment of service functionality X have on user need Y? The result is the prioritization of service functionalities for further elaboration. Afunctional model was developed with an online tool that enables a collaborative work mode with the simultaneous participation of each team member.

In this paper, we present a procedure from the defined service idea to the actual data model of the digital twin. This does not include its validation or implementation in the service, as this represents a later step in the research project. We thus address the research question: How to model the data model for the digital twin based on the AAS for a use case-specific service?

2. Need for a procedure for creating a digital twin

According to the aforementioned definition of the DT, meeting the requirements of use cases is a central point determining its overall quality and meaningfulness. One can proceed by deriving the DT data model based on an already existing use case or by first deriving a data model and then validating it against the use case requirements. In this research project, we decided to first model the use cases in digital services in using an iterative and systematic approach. The Industrial Digital Twin Association e. V. has published a guideline for creating a submodel template. One of the topics addressed is that different stakeholders and experts should be involved in creating a submodel template. In this project, research team also consists of experts from different domains. However, the guideline does not address how to build the AAS with the necessary submodels for specific use cases - this includes the creation of proprietary submodels or the selection of existing submodels [8]. Liu et al. also describe the problem that despite the long existence of the DT terminology, in addition to the lack of a unified definition, there is also no unified creation and deployment process [9]. Regarding the DT product-service systems, Bertoni indicates that research projects often focus on the development of standalone applications. Also, the focus is often on the development of frameworks and methods rather than on models, tools, or algorithms. Bertoni explicitly poses the research question of how virtual product models and the DT should be developed as a link between the real and virtual worlds to support decision-making in the early design stages [10]. There is already work on the automatic generation of AAS by using neural language models. However, this approach requires that there are already information sources whose contents can be mapped into standardized submodels of the AAS [11]. Also described is that there remains a poor understanding of what data should be collected from the usage phase of product-service systems (PSS) that can be used to design better PSS [12]. Lack of knowledge about the data to be collected inevitably leads to lack of knowledge about the data structure of a DT and the properties to be contained in it.

Acatech, the German Academy of Engineering Sciences, addresses further specific research needs. Primary research needs have been defined, such as knowledge provision based on feedback information from earlier product generations or approaches to knowledge generation from product usage data for new requirements specifications [13]. Later, operational data usage was addressed associated with the DT to optimize or develop systems. It was noted that implementation and use in practice, however, is still very much in its early stages [14]. In this research project, services are also being worked on to support the data-based optimization of product sizing and the development of products. For such use cases, it has also already been described that AAS, in particular, is a possible technology as a manifestation of DT [15].

We present our process to address challenges like the ones mentioned. By presenting our procedure, we want to share our approach for a systematic derivation of the DT. In our research project, the DT is based on the AAS. Hence it concludes that this is a matter of systematically deriving the data model and composing it from different submodels of the AAS. This is also intended to address the gap between the functional view of a defined use case and a potentially standardized modelling DT to enable that very use case. As mentioned before, meeting requirements for a digital representation is central to our used definition of a digital twin. Therefore, our approach is strongly driven by requirements engineering and by the related aspects to model a use case as holistically as possible [16]. The modeling of the submodels also depends in particular on the type of asset, the lifecycle and the deployment scenario [17]. With regard to the metamodel, it should become clear, among other things, which submodels are necessary, what its properties are or whether the asset is a type or an instance.

3. Modelling of the use cases

The procedure described in the following is based on functional use case descriptions. However, regarding data structure and flow, these use case descriptions still represent black boxes. The goal of the modelling was to move from this black box approach to a detailed view creating a deeper detailed understanding of the services. The Unified Modelling Language (UML) was chosen because it is internationally established as a uniform modelling language for information systems and is, thus, considered an adequate tool for the research group, which consists of experts from different domains [18].

The modelling of the services consists of three parts. First, the system structure is addressed. The system is modelled together with all components relevant for implementing the use case - corresponding to a Tier 3 architecture. The AAS functions here as an access layer that, for the prototypical implementation, references the operating data in a separate database and already contains the catalogue data of the components. In the future, it is also possible to reference data in other data sources or carry additional information. Thus, the structure and relationships of the components are documented and readable. The component diagram already contains all components that are important for the project's various services. Figure 1 shows an illustration of the component diagram in which the Tier 3 architecture for the services was designed.

The respective services were modelled separately. Only the relevant components were transferred in sequence diagrams in the next step. The sequence diagrams reveal the mutual interactions between components and the services' functionalities. This shows which procedures use the AAS. If applicable, it should also be made clear which functions are called up via the AAS or which information is retrieved from it. Figure 2 illustrates a sequence diagram describing the processes of "Innovation-as.-a-Service".

Last, but not least, the services are modelled in class diagrams. They are particularly valuable for modelling the objects relevant for the service together with their attributes and for defining the relationships between the objects. From them, it should be evident which properties must be included in the data model DT. In the use case considered here, the data relevant for the following evaluations is collected in a targeted manner. However, a broader database may also be available, and an explorative approach to a project can be pursued.

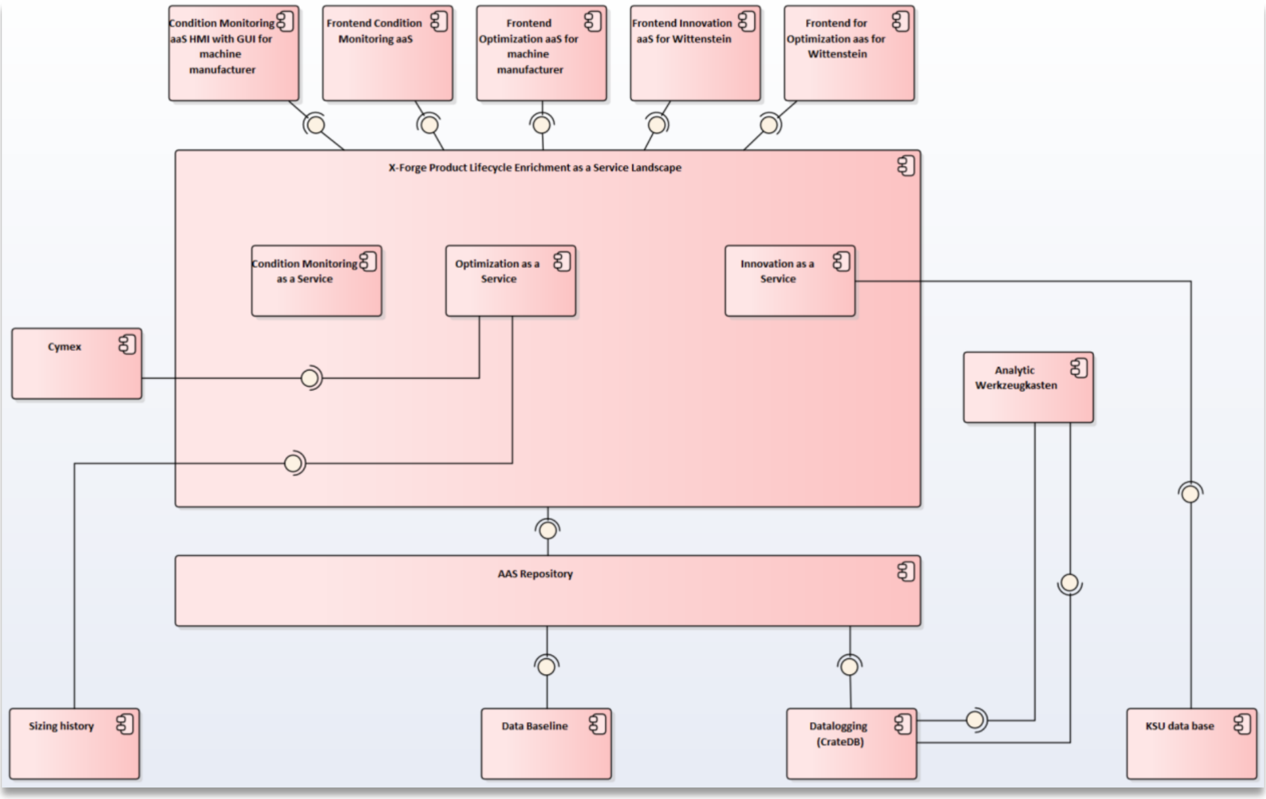


Figure 1: Component diagram of the Tier 3 architecture for the service landscape of the research project

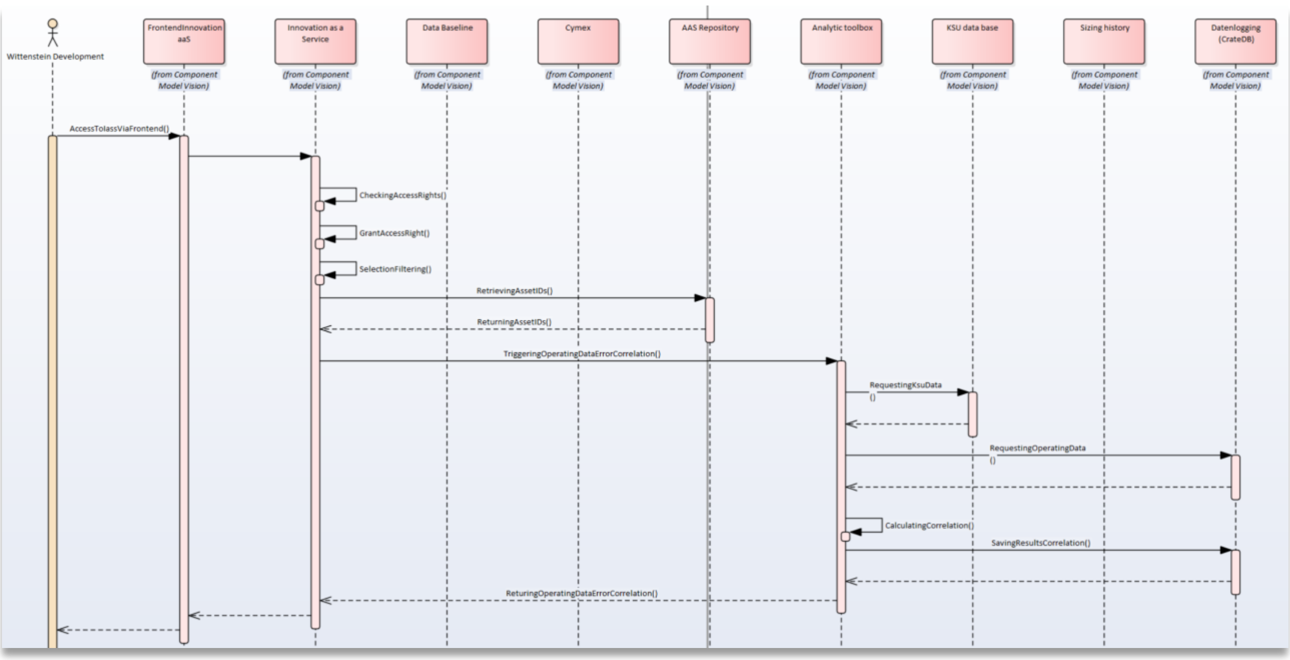


Figure 2: Excerpt from the sequence diagram for "Innovation as a Service"

In this case, a detailed consideration should clarify whether all properties must be included in the data model. Figure 3 hows excerpts of the class diagram and indicates the properties that will be processed as part of "Innovation-as-a-Service".

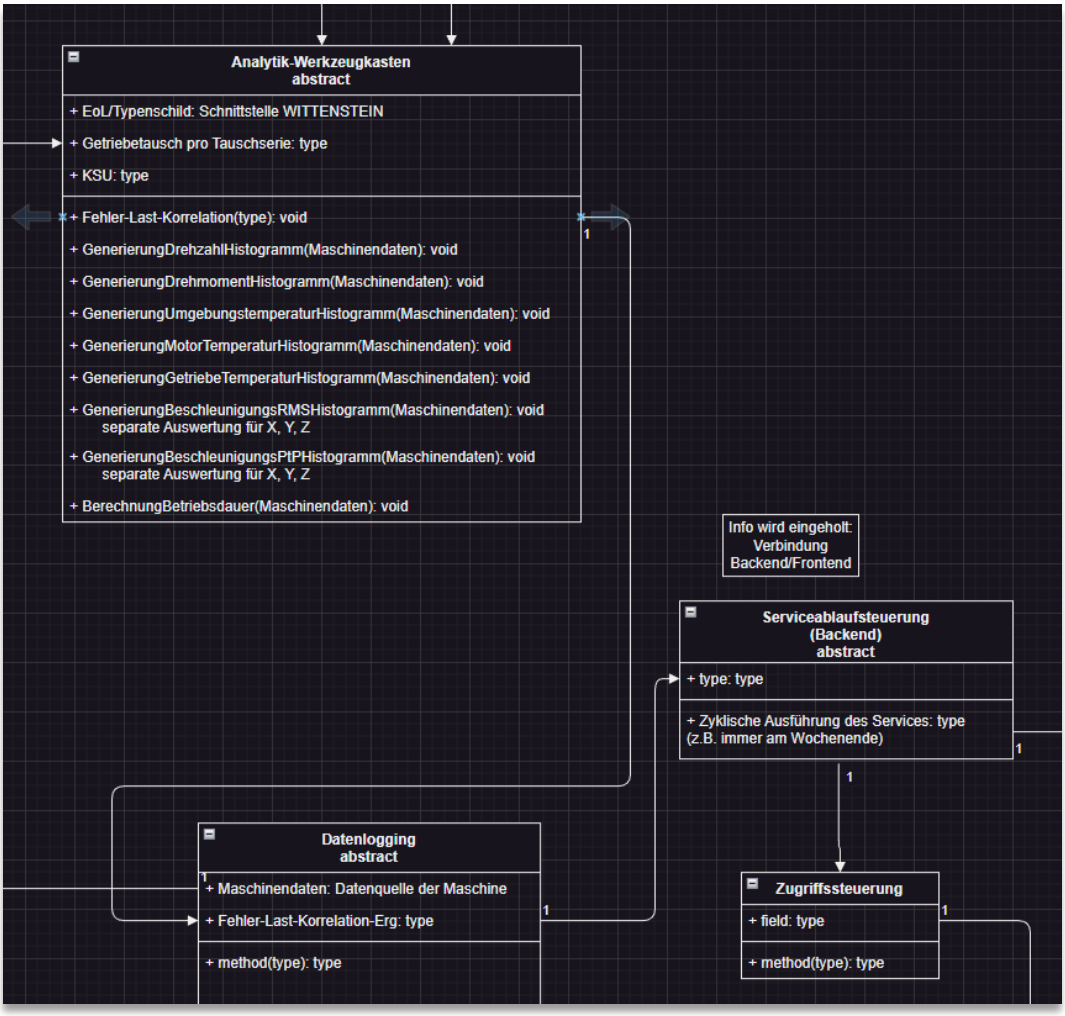


Figure 3: Excerpt from the class diagram for "Innovation as a Service"

4. Structuring the data model of the digital twin

The use cases are defined in several stages and modelled from different perspectives, creating a uniform understanding within the team of the services to be implemented in the research project. The rough idea of the services as defined at the beginning of the research project served as input for this. This is shown in steps one and two of Figure 5. The next step is the concrete derivation of the submodels of the AAS. Important aspects of the AAS are the standardization activities that define submodels. Their reuse and uniform structure simplify the digital twin's derivation and foster interoperability in the industrial context. The Industrial Digital Twin Association (IDTA) publishes these submodels. It is assessed whether there are completed submodels that have already gone through the standardization process and are suitable for application in the specific use case. In the same way, it is assessed whether there are non-standardized proprietary submodels that may already be used in the company's context. In our case, it is about identifying specific drive systems. As a result of these steps, the necessity of the standardized submodel "digital nameplate" was determined. Based on our described data and knowledge of the associated data types, we know the need for a submodel based on the submodel for time series data that is in the process of standardization. According to Figure 5, step 3 visualizes this procedure.

To successively enrich the AAS with further submodels relevant to the use case, steps four and five are devoted to the created models of the services (see section 3). On the one hand, already specified submodels can be adapted and enriched with additional properties. On the other hand, it is also intended to develop and use proprietary submodels that only meet specific requirements. The adapted or proprietary submodels benefit from the standardized interfaces of the AAS and thus ensure interoperability between AAS and other systems. Figure 4 shows an example of how the derivation of the submodels, including properties, can occur based on the previous modeling. To list exemplary structures adopted: assess which components need an

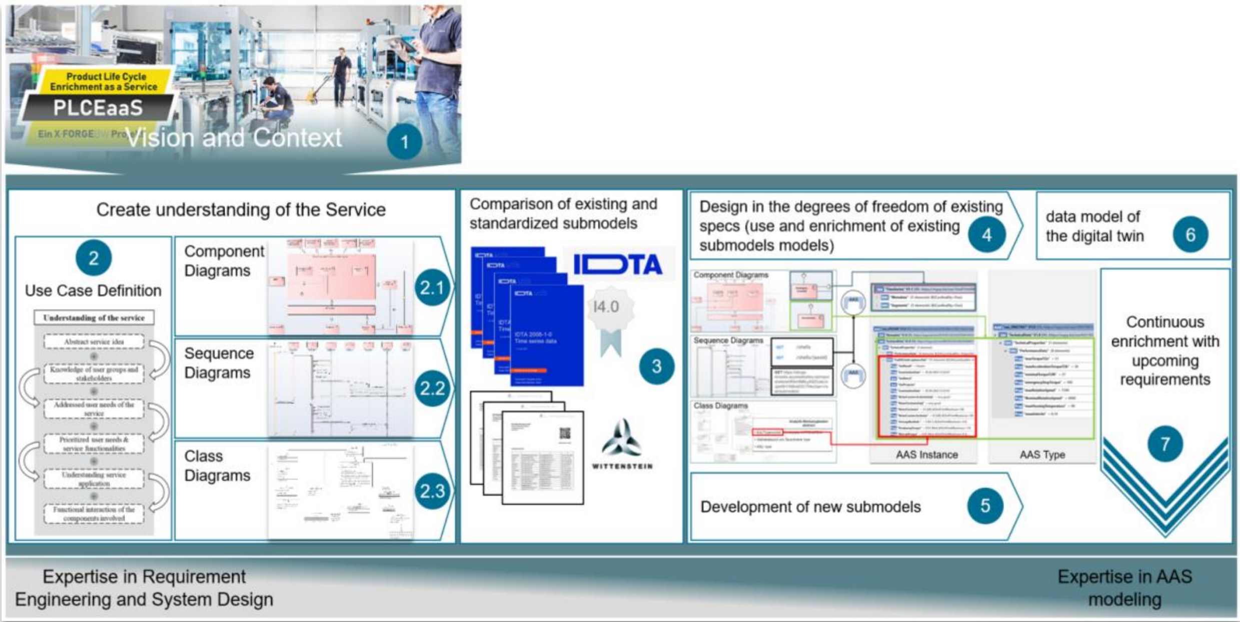


Figure 5: Process for creating a use case specific DT based on the AAS

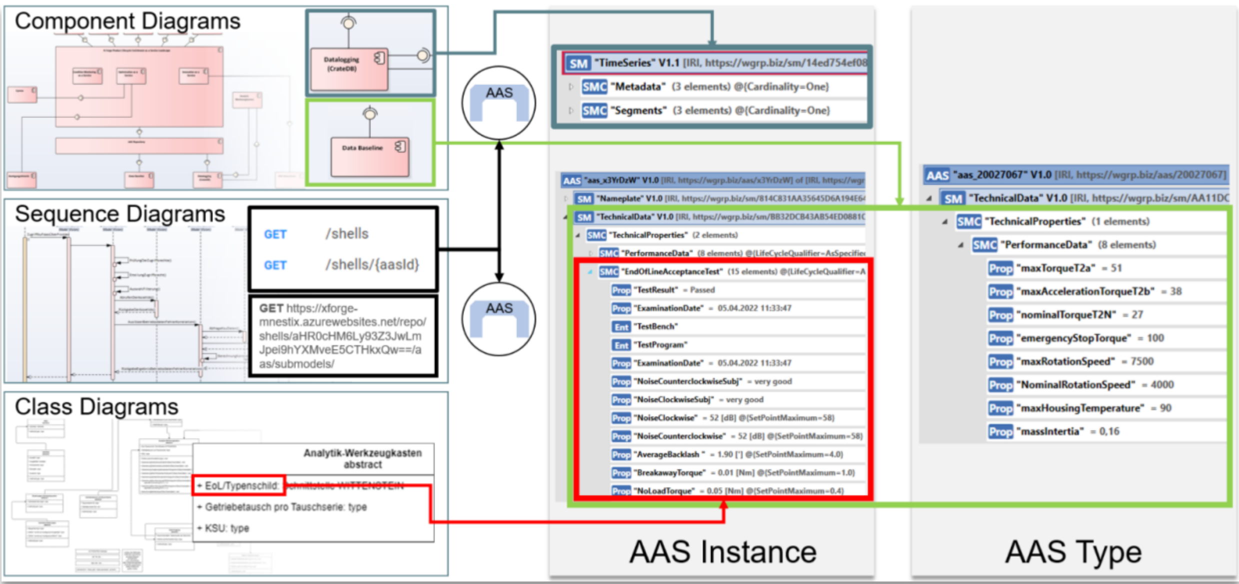


Figure 4: Derivation of specific data structure and properties from previous modelling

AAS based on the component diagram. It is not necessary to assign an AAS to each component. Rather the communication structure must be considered to see which entities communicate with each other and exchange data. For this user-specific case, the current strategy and state of the art focuses primarily on equipping the hardware (gearbox) with the AAS.

The operational data recorded and stored in a CrateDB are all in the form of time series data, so the need for the time series data submodel can be derived from their nature. The AAS represents an abstract construct that enables interoperability and a description with metadata, independent of technologies already in use and ideal technologies for the use case. In this case, CrateDB was chosen for reasons of performance, the capabilities of the project partner, and integration into their existing data platform. The service Data Baseline provides the customer catalogue and test bench data. On the one hand, specific properties for the AAS type can be derived from this. On the other hand, the properties for the respective AAS instance are also enriched with instance-specific measurement data.

The sequences of the sequence diagrams determine which data should be retrieved through the AAS or which functions should be called. It is necessary to consider this in advance so that the exact data required is loaded with individual commands without redundant data being included or data missing. For example, the get command is shown, which refers once to multiple AAS and once to an asset with a specific ID. A single flow in the diagram should usually be considered a single query providing data necessary for the interaction.

The respective properties and parameters can be taken from the class diagram. The example given shows how the exact data points relevant for the end-of-line test of a drive system and, thus, also for the data baseline service can be read from the respective class properties in the UML class diagram. The example shows the service, which processes data not only from the gearbox but also from the engine. The listing of the parameters can, therefore, not be transferred without further thinking to a model, so the integration of the parameters must be product-specific. Information and properties may well be provided several times by different submodels in the AAS to meet the different requirements.

If an asset has been provided with an AAS and its submodels are defined, this does not mean that the data model is unchangeable. Instead, new requirements imposed on an asset, for example, as a result of ongoing servitization or changing user needs, should be included. Individual submodels can still be added, removed, or adapted. Different expert knowledge is required for the respective tasks. While expertise from requirements engineering and system design is needed, particularly in the beginning, the later phases require more expertise to model the AAS. In the beginning, it is especially relevant to capture the stakeholders' needs to define necessary capabilities or systems properties and to transfer these needs, capabilities, or properties into a documented representation [16]. The latter phases, on the other hand, require much more knowledge about data, interfaces, and interaction with other systems.

5. Critical reflection

Although the interdisciplinary research team accepted our approach very well and the approach consolidated the understanding of all participants, it should be further questioned to what extent this elaborate procedure is justified. There is no comparison to an approach with prior modelling and then testing against the requirements of a use case. With the presented approach and the effort involved, the detailed conception should not hinder the implementation. Rather, the aim is to parallelize activities.

There may be several applicable modelling languages for transferring the use cases and, thus, the requirements into a documented representation. We focused on widely known and widespread tools. This selection does not imply that only these types of modelling are useful or that one should limit oneself to them. It is important that all views of the use case are covered, documented, and still practicably adaptable. It should also be noted that the current state of the use case specifications may be adjusted as the project progresses.

The submodels' basic structure and hierarchical order have not yet been worked out. Here, the content has been derived, but it makes sense and serves a standardized approach if the structure also follows a logic independent of the different domains in the production context. This general structure provides orientation and can then be filled with content using the approach shown.

Sequence diagrams can provide insight into different roles in the distribution of access rights. Currently, the security aspect is not explicitly considered, and all users have access to all data. For an industrial application, this aspect needs to be addressed.

6. Outlook

In the project, the prototypical implementation of the services is planned. For this purpose, relevant operating data must be collected on a test bed, and fault scenarios are to be simulated. The actual implementation will show to what extent the DT data model meets the requirements and provides all the data necessary for the services. Based on this, assessing whether the analytical methods chosen achieve the desired results will be necessary.

The success of AAS will undoubtedly depend on the extent to which it is adopted in industrial practice, the role of shared data spaces, and the need for operability of a wide range of assets. An idea of how AAS can be derived can help in the acceptance of the concept. This requires further elaboration to be more generally applicable and to provide detailed recommendations for action. In the context of the progressing research, it should be an object of consideration to what extent general statements can be made for deriving the data model from the models. The goal is a comprehensive chain of methods that accompanies the development of a digital twin based on the management shell, starting from a functional understanding of the service. For this purpose, steps 4 to 7 of the presented procedure, in particular, should be generalized for more services and enriched with more details at the same time. This should also include checking if any aspects are missing or any blind spots that are fundamental for the implementation.

Currently, the AAS provides a static API built on top of its data structures. A query or search interface is currently not planned and subject to future development. The mentioned queries of submodels are thus dependent on the current API specifications. This may result in further input for the standardization activities regarding the operationalization of the AAS. Thus, we currently have a reactive form of AAS with which software can interact. A proactive form of AAS, which require peer-to-peer interactions between AAS of I4.0 components and allow the components to communicate with an I4.0 language in order to realize plug&play scenarios, is not present here [19].

The scalability issue from DT [10,20] is considered because, on the basis of the AAS, we tried to store and provide data of individual assets as well as aggregated data that is fed from several assets. This consideration will also be relevant for individual services from the projects - for example, for Optimization-as-a-Service, the data of a specific product is relevant, and for Innovation-as-a-Service, the aggregated data of several products.

Acknowledgements

X-Forge is funded by State Ministry of Baden-Wuerttemberg for Economic Affairs, Labour and Tourism and implemented by VDI / VDE. The partners involved in the project are Wittenstein SE, ASCon Systems Holding GmbH, TruPhysics GmbH and Fraunhofer IPA.

References

[1] Bauernhansl, T., 2020. Die Entwicklungsstufen der Digitalen Transformation, in: Hompel, M. ten, Vogel-Heuser, B., Bauernhansl, T. (Eds.), Handbuch Industrie 4.0. Springer, Berlin, Heidelberg, pp. 1–10.

[2] Tao, F., Zhang, H., Liu, A., Nee, A.Y.C., 2019. Digital Twin in Industry: State-of-the-Art. IEEE Trans. Ind. Inf. 15 (4), 2405–2415.

[3] Tao, F., Cheng, J., Qi, Q., Zhang, M., Zhang, H., Sui, F., 2018. Digital twin-driven product design, manufacturing and service with big data. Int J Adv Manuf Technol 94 (9-12), 3563–3576.

[4] Grieves, M., Vickers, J., 2017. Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems, in: Kahlen, F.-J., Flumerfelt, S., Alves, A. (Eds.), Transdisciplinary Perspectives on Complex Systems. Springer International Publishing, Cham, pp. 85–113.

[5] Grieves, M., 2015. Digital Twin: Manufacturing Excellence through Virtual Factory Replication.

[6] 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.

[7] Abdel-Aty, T.A., Negri, E., Galparoli, S., 2022. Asset Administration Shell in Manufacturing: Applications and Relationship with Digital Twin. IFAC-PapersOnLine 55 (10), 2533–2538.

[8] Industrial Digital Twin Association, 2022. How to create a submodel template specification. Industrial Digital Twin Association. https://industrialdigitaltwin.org/content-hub/downloads. Accessed 7 February 2023.

[9] Liu, M., Fang, S., Dong, H., Xu, C., 2021. Review of digital twin about concepts, technologies, and industrial applications. Journal of Manufacturing Systems 58, 346–361.

[10] Bertoni, M., 2022. Boosting Value Co-creation in Design Through the Product-Service System Digital Twin: Questions to Be Answered, 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. 592–602.

[11] Xia, Y., Jazdi, N., Weyrich, M., 2022. Automated generation of Asset Administration Shell: a transfer learning approach with neural language model and semantic fingerprints, in: 2022 IEEE 27th International Conference on Emerging Technologies and Factory Automation (ETFA). 2022 IEEE 27th International Conference on Emerging Technologies and Factory Automation (ETFA), Stuttgart, Germany. 06.09.2022 - 09.09.2022. IEEE, pp. 1–4.

[12] Machchhar, R.J., Toller, C.N.K., Bertoni, A., Bertoni, M., 2022. Data-driven value creation in Smart Product-Service System design: State-of-the-art and research directions. Computers in Industry 137, 103606.

[13] Abramovici, M., Gebus, P., Savarino, P., 2018. Engineering smarter Produkte und Services: Plattform Industrie 4.0 STUDIE. acatech – Deutsche Akademie der Technikwissenschaften. https://www.plattform-i40.de/IP/Redaktion/DE/Downloads/Publikation/hm-2018-fb-smart.pdf?__blob=publicationFile&v=3. Accessed 20 February 2023.

[14] Gausemeier, J., Meyer, M., Steglich, S., Eva-Maria, G., Rasor, R., 2022. Strategie Advanced Systems Engineering: Leitinitiative zur Zukunft des Engineeringund Innovationsstandorts Deutschland. acatech – Deutsche Akademie der Technikwissenschaften. https://www.acatech.de/publikation/die-advanced-systems-engineering-strategie/. Accessed 20 February 2023.

[15] Himmelstoss, H., Bildstein, A., Schel, D., 2021. Solution Approach For Challenges In Product Development In The Context of Emerging Cyber-Physical Systems. Hannover : publish-Ing.

[16] Pohl, K., Rupp, C., 2021. Basiswissen Requirements Engineering: Aus- und Weiterbildung nach IREB-Standard zum Certified Professional for Requirements Engineering Foundation Level, 5., überarbeitete und aktualisierte Auflage ed. dpunkt.verlag, Heidelberg, 241 pp.

[17] Bedenbender, H., Bock, J., Boss, B., Diedrich, C., Garrels, K., Gatterburg, A., Heidrich, K., Hillermeier, O., Rauscher, B., Sauer, M., Schmidt, J., Werner, T., Zimmermann, P., 2020. Verwaltungsschale in der Praxis: Wie definiere ich Teilmodelle, beispielhafte Teilmodelle und Interaktion zwischen Verwaltungsschalen (Version 1.0). https://www.plattform-i40.de/IP/Redaktion/DE/Downloads/Publikation/2020-verwaltungsschale-in-der-praxis.html. Accessed 8 September 2023.

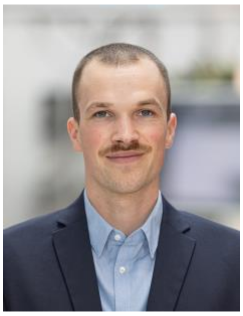
[18] Tremp, H., 2022. Agile objektorientierte Anforderungsanalyse. Springer Fachmedien Wiesbaden, Wiesbaden.

[19] Miny, T., Stephan, G., Usländer, T., Vialkowitsch, J., 2021. Functional View of the Asset Administration Shell in an Industrie 4.0 System Environment: Discussion Paper. https://www.plattform-i40.de/IP/Redaktion/DE/Downloads/Publikation/Functional-View.html. Accessed 7 September 2023.

[20] Bertoni, M., Bertoni, A., 2022. Designing solutions with the product-service systems digital twin: What is now and what is next? Computers in Industry 138, 103629.

Biography

Henry Himmelstoß (*1991) is a research associate and project leader at the Fraunhofer Institute for Manufacturing Engineering and Automation IPA in Stuttgart, Germany. Since 2019 he has been working in the department Competence Centre for Digital Tools in Manufacturing.



Roland Hall is a research associate at the Fraunhofer Institute for Manufacturing Engineering and Automation in Stuttgart, Germany. As part of the research group "Digital Industrial Engineering", his research topics focus on the interaction of Lean Production and Industrie 4.0 and the conception of digital tools for production.

Bernd Vojanec, expert in cooperating I4.0 systems at WITTENSTEIN SE, places particular emphasis on cross-manufacturer networking and the interoperability of I4.0 solutions, which is not limited to smart products and data-driven services but is especially relevant for business processes and the digital product twin. Furthermore, Bernd Vojanec is active in working groups of the ZVEI, VDMA and IDTA.

Paul Thieme (*1970) has been researcher and project leader at the Fraunhofer Institute for Manufacturing Engineering and Automation IPA since 2005. Paul Thieme received his PhD in 2013 in the field of process performance measurement in administration, teaches at various universities in Stuttgart, and gives guest lectures at various European universities. Since 2017 he has been working in the department Competence Centre for Digital Tools in Manufacturing.

Prof. Dr.-Ing. Thomas Bauernhansl has been head of the Fraunhofer Institute for Manufacturing Engineering and Automation IPA in Stuttgart and the Institute for Industrial Manufacturing and Factory Management IFF at the University of Stuttgart since September 2011. Bauernhansl studied mechanical engineering at the RWTH Aachen and received his doctorate in 2002. He then worked for Freudenberg, most recently as Director of the Technology Centre at Freudenberg Sealing Technologies.

His scientific focus areas include personalized production, the biological transformation and Industrie 4.0.

5th Conference on Production Systems and Logistics

An Approach For Analysis Of Human Interaction With Worker Assistance Systems Based On Eye Tracking And Motion Capturing

Fabian Hock[1], Joachim Metternich[1]

[1]*Technical University of Darmstadt, Institute for Production Management, Technology and Machine Tools (PTW), Otto-Berndt-Straße 2, 64287 Darmstadt, Germany*

Abstract

Human behavior in production systems influences productivity, product quality, work safety and overall process performance. To guide human behavior, digital worker assistance systems can be used to support cognitive decision tasks and sensory perception tasks. In doing so, the design of the assistance systems affects user experience and work results. To optimize and develop human-centric productions systems, data on human behavior and interaction with manufacturing equipment must be collected and analyzed. This analysis is expected to yield benefits regarding process monitoring, quality assurance, user experience and ergonomics. In addition, the results could be used for training purposes to monitor skill improvements.

This paper presents a framework for data acquisition and analysis of human interaction with digital worker assistance systems. In addition to the overall system architecture, the individual development steps are discussed. An eye tracking device and a motion capturing camera are used for data collection and provide live information about human behavior in conjunction with a digital worker assistance system. The data is stored in a database and analyzed by custom analysis algorithms. The results are displayed in a dashboard application and show that the presented framework with eye tracking and motion capturing is suitable for the analysis of human interaction with worker assistance systems.

Keywords

Human; Interaction; Data Acquisition; Data Analysis; Framework; Worker Assistance Systems; Eye Tracking; Motion Capturing; Assembly; Dashboard; Cyber-physical Production Systems

1. Introduction

Human behavior in production systems affects productivity, quality and flexibility [1]. However, training of workers is not always possible, because companies often rely on temporary employment, which may lead to a decrease in productivity [2]. Furthermore, customization and multiple product variants pose additional challenges [3]. One solution to provide support are digital worker assistance systems that help with cognitive decision tasks (e.g., assembly sequence) and sensory perception tasks (e.g., torques) [4]. Keller found that digital worker assistance systems increase productivity for untrained assembly workers, but the changes in human behavior which lead to the improvements were not monitored [5]. There is a lack in knowledge about the interaction between humans and worker assistance systems, which conceals optimization opportunities.

DOI: https://doi.org/10.15488/15288
ISSN: 2701-6277

The analysis of human behavior at digital worker assistance systems is motivated to support research similar to the use cases in the annotated references:

- Determine maturity level of lean production and worker movements [8,6,9,7,10].
- Discover inefficient hand movements and optimize assembly station layout [8,6,9,10].
- Monitor standard conformance, ergonomics and safety [8,6,10,11].
- Discover poorly understandable instructions and optimize texts, images and videos [8,9,11].
- Competency measurement before and after training sessions [8,10,11].
- Analyze usage of worker assistance systems to determine necessity after training period [8,10,11].
- Anomaly detection and process locking to support quality assurance [6,10].
- Create instructions automatically from captured behavior of expert worker [10].

To increase transparency and allow for improvements of digital worker assistance systems according to the listed use cases, this paper presents a framework for data acquisition and analysis based on an existing digital worker assistance system [12], an eye tracking device [13] and a motion capturing camera [14] as data sources. While the data sources already come with dedicated software tools, the authors identified the following issues, which lead to the development of the presented framework:

- Lack of standardized communication interfaces across data sources.
- No merging of multiple data sources across software tools.
- Implementation of custom analysis algorithms not possible.
- Not suitable for live data analysis and dashboard generation.
- Insufficient documentation about database structure of existing worker assistance system.
- Analysis software for eye tracking device is expensive [15].

The developed framework eliminates these issues. The communication is based on the open platforms communication unified architecture (OPC UA) and allows the connection of multiple data sources. In addition, the framework supports the implementation of custom analysis algorithms. The analysis runs on live data and the results are displayed in a dashboard application. The database and dashboard applications are based on free open-source software. Due to the implementation of custom analysis algorithms, there is no need for expensive proprietary software. The next sections provide information about the background of this work, the framework development and implementation as well as a conclusion of the results.

2. Background

A survey on digitization shows that 86 % of the participating companies want to increase efficiency through digitization, which is the highest rating category. The second most important request is an increase in transparency at 75 % [16]. To gain insights and find optimization potentials, the lean philosophy already introduces “Standing in the circle” also known as “Go & See” where shop floor managers observe workers in the factory [7]. Hofmann et. al. found that the visualization of live process information along with Go & See allows for better bottleneck identification [8]. In addition, the analysis of human interaction with manufacturing unveils optimization possibilities beyond productivity improvements. For example, Lange et. al. conducted interviews on the operability of tooling machines and identified multiple design dimensions which all affect user experience [9]. Regarding sensor technology for the analysis of human-machine interaction, Zheng et. al. present how eye tracking information can yield benefits regarding process performance, human performance, work environment and safety [11]. Their work also includes selected eye tracking measures to be used in various manufacturing and logistics areas. For analysis of worker movements, Jathe et. al. present an exemplary use case of motion capturing to identify work activities in the car industry [6]. Peruzzini et. al. combine multiple human factors to analyze user experience, but their implementation only targets data post-processing and does not support live analysis of streamed data [17].

3. Methodology and Framework

The presented data acquisition and analysis framework is developed based on the methodology “Development of mechatronic and cyber-physical systems”, as presented in VDI/VDE 2206:2021-11 [18]. The methodology – also known as the V-model – proposes five major steps for system development, which are shown in Figure 1. The next five sections of this paper show the application of the V-model to the development of the presented framework.

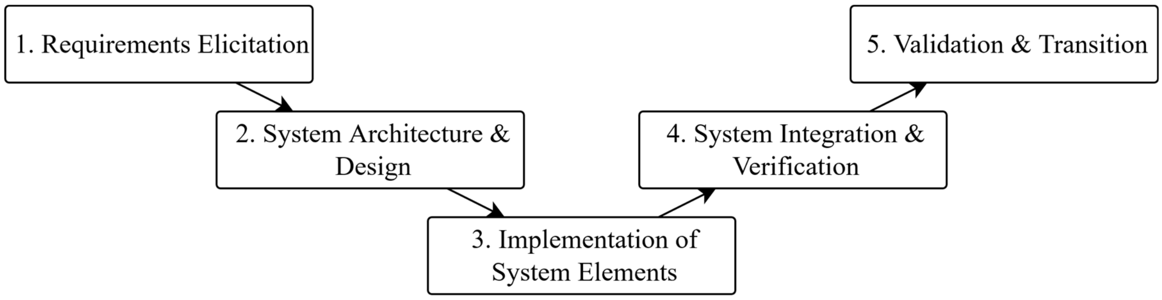


Figure 1: Methodology for Development of presented Framework according to VDI/VDE 2206:2021-11 [18]

3.1 Requirements Elicitation

The first step towards system development according to the V-model is the elicitation of requirements. The requirements for the presented framework are based on the use cases and issues with existing solutions as presented in the introduction of this paper. Figure 2 shows the use cases and derived requirements. There are use cases which share essential requirements and were merged into the groups A and B to reduce the number of connection lines. At the worker assistance system, the worker’s gaze on the instructions (R1.1) and movements (R1.2) must be tracked to collect data about human behavior according to the intended use cases.

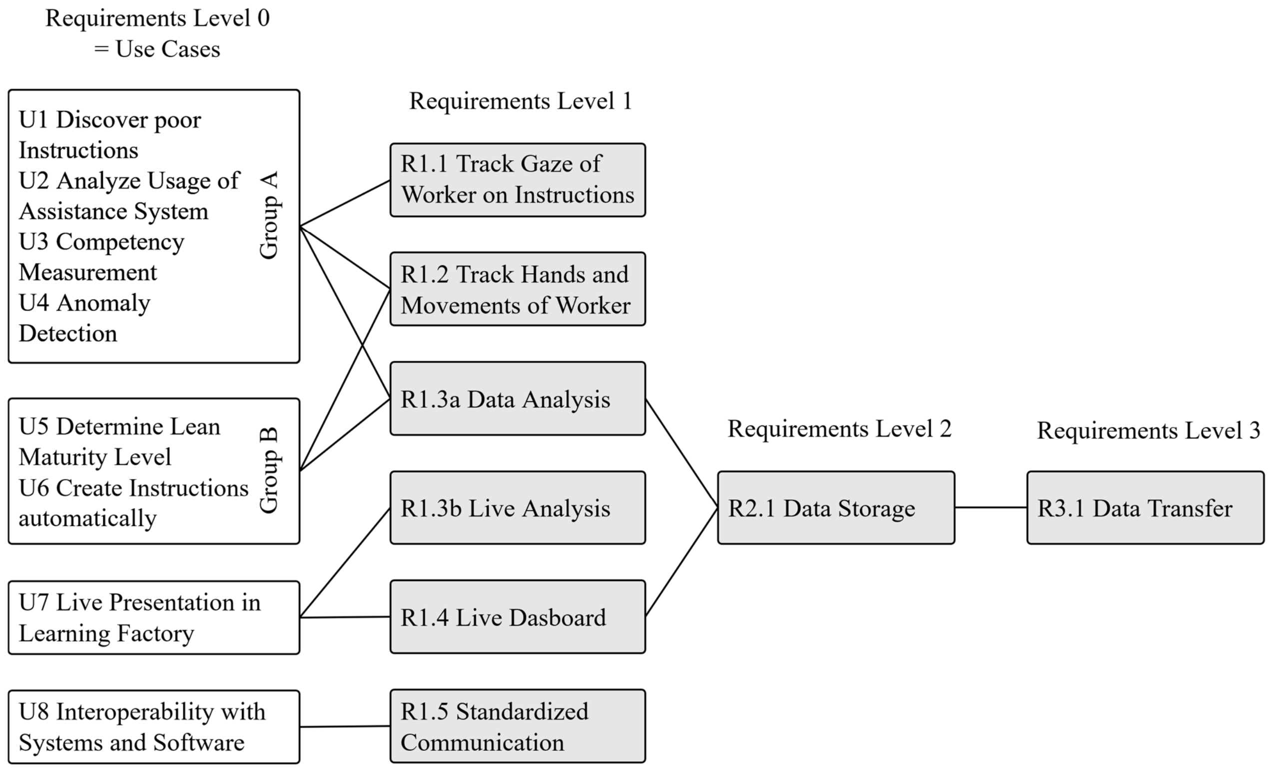


Figure 2: Requirements Elicitation for Data-driven Analysis of Human Interaction with Digital Worker Assistance Systems based on Use Cases

Use case U7 extends the data analysis requirement to also support live analysis of data. From the requirements of data analysis (R1.3a) and the integration of a dashboard (R1.4), the requirement for data storage (R2.1) is derived on the second requirements level. The data storage then requires data transfer software (R3.1) to save the live information into the data storage, which is displayed requirements level three. The next section discusses the system architecture of the framework based on the requirements.

3.2 System Architecture & Design

Figure 3 shows the system architecture of the framework which is tailored to the identified requirements. The chosen architecture was designed based on the guidelines for event-driven processing [19] and cyber-physical production systems [20]. At the bottom of figure 3, there is the data source layer, which consists of a worker assistance system, an eye tracking device and a motion capturing camera according to the requirements R1.1 and R1.2. Following the guidelines for event-driven processing, the information flow between the components is realized using a publish and subscribe paradigm [21]. OPC UA is the preferred communication standard for production systems and was chosen for the framework [22]. The provided information is available in the form of standardized OPC UA data streams, which satisfies requirement R1.5. For debugging purposes, free OPC UA clients can be used to view the data streams [23].

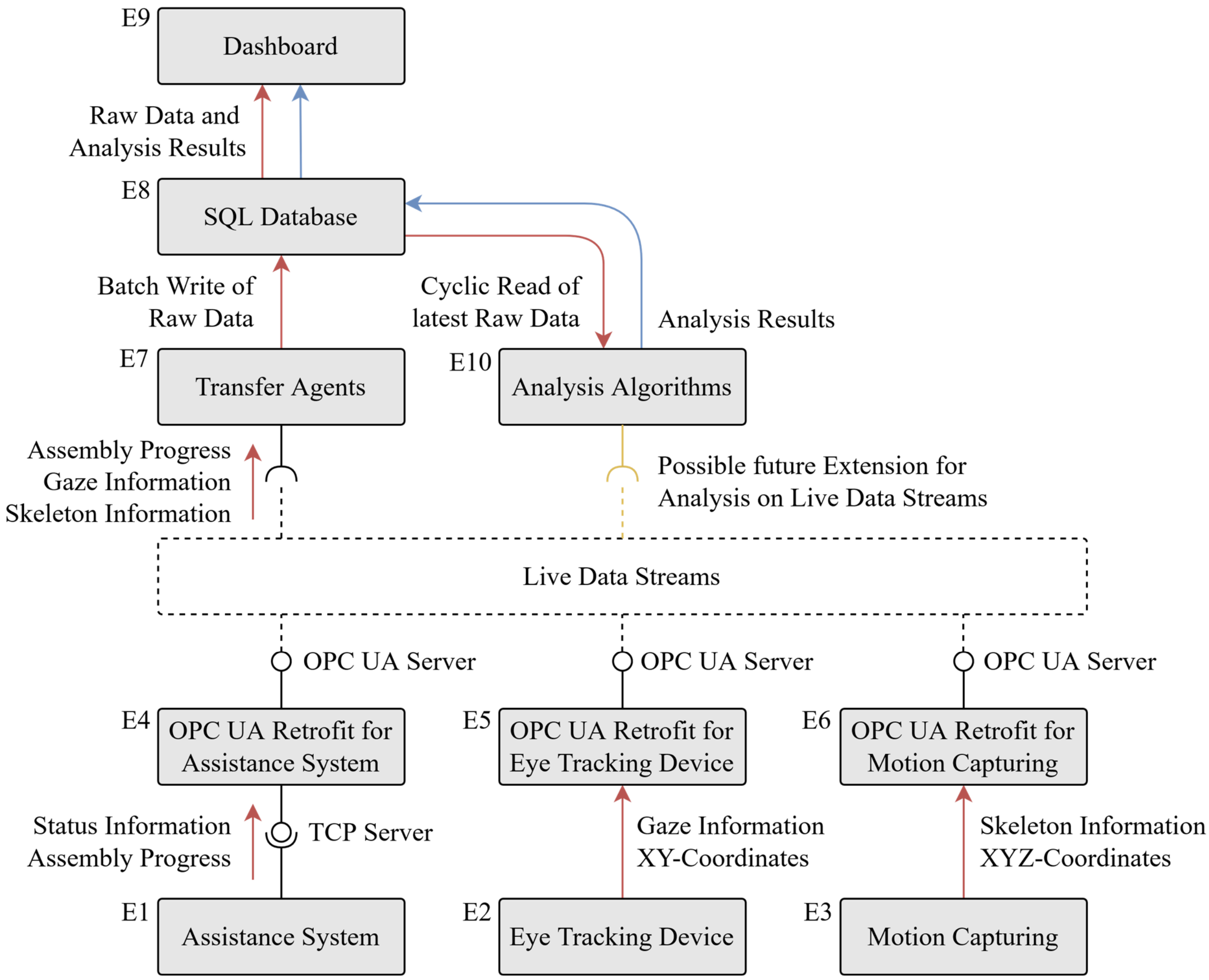


Figure 3: System Architecture of Framework for Data-driven Analysis of
Human Interaction with Digital Worker Assistance Systems

Above the data stream layer, there are transfer agents that write into a database, which supports the Standard Query Language (SQL), satisfying the requirements R1.5, R2.1 and R3.1. The analysis algorithms consume the latest batches of stored data, satisfying requirements 1.3a and 1.3b. To provide a visualization and to satisfy requirement 1.4, there is a dashboard application, which is customized to show the raw data and analysis results. The next section presents the implementation of the individual system elements, which are numbered as E1 – E10.

3.3 Implementation of System Elements

After the specification of the system architecture and design, the individual system elements are implemented. As proposed in the V-model, the implementation involves multiple disciplines for hardware and software. The framework consists of ten system elements according to figure 3. The system elements can be distinguished into three types: standard components (T1), standard components with custom configuration (T2) and fully custom components (T3). Table 1 shows an overview of the system elements and states information on their implementation. The framework includes four custom software components written in Python [24]. For the OPC UA retrofit on the motion capturing camera, the original body tracking library by Microsoft was incorporated, which is written for C++. The library takes the RGB-color and depth images from the camera and uses artificial intelligence and computer vision algorithms for motion capturing.

Table 1: System Elements and Implementation Information

ID	Type	Implementation	Comments
E1	T2	Desoutter Pivotware V7	Configured to send TCP messages to OPC UA retrofit.
E2	T1	Tobii Pro Nano	Provides XY-coordinates of the worker's gaze at 60 Hz.
E3	T1	Microsoft Azure Kinect DK	RGB+D camera, comes with library for motion capturing.
E4	T3	Python Application	Forwards information from TCP to OPC UA server.
E5	T3	Python Application	Fetches eye tracking data, forwards to OPC UA server.
E6	T3	C++ Application	Fetches motion data and forwards to OPC UA server.
E7	T3	Python Application	Subscribes to OPC UA servers and batch writes every 5 s.
E8	T1	PostgreSQL Database	Hosts database for raw data and analysis results.
E9	T2	Grafana Dashboard	Plots raw data and analysis results.
E10	T3	Python Applications	Read from database every 5 s for analysis, write results.

3.4 System Integration & Verification

The framework is integrated at one of three assembly stations for assembly of an electric motor replica. The chosen assembly station involves 19 assembly steps. Figure 4a shows the setup for integration and verification of the framework. The eye tracking device is mounted below the screen of the assistance system at an assembly station. Based on the included calibration software, the position of the worker's head is within the best range for tracking when standing straight in front of the assembly station. The motion capturing camera is mounted at the top of the assembly station. The settings of the camera allow for a wide and narrow field of view, where the narrow option has proven to be more accurate for motion capturing.

Figure 4b shows the image of the motion capturing camera with visualization of the skeleton joints. The viewport includes the relevant desk area. The boxes for material supply are not visible on the camera image but when the worker grabs material, the motion capturing algorithm still provides XYZ-coordinates at the positions of the boxes. Figure 4c shows a closeup of the screen of the assistance system and a scatter plot of the XY-coordinates for the worker's gaze at the screen.

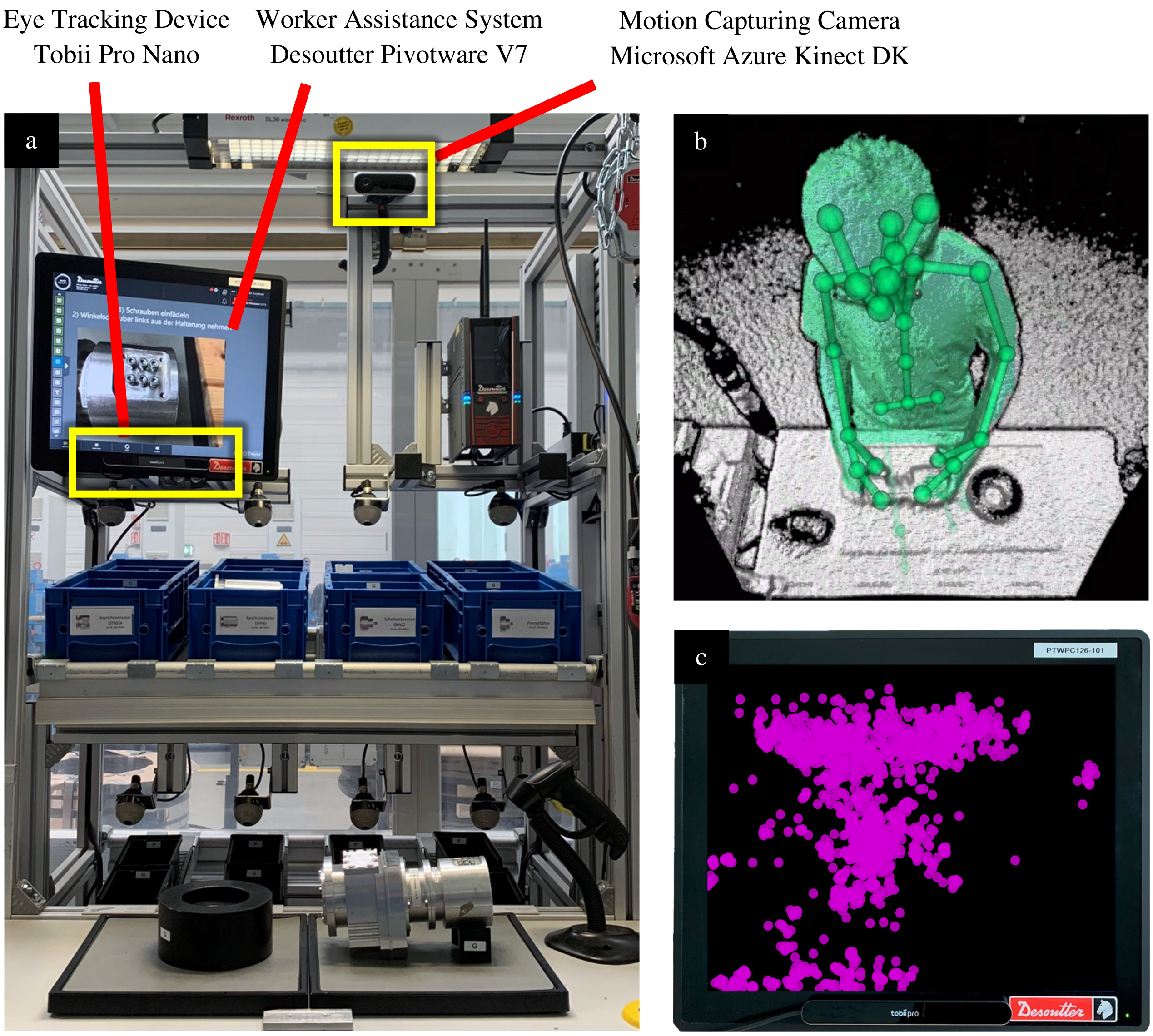


Figure 4: Setup with Integration of Framework for Data-driven Analysis of Human Interaction with Digital Worker Assistance Systems

To verify that the developed framework behaves according to specifications, all 19 assembly steps were carried out by unexperienced worker. Figure 5 shows the dashboard application with visualization of raw data and analysis results with annotations which are discussed in the validation section of this paper. The first plot shows the assembly progress. The eye tracking section shows when the worker looked at the screen, but there is no information about the tracking algorithm detecting head or eyes. The XY-coordinates of the worker's gaze are not shown as time series but as a scatter plot in figure 4c and focus on the instruction text and image area. The motion capturing section of figure 5 shows the detected person count and indicates that the motion capturing algorithm only lost tracking a few times. The Z-coordinates of the right hand are at about 1000 mm distance from the camera, which is reasonable based on the setup shown in figure 4a. The XY-coordinates of the right hand move around the center of the assembly station as expected.

Figure 5: Dashboard with Visualization of Raw Data and Analysis Results

The dashboard refreshes every five seconds and shows the history of data recorded during the assembly process. Due to the batch write logic of the transfer agents (E7) and the cyclic read logic of the analysis algorithms (E10), the dashboard is lacking a few seconds behind real-time. The data is still perceived as live generated for demonstration purposes. A detailed investigation of the data shows some anomalies, which are discussed in the following validation section, highlighting the links to the worker's activities.

3.5 Validation and Transition

The final step of the V-model is to validate that the developed framework is suitable for the intended analysis of human interaction with worker assistance systems. The initial analysis results include the timewise percentage of the worker looking at the screen of the assistance system for each assembly step. In addition, the distance between the right hand and the top right material box D2 is monitored to incorporate the motion capturing data. In the following, the link between work activities and anomalies in the collected data are discussed based on figure 5.

Assembly step six takes the longest to complete and starts at around 15:16:45 h. During most of the time of the sixth step, the worker does not look at the screen, but the right hand shows minor movements. This correlates with the fact that small hard to mount screws are attached during this step. The analysis results for the percentage of the worker looking at the screen is also the lowest of all major assembly steps.

Furthermore, there are two very short assembly steps in the recordings that are related to minor tool handling activities. These steps are separated from the adjacent activities by the assistance system but do not yield conclusive analysis results for the looking at screen value, because the time durations are too small.

Another observation shows a correlation between the motion capturing losing tracking of the worker and the position data of the right hand, e.g., at around 15:17:50 h. The tracking fails to detect the worker when there are peaks in the X-coordinate of the right hand and the worker moves towards the edges of the tracking area.

According to the instructions, material should be taken from box D2 only once. However, the distance measurement between the right hand and material box D2 indicates that the worker has reached three times into the box towards the end of the assembly process. This correlates with a confusion that the worker experienced because the provided parts did not look like the ones on the instruction image.

Besides the instruction text and image area, the eye tracking data in figure 4c shows a cumulation at the lower left part of the screen. This is where multiple buttons are placed on the user interface of the assistance system to skip or retry steps. Although the buttons were not pressed during assembly, the worker's gaze moved around the area several times.

4. Conclusion and Outlook

After motivating the analysis of human interaction with production systems, the requirements of the presented framework are derived from research use cases and issues with existing tools. The chosen system architecture follows guidelines for event-driven processing and cyber-physical production systems. The data sources are equipped with OPC UA interfaces to provide standardized publish and subscribe communication. For data storage and visualization, the framework relies on free open-source software. For future improvements in performance and query logic, the database will be replaced by a time-series database. The data analysis is performed by custom algorithms. For verification, the developed framework is implemented at an assembly station with a worker assistance system. The motion capturing algorithm only lost tracking a few times. The eye tracking data must be investigated further as by now, there is no distinction between the worker not looking at the screen and the worker not being in the tracking range. Regarding the analysis results, the first algorithm successfully merges signals from the worker assistance system and eye tracking device. The initial motion capturing analysis is kept simple but could be extended in the future. To minimize the lag between data acquisition and display of analysis results, the algorithms will be connected to the live data streams instead of the database in the future as indicated in figure 3. The validation shows links between the worker’s activities and analysis results but must be extended to more detailed statistics in the future.

Further research will include the application to more use cases as listed in the introduction of this paper. After developing additional analysis algorithms, the authors plan to record and analyze multiple datasets. The findings are expected to reveal optimization possibilities for the design of worker assistance systems.

Acknowledgements

The research leading to these results was conducted as part of the project Plattform dataPro and has received funding from the Förderprogramm Dist@l of the Hessische Ministerium für Digitale Strategie und Entwicklung.

HESSEN

Hessische Staatskanzlei

Hessische Ministerin für Digitale Strategie und Entwicklung

digitales.hessen

DISTR@L

References

[1] Keller, T., Bayer, C., Bausch, P., Metternich, J., 2019. Benefit evaluation of digital assistance systems for assembly workstations. Procedia CIRP 81, 441–446.

[2] Lisi, D., Malo, M.A., 2017. The impact of temporary employment on productivity. J Labour Market Res 50 (1), 91–112.

[3] Da Silveira, G., Borenstein, D., Fogliatto, F.S., 2001. Mass customization: Literature review and research directions. International Journal of Production Economics 72 (1), 1–13.

[4] Hock, F., Sandner, S., Metternich, J., 2023. Reifegrade digitaler Werkerassistenzsysteme. Zeitschrift für wirtschaftlichen Fabrikbetrieb 118 (6), 382–386.

[5] Keller, T., 2021. Analyse der Effekte von Werkerassistenzsystemen auf die Leistungsfähigkeit manueller Montagesysteme, 1. Auflage ed. Shaker Verlag, Düren, 139 pp.

[6] Jathe, N., Lütjen, M., Petzoldt, C., Boger, D., Freitag, M., 2023. Intelligente Kontexterfassung im Automobilumschlag. Zeitschrift für wirtschaftlichen Fabrikbetrieb 118 (6), 376–381.

[7] Liker, J.K., Meier, D., 2013. Toyota way fieldbook: A practical guide for implementing Toyota's 4Ps. McGraw-Hill, New York, 475 pp.

[8] Hofmann, C., Staehr, T., Cohen, S., Stricker, N., Haefner, B., Lanza, G., 2019. Augmented Go & See: An approach for improved bottleneck identification in production lines. Procedia Manufacturing 31, 148–154.

[9] Lange, L., Buxbaum-Conradi, S., Redlich, T., Wulfsberg, J.P., 2023. Sozio-technische Einflussfaktoren auf die Bedienbarkeit von Werkzeugmaschinen. Zeitschrift für wirtschaftlichen Fabrikbetrieb 118 (6), 371–375.

[10] Rocha, C.A.P., Rauch, E., Vaimel, T., Garcia, M.A.R., Vidoni, R., 2021. Implementation of a Vision-Based Worker Assistance System in Assembly: a Case Study. Procedia CIRP 96, 295–300.

[11] Zheng, T., Glock, C.H., Grosse, E.H., 2022. Opportunities for using eye tracking technology in manufacturing and logistics: Systematic literature review and research agenda. Computers & Industrial Engineering 171, 108444.

[12] Desoutter Industrial Tools. Pivotware: Innovative Process Control & Worker Guidance Systems. https://us.desouttertools.com/tools/64/process-control-pivotware.

[13] Tobii AB. Easy to use, small, portable eye tracker - Tobii Pro Nano. https://www.tobii.com/products/eye-trackers/screen-based/tobii-pro-nano. Accessed 18 July 2023.

[14] Microsoft Cooperation. Azure Kinect DK. https://azure.microsoft.com/de-de/products/kinect-dk. Accessed 18 July 2023.

[15] Tobii AB. Tobii Pro Lab Full Edition. https://uk.shop.tobii.com/tobii-pro-lab-full-edition/?utm_source=tobii.com&utm_medium=referral&utm_campaign=tobii.com. Accessed 18 July 2023.

[16] Staufen AG, 2023. Studie: Zukunft Industrie: Die vier Dimensionen der Wettbewerbsfähigkeit, Köngen. www.staufen.ag/studien.

[17] Peruzzini, M., Grandi, F., Pellicciari, M., 2017. Benchmarking of Tools for User Experience Analysis in Industry 4.0. Procedia Manufacturing 11, 806–813.

[18] VDI Verein Deutscher Ingenieure e.V. Development of mechatronic and cyber-physical systems.

[19] Bruns, R., Dunkel, J., 2010. Event-Driven Architecture. Springer Berlin Heidelberg, Berlin, Heidelberg.

[20] Biffl, S., Lüder, A., Gerhard, D., 2017. Multi-Disciplinary Engineering for Cyber-Physical Production Systems: Data Models and Software Solutions for Handling Complex Engineering Projects. Springer International Publishing, Cham, 472 pp.

[21] Sai Lohitha, N., Pounambal, M., 2023. Integrated publish/subscribe and push-pull method for cloud based IoT framework for real time data processing. Measurement: Sensors 27, 100699.

[22] DIN. Reference Architecture Model Industrie 4.0 (RAMI4.0), 2016th ed. https://www.din.de/en/wdc-beuth:din21:250940128. Accessed 9 July 2023.

[23] Unified Automation GmbH. UaExpert: Ein vollausgestatteter OPC UA Client. https://www.unified-automation.com/de/produkte/entwicklerwerkzeuge/uaexpert.html. Accessed 9 July 2023.

[24] Python Software Foundation. Welcome to Python.org. https://www.python.org/. Accessed 13 July 2023.

Biography

Fabian Hock, M.Eng. (*1997) has been a research associate and PhD student at the Institute for Production Management, Technology and Machine Tools (PTW) at the Technical University of Darmstadt since 2022. His research interests include human-centric assistance systems in cyber-physical production systems.

Prof. Dr.-Ing. Joachim Metternich (*1968) has been head of the Institute for Production Management, Technology and Machine Tools (PTW) at the Technical University of Darmstadt since 2012. He is also the spokesman for the Center of Excellence for Medium-Sized Businesses in Darmstadt and was president of the International Association of Learning Factories (IALF).

5th Conference on Production Systems and Logistics

Machine Learning Driven Design Of Experiments For Predictive Models In Production Systems

Sebastian Maier[1], Patrick Zimmermann[1], Rüdiger Daub[2]
[1]Fraunhofer Institute for Casting, Composite and Processing Technology IGCV, Augsburg, Germany
[2]Institute for Machine Tools and Industrial Management, Technical University of Munich

Abstract

Machine learning (ML) describes the ability of algorithms to structure and interpret data independently or to learn correlations. The use of ML is steadily increasing in companies of all sizes. However, insufficient market readiness of many ML solutions inhibits their application, especially in production systems. Predictive models apply ML to understand the complex behavior of a system through regression from operational data. This enables determining the relationship between factors and target variables. Accurate predictions of these models for production systems are essential for their application, as even minor variations can significantly affect the process. This accuracy depends on the available data to train the ML model. Production data usually shows a high epistemic uncertainty, leading to inaccurate predictions unfit for real-world applications. This paper presents ML-driven, data-centric Design of Experiments (DoE) to create a process-specific dataset with low epistemic uncertainty. This leads to improved accuracy of the predictive models, ultimately making them feasible for production systems. Our approach focuses on determining epistemic uncertainty in historical data of a production system to find data points of high value to the ML model in the factor space. To identify an efficient set of experiments, we cluster these data points weighted by feature importance. We evaluate the model by running these experiments and using the collected data for further training of a prediction model. Our approach achieves a significantly higher increase in accuracy compared to continuing the training of the prediction model with the same amount of regular operating data.

Keywords

Machine Learning; Design of Experiments; Epistemic Uncertainty; Predictive Models; Production Systems

1. Introduction

At the latest since the publication of ChatGPT by OpenAI, Machine Learning (ML) has received much attention [1]. This type of generative artificial intelligence (AI) is considered a technical revolution with a potential impact on a wide variety of industries and society as a whole [2]. In line with this trend, the use of AI continues to increase in companies of all sizes, although primarily in large companies with more than 1000 employees [3]. Barriers to deploying AI in companies include a lack of expertise in the ML area, insufficient market maturity of AI solutions, and a lack of data [4].

After the IT industry, manufacturing ranks second among the most important application areas for AI in Germany [5]. However, compared to the IT industry, manufacturing requires significantly more effort to generate data on the operational technology (OT) level and to transfer it to the application level. It becomes clear that the algorithms behind ML models might not always be the limiting factor but rather the limited data available to train these models. Instead of improving a model on a given dataset, data-centric AI focuses

DOI: https://doi.org/10.15488/15289
ISSN: 2701-6277

on data quality and reliability [6]. The methodology presented in this paper utilizes this data-centric approach and addresses the creation of robust predictive ML models for complex production processes.

2. Data in production systems and its effect on predictive models

Production systems use actuators to control the process and sensors to generate data. These input data points are called factors and consist of disturbance variables and control variables, as shown in Figure 1.

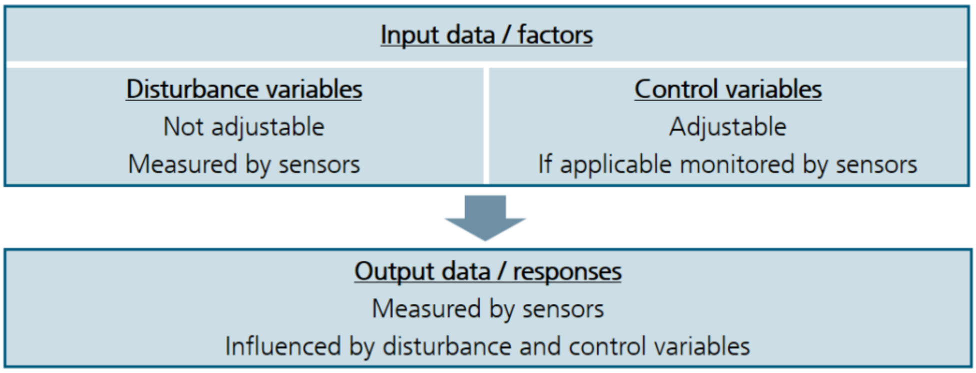


Figure 1: Types of data in a production system

Disturbance variables are factors that the operator of a production system cannot adjust. In contrast, control variables can be set to predefined values. Control variables are actuators that are often equipped with sensors to monitor their current state. All factors influence one or more output data points called responses. In production systems, responses are usually one or more measurable product quality characteristics. Production systems typically rely on the empirical knowledge of experts and plant personnel who adjust the control variables to achieve the desired responses.

In this work, we specifically address a subset of ML, namely predictive models, which learn the behavior of the plant using regression. These models use historical data collected during the operation of the production system to determine the relationship between factors and responses. Thus, the trained predictive model can quantify the effect of factor changes on responses independently of the process experts' empirical knowledge.

Since the predictions take place simulatively without affecting the real-world production system, finding the factors for the desired responses based on the predictions of a trained model is an optimization problem. Given the current disturbance values of the real-world production system, a set of control variables is sought, reproducing the desired responses according to the prediction model as accurately as possible. These simulatively determined control variables can be set in the actual production system afterward. The goal of this optimization is to avoid scrap or to increase efficiency. In production, this method is called predictive quality. However, applying these predictive models in production is associated with some challenges.

Most of the data generated in production systems is available as time series data. Programmable Logic Controllers (PLCs) cyclically retrieve individual measured values and provide them with a time stamp. The combination of all process factors forms the input space, also called design space or factor space. Figure 2 shows a simplified 2D factor space. In this simple example, the factors x1 and x2 create the factor space. Within the green area there are data points, represented as black dots. These data points are recordings during the regular operation of the production system. The distribution of data points within the green area is not homogeneous, so there are areas with an accumulation of data points as well as areas with few or no data points.

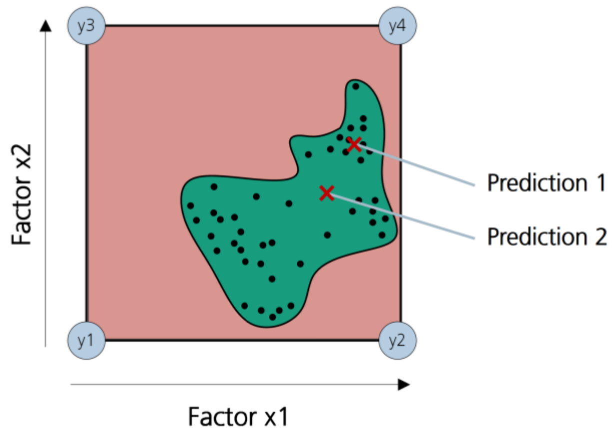


Figure 2: 2D factor space with data points illustrated as black dots

This distribution of data for training predictive models significantly impacts their robustness [7]. Areas with many data points lead to accurate predictions due to the prevalence of low uncertainty, like prediction 1 in Figure 2. Prediction 2 in Figure 2, on the other hand, lies in an area with few data points nearby, leading to higher uncertainty and less accurate predictions. This type of uncertainty arises from various forms of insufficient knowledge or incomplete data and is referred to as "epistemic uncertainty" [8]. Therefore, providing additional data reduces epistemic uncertainty. Predictions within the green range can also have high epistemic uncertainty and thus produce inaccurate predictions. All predictions within the green region are also referred to as "in-distribution" predictions [9]. However, this does not mean they are independent and identically distributed [10]. Accurate predictions within this range are essential for applying predictive models since even slight fluctuations can significantly affect the process. The prediction of desired target variables, therefore, only allows minor errors. High epistemic uncertainty leading to high inaccuracy makes predictions unusable for production systems.

Predictions in the red region of the factor space have a very high epistemic uncertainty and produce incorrect predictions because of factor compositions that the training data does not cover. All predictions within the red region are referred to as "out-of-distribution" (OOD) predictions [9,10]. Valid predictions in the OOD region can still be highly relevant in applications where process experts want to identify new operating conditions. In this case, the objective is to find factor compositions in the red region that are more efficient than previous operating regions "in-distribution" or more consistently achieve the desired product quality.

Reducing epistemic uncertainty with new data in the factor space is difficult to achieve in an application. Instead of only having two factors, as shown in Figure 2, real-world applications often deal with tens or even hundreds of factors. This high dimensionality and the often complex interrelationship of the factors limit the applicability in production systems. This work focuses on improving "in-distribution" predictions through new data points. We present a method that evaluates feature importance and model uncertainty in the factor space to create an effective set of experiments. The effect of gathering data during these experiments shows a more significant decrease in model error compared to training the model further with regular training data.

3. State of the art

This chapter presents the state of the art regarding our research. First, we discuss the role of uncertainties, feature importance, and their corresponding methods for explainable AI. Subsequently, we point out current research in the field of ML-based experimental design.

3.1 Understanding ML models

Explainable AI aims to provide interpretable insights into the decision-making process of AI models to understand them better. Explainability is particularly important in production systems since incorrect predictions can cause property damage or even cause injuries. There are many tools and methods to evaluate the correctness and relevance of a prediction. In this work, however, we focus on two approaches: uncertainty and feature importance. Feature importance indicates the influence of individual factors on the responses. In the context of feature importance, global model-agnostic methods describe the average behavior of models [11]. The most prominent global model-agnostic method is permutation feature importance. By randomly shuffling a factor's value and measuring the model error, permutation importance provides the importance of each factor for the responses [12]. Local model-agnostic methods, on the other hand, explain individual model predictions [11]. SHapley Additive exPlanations (SHAP) is a method that uses Shapley values, known from coalitional game theory, to find the contribution of each factor to the prediction [13].

According to [14], the shell model of uncertainties divides the uncertainty of AI or ML applications into three areas: The innermost layer, "Model Fit," indicates whether the used model can represent the complexity of the data. The subsequent layer, "Data Quality," indicates whether the data contains the information and correlations related to the target variable. The outermost layer, "Scope Compliance," includes uncertainty due to differences between the model and application context. This work concerns the "Data Quality" layer, which describes epistemic uncertainty. Bayesian methods are essential in determining the amount of uncertainty [15,16]. However, since Bayesian approaches are often more computationally expensive and less performant than conventional ML models, [17] demonstrated that dropout in neural networks can be used to approximate uncertainty, combining the advantages of conventional ML with Bayesian methods.

3.2 ML-driven Design of Experiments

Factorial or screening experimental plans quickly reach their limits when there are many factors and complex processes. ML-based Design of Experiments (DoE) attempts to solve this problem and helps to determine process interrelationships through targeted experiments. Determining the most efficient experiments is called "Optimal Experimental Design" (OED). Approaches in this area use, for example, iterative exploration of areas in the factor space with high information content by predicting the variance [18] or introducing estimators for the information gain of an experiment [19]. ML-based DoE already finds application in the field of materials science [20], chemical reactions [21], or in the selection of fast-charge protocols [22]. However, these approaches are limited to discrete factor spaces and do not account for continuous factor spaces as they prevail in production systems.

4. Methodology

This section introduces our ML-driven DoE for predictive models in production systems. Figure 3 shows the workflow of the method.

Figure 3: Workflow for the ML-driven approach to DoE for predictive models in production systems

For this method to be applicable, the production system must run and provide the data generated during the process. All data points are snapshots of the production system at a certain time and consist of *n* factors. The first step is to train an ML model using historical data from the operation of the production system. The type of selected regression model must either provide the uncertainties in its predictions (i.e. Bayesian methods) or allow to calculate the uncertainty of its prediction with additional methods (i.e. neural networks with the approximation of [17]). These requirements are important at a later stage in the workflow. In some cases, this regression model might already produce sufficient predictions. However, the predictions are too inaccurate for many use cases in production systems, which is where our method comes into place. In step two, we calculate the feature importance of all control variables. Since we are interested in the feature importance over all data points, we apply a global model-agnostic method like permutation importance.

In the third step, we determine the uncertainty of the model over historical data points. Ideally, these data points are a test set which the model has not been trained on. Then we pick *m* data points with the highest uncertainty for further investigation in the next step. The amount of data points to choose varies depending on the number of experiments and fluctuation in the data. If we plan a high amount of experiments and the data fluctuates considerably, an increased number of data points is necessary for step 4.

Since it is expensive to perform many experiments, we do not want to run separate experiments for *m* data points. Instead, we want to design an efficient set of experiments that generate as much useful information for the ML model as possible. This is why we cluster the data points with high uncertainty in step 4. By clustering similar data points, we aim to compress the information of *m* data points into fewer experiments. Algorithms like k-means minimize the variance of data points within a cluster. In this case, we want to minimize the variance of all control variables since we cannot influence disturbance variables during experiments. Additionally, we weight all control variables by their feature importance. This ensures efficiency since factors with a high impact on model estimates also have a higher impact during clustering. To get a single experiment from each cluster, we calculate the average for the factors in each cluster. The set of all averaged clusters acts as an experiment plan for the production system. This plan provides a set of experiments that target areas in the factor space where the model is uncertain while focusing on the factors that influence the responses the most.

In step 5, we set the control variables according to the first experiments from the experiment plan and record all data during production. After completing all experiments, we use the data from the experiments to further train the model in step 6.

5. Evaluation

In this chapter, we evaluate our method based on its effect on the error of predictive models in production systems. We apply the method at a geothermal power plant (GPP) that produces power by extracting heat from hot thermal water. We use 22 sensors in the process. The process operators have written the operational data cyclically into a database every 5 minutes for 268 days. These sensor values are the historical data and consist of different physical properties like water flow rate, pressure, temperatures, etc. Out of these 22 values, we use three adjustable factors as the control variables for our method. In addition, one of the values that the process operators recorded is the net energy gain of the GPP, which acts as the response of the predictive model. After training a basic feed-forward neural network on this data, we evaluate the feature importance of all control variables using permutation importance. Table 1 shows the feature importance of all control variables.

Table 1: Feature Importance of the control variables

Control variable	Feature Importance
Number of active air condensers	33.6068
Blade angle of air condenser ventilators	32.9897
Receiver condensate level	29.4302

In the next step, we predict the net energy gain based on unseen data. We use the dropout method of [17] to estimate the epistemic uncertainty of these predictions. Figure 4 shows the uncertainty of the predictions over a period of 30 days.

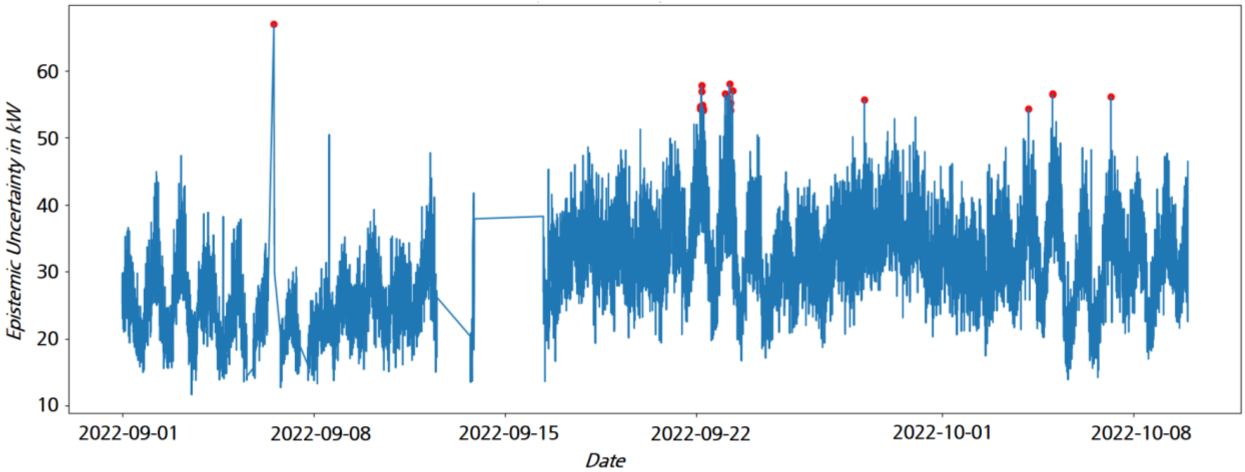


Figure 4: Epistemic uncertainty of the model on test data

Since maintenance work was done on the GPP during this time, we left out some uncertainty data to avoid faulty estimates. The red dots mark 20 predictions with the highest epistemic uncertainty. To reduce the total number of experiments, we build five clusters from these 20 data points weighted by their feature importance and calculate the average of each cluster. The five clusters act as five separate experiments. Therefore, we compress the information of twenty data points into only five experiments. We adjust each control variable according to an experiment and run the GPP with these settings for 24 hours. We record all 21 factors and the corresponding response during the experiments for further training of the feed-forward neural network.

We use the root-mean-square error (RMSE) between the predictions and the actual net power output to evaluate the performance of the model. Table 2 shows the RMSE of three models, which all share the same hyperparameters. We train model 1 on just 268 days of historical data. Model 2 utilizes an additional five days of regular operational data from the GPP. Model 3 uses the 268 days of historical data and the five days of experiments we performed based on our method. This means we trained models 2 and 3 on the same amount of data, whereas model 1 uses five fewer days of data.

Table 2: Evaluation of the models based on their RMSE

Model	RMSE
Model 1: 268 days of data of regular operation data	12.006
Model 2: 268 regular + 5 days of regular operation data	11.935
Model 3: 268 regular + 5 days of experiment data (our method)	10.294

As expected, model 1 with an RMSE of 12.006 performs worse than models 2 and 3 since we provide less training data. While model 2 achieves an RMSE drop of ~0.6% to 11.935, the RMSE of model 3 drops to 10.294, a decrease of ~14.3%. The five days of experimental data provided by our method are more beneficial to the model than five days of regular operating data. This shows that a data-driven approach to predictive models can help lower the error of predictions and make these models more feasible for production systems.

6. Conclusion and future work

It is vital to decide which ML model to use and to find its best hyperparameters for any type of application. However, instead of focusing on models and algorithms, research in data-driven AI focuses on data quality and reliability. In this work, we introduce a method for ML-driven DoE for predictive models in production systems to generate high-quality training data yielding lower prediction errors. We achieve this by considering the epistemic uncertainty of model predictions and clustering them weighted by feature importance. With this, we create data with high value to the model while keeping experimental efforts as low as possible. We have shown that our method yields significantly higher-quality data than regular operation.

This work focused on "in-distribution" predictions, meaning we generated data within the range of regular operation of the production system. However, in some cases, the optimal point of operation does not lie within this area of the factor space. Exploring OOD predictions might produce higher efficiency, better product quality, or higher overall production. Therefore, in future work, we want to focus on OOD predictions to find new operating conditions in production systems.

Acknowledgments

This research has been conducted within the scope of the project "REIF - Resource-efficient, Economic and Intelligent Foodchain," funded by the German Federal Ministry for Economic Affairs and Climate Action. We also want to thank the "Geothermische Kraftwerksgesellschaft Traunreut mbH" for providing the data of their production process and conducting the experiments necessary for this research.

References

[1] J. Schulman et al., 2022. ChatGPT: Optimizing Language Models for Dialogue.

[2] Faraj, S., Pachidi, S., Sayegh, K., 2018. Working and organizing in the age of the learning algorithm. Information and Organization 28 (1), 62–70.

[3] 2021. Mannheimer Innovationspanel: Studie n=1521.

[4] 2022. Künstliche Intelligenz – Wo steht die deutsche Wirtschaft?: Studie n=606.

[5] 2020. State of AI in the Enterprise: Studie n=168.

[6] Zha, D., Bhat, Z.P., Lai, K.-H., Yang, F., Hu, X., 2023. Data-centric AI: Perspectives and Challenges, in: Banerjee, A., Zhou, Z.-H., Papalexakis, E.E., Riondato, M. (Eds.), Proceedings of the 2023 SIAM International Conference on Data Mining (SDM). Society for Industrial and Applied Mathematics, SIAM, Philadelphia, Pennsylvania, pp. 945–948.

[7] Wiesbaden, S.F., 2013. Kompakt-Lexikon Wirtschaftsmathematik und Statistik: 750 Begriffe nachschlagen, verstehen, anwenden, 1st ed. ed. Springer Gabler, Wiesbaden, 157 pp.

[8] Hüllermeier, E., Waegeman, W., 2021. Aleatoric and epistemic uncertainty in machine learning: an introduction to concepts and methods. Mach Learn 110 (3), 457–506.

[9] Arjovsky, M., 2021. Out of Distribution Generalization in Machine Learning. https://arxiv.org/pdf/2103.02667.

[10] Shen, Z., Liu, J., He, Y., Zhang, X., Xu, R., Yu, H., Cui, P., 2021. Towards Out-Of-Distribution Generalization: A Survey. https://arxiv.org/pdf/2108.13624.

[11] Molnar, C., 2022. Interpretable machine learning: A guide for making black box models explainable, Second edition ed. Christoph Molnar, Munich, Germany, 318 pp.

[12] Breiman, L., 2001. Random Forests. Mach Learn 45 (1), 5–32.

[13] Lundberg, S., Lee, S.-I., 2017. A Unified Approach to Interpreting Model Predictions.

[14] Kläs, M., Vollmer, A.M., 2018. Uncertainty in Machine Learning Applications: A Practice-Driven Classification of Uncertainty, in: Computer Safety, Reliability, and Security. Springer International Publishing, Cham, pp. 431–438.

[15] Bickel, P.J., Blackwell, D., 1967. A Note on Bayes Estimates. Ann. Math. Statist. 38 (6), 1907–1911.

[16] Weiss, R.E., 2010. Bayesian methods for data analysis. American journal of ophthalmology 149 (2), 187-188.e1.

[17] Gal, Y., Ghahramani, Z., 2016. Dropout as a Bayesian Approximation: Representing Model Uncertainty in Deep Learning, in: Proceedings of The 33rd International Conference on Machine Learning. PMLR, New York, New York, USA, pp. 1050–1059.

[18] Cohn, D.A., 1996. Neural Network Exploration Using Optimal Experiment Design. Neural networks : the official journal of the International Neural Network Society 9 (6), 1071–1083.

[19] Foster, A., Jankowiak, M., Bingham, E., Horsfall, P., Teh, Y.W., Rainforth, T., Goodman, N., 2019. Variational Bayesian optimal experimental design.

[20] Dieb, T.M., Tsuda, K., 2017. Machine Learning-Based Experimental Design in Materials Science, in: Tomlinson, M., Jung Tjhai, C., Ambroze, M.A., Ahmed, M., Jibril, M. (Eds.), Error-Correction Coding and Decoding: Bounds, Codes, Decoders, Analysis and Applications. Springer, Cham, pp. 65–74.

[21] Burger, B., Maffettone, P.M., Gusev, V.V., Aitchison, C.M., Bai, Y., Wang, X., Li, X., Alston, B.M., Li, B., Clowes, R., Rankin, N., Harris, B., Sprick, R.S., Cooper, A.I., 2020. A mobile robotic chemist. Nature 583 (7815), 237–241.

[22] Attia, P.M., Grover, A., Jin, N., Severson, K.A., Markov, T.M., Liao, Y.-H., Chen, M.H., Cheong, B., Perkins, N., Yang, Z., Herring, P.K., Aykol, M., Harris, S.J., Braatz, R.D., Ermon, S., Chueh, W.C., 2020. Closed-loop optimization of fast-charging protocols for batteries with machine learning. Nature 578 (7795), 397–402.

Biography

Sebastian Maier is a research associate at the Fraunhofer Institute for Casting, Composite, and Processing Technology IGCV since 2020 and works in the Digital Engineering and AI group. He studied mechanical engineering at Ulm University of Applied Sciences and Applied Research on Computer Science at Augsburg University of Applied Sciences.

Patrick Zimmermann is a research associate at the Fraunhofer Institute for Casting, Composite, and Processing Technology IGCV since 2018 and works in the area of plant connectivity, data models for operational technology, and process optimization. He studied mechanical engineering at the Technical University of Munich.

Rüdiger Daub is the holder of the Chair of Production Engineering and Energy Storage Systems at the Technical University of Munich and director of the Fraunhofer IGCV. After studying Electrical Engineering and Information Technology at the Karlsruhe Institute of Technology (KIT), he earned his doctorate at the Technical University of Munich (TUM). From 2012 to 2021, he held several positions at BMW Group Munich, most recently as Head of Technology Development and Prototype Construction of Lithium-Ion Cells.

5th Conference on Production Systems and Logistics

Investigation of Deep Learning Datasets for Warehousing Logistics

Dimitrij-Marian Holm[1], Philipp Junge[1], Jérôme Rutinowski[2], Johannes Fottner[1]

[1]*Technical University of Munich, Chair of Materials Handling, Material Flow, Logistics, Garching b. München, Germany*

[2]*TU Dortmund University, Chair of Material Handling and Warehousing, Dortmund, Germany*

Abstract

Deep Learning for Computer Vision holds great potential in warehousing logistics, for example for applications such as mobile robots or autonomous forklifts. However, the availability of labelled image datasets within this area is limited. To address this problem, we benchmarked two different datasets, LOCO (Logistics Objects in Context) and TOMIE (Tracking Of Multiple Industrial Entities), to find out, if these datasets can be used interchangeably. Therefore, we examine the usability of these datasets for Object Detection tasks using the YOLOv7 framework. For this we trained several networks and compared them with each other. A deep analysis between these two datasets shows that they are quite different and only suitable for specific tasks which are not interchangeable, despite having emerged from the same research domain. More thorough investigations are performed to find the reasons for this lack of compatibility. To close the gap between LOCO and TOMIE, a synthetic data generation pipeline for pallets is developed and 18,000 synthetic pallet images are rendered. Furthermore, models are trained based on the synthetic data and compared with the models trained on real data. The synthetic data generation pipeline successfully closes the reality gap, and the performance on TOMIE is increased, but the performance on LOCO remains significantly weaker, in comparison. To develop a deeper understanding of this behaviour we examine the underlying datasets and the reasons for the performance difference are identified.

Keywords

Warehousing Logistics; Datasets Generation; Deep Learning; Object Detection

1. Introduction

Robotic systems, such as AGVs (autonomous guided vehicles) and autonomous forklift trucks are encountered more and more in warehousing environments, solving tasks, like recognising, storing and collecting pallets and other objects of interest [1]. To enhance the abilities of such robotic systems, they require the capability of a deeper understanding of the environment by using sensors such as cameras and algorithms to extract semantic information. For this task, there still remains a huge untapped potential for Deep Learning (DL) and Computer Vision (CV). For Deep Learning however, lots of data is necessary, which is sparsely available for warehousing environments [2].

Since existing datasets from the context of warehousing logistics are limited, it first leads us to LOCO (Logistics Objects in COntext), which was the first dataset of its kind [3]. Also, TU Dortmund University recently published a tracking dataset in the field of warehousing logistics called TOMIE (Tracking Of Multiple Industrial Entities) [4].

DOI: https://doi.org/10.15488/15311
ISSN: 2701-6277

Both datasets are designed for Object Detection in warehousing environments, providing semantic data of logistical entities within their images. In addition, we address the question to what extent synthetic data can improve the combination of both datasets in terms of Object Detection results.

Therefore, LOCO as well as TOMIE are being investigated in terms of their usability for DL. The use of synthetic data is also evaluated, and an image generation pipeline is developed for this purpose. Experiments are conducted using the state of the art Object Detection framework YOLOv7 [5].

2. Related Work

Object Detectors are normally used on a special domain, therefore the need for a specialised dataset is present. In the field of warehousing logistics, there was no publicly available dataset until the release of LOCO [3] as well as the recently published paper of TOMIE [4]. Nevertheless, there is some work that dealt with Object Detection in logistics using real data: In [6] a survey on DL-based Object Detection in industrial manufacturing lines was conducted. Another paper [1] deals with the automated detection of pallets by unmanned forklifts. 4,620 photos from real warehouses were used for training with the Single-Shot-Detection (SSD) architecture. The work of [7] aimed to detect pallets and their associated pallet pockets using Object Detection. For this purpose, Faster-RCNN, SSD and YOLOv4 were compared, with the result that Faster-RCNN and SSD achieve better performance, but small objects are detected significantly better by YOLOv4. Pallet detection with YOLOv5 was investigated in [8]. 1,350 images were captured with three different cameras at different times of the day. In addition to pallet Object Detection with SSD, [9] used depth data to extract the 3D pallet point-cloud model for accurate positioning. For this purpose, more than 1,000 images of pallets were taken under different lighting conditions and at normal forklift reach.

Due to the lack of datasets in the real logistics environment, there are many efforts to generate them synthetically. There are different ways of creating synthetic data, one of which is rendering images with 3D software, e. g. with Blender or Unity. This can be roughly divided into trying to render photo-realistic images, imitate real world parameters as close as possible, or using Domain Randomisation (DR), for which the realism is not that important. DR is an approach where parameters of the source domain are randomized with the idea that the target domain is recognised as just another variation of the source domain by the model [2]. [10] focused on the detection of retail-objects, using a DR approach with random 3D objects in the background of the objects of interest. The Hamburg University of Technology [11] dealt with the pose estimation of a Euro-pallet, also using Blender. However, the focus here lays more on photorealism, the textures consist of RGB images from a real camera. An mAP of 0.94 was reached on own test data. In [2], an industry-based synthetic dataset consisting of small load carriers was used to evaluate their data generation pipeline using Blender and DR. In addition to rendering images and compositing real data, there is another promising way to generate synthetic data, which is generative AI. AI has been given a whole new meaning by Large Language Models like ChatGPT, but are also potentially useful in the field of Object Detection. GANs (Generative Adversarial Networks) for instance, can be helpful in domain adaptation in order to bring synthetic images closer to reality [12]. However, research on generative AI for Object Detection in warehousing logistics is still at the beginning.

In the context of warehousing, only one synthetic dataset is known to us [13]. This dataset, however, is suited for re-identification and not for Object Detection tasks. One further dataset, which is currently available only for collaborators and partners, is SORDI [14], created to tackle the lack of industrial synthetic datasets. 200,000 bounding box annotated images were rendered, containing eight different assets in 32 scenarios, resulting in more than 1 million bounding boxes.

3. Methodology

The goal of this paper is the investigation of the LOCO and TOMIE dataset in terms of usage potential for Object Detection. We evaluated if the Object Detection performance of LOCO can be improved by using a modern framework, the TOMIE dataset or self-created synthetic data. The best-case scenario would be a model which generalises well on all data in context of logistics by using all three sources of data.

First, data exploration and comparison for both LOCO and TOMIE is conducted. With the base models of both real datasets, reciprocal inference is conducted to evaluate how well each model is performing on the other dataset. Regarding synthetic data (from now on referred to as the SYNTH dataset), first, a pipeline was created using Blender, generating images of the pallet class. To bridge the reality gap, DR as well as domain knowledge are used. In this case, the latter means that we already know where and under which conditions (i. e., loaded, on shelves) pallets are often seen. After generating these images, the pipeline also must prepare the data for training and data exploration. Following that, training with YOLOv7 is conducted, leading to a base model trained on SYNTH. As with the real data, inference is conducted with TOMIE and LOCO to determine how well purely synthetic pallet data works in the logistics domain. With the then available base models, fine-tuning is done - for the SYNTH base model with LOCO and TOMIE, for the real datasets only with the respective other dataset. Afterwards, inference is conducted again with LOCO and TOMIE to evaluate how fine-tuning helps to generalise or if catastrophic forgetting occurs. To compare the performance of the SYNTH dataset, base models are again trained with LOCO and TOMIE also using only the pallet class. The overall approach can be seen in Figure 1.

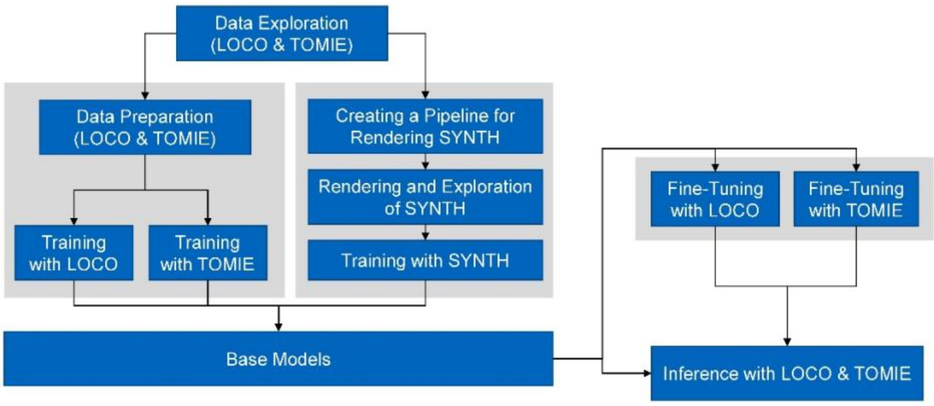


Figure 1: Training and test approach.

4. Data Exploration

4.1.1 LOCO

LOCO is a dataset which is split into five subsets, representing different warehousing logistics environments. A total of 64,993 images were captured, images 39,101 remained after removing blurred and similar images. From those, 5,593 were selected for bounding box annotation for five classes: pallets, small load carriers, stillages, forklifts and pallet trucks. In total there are 151,428 instances of those classes, which have a unbalanced class distribution. Pallets make up the biggest part of the annotations, followed by small load carriers. Forklifts occur only 598 times in the dataset. There are 496 images without any annotations, the majority of the images hold at least ten annotations and a significant number even more than 50 annotations. Also, the relative size of the objects is smaller in LOCO than in common datasets like COCO. 90% of the annotations have a bounding box size smaller than 2% of the image size. In COCO, that is only the case for 70% of the objects. The majority of LOCO annotations are even smaller than 1% of the image size.

4.1.2 TOMIE

TOMIE [4] was recorded in a research facility representing a warehousing environment. In this environment, different warehousing scenarios were recorded using six cameras in different locations, creating six different data subsets. The dataset consists of 112,860 frames and 640,936 entity instances of nine classes including pallets, stillages, small load carriers and forklifts. Compared to LOCO this means that it offers the same object classes, except for the pallet trucks. The number of annotations per class is more balanced in TOMIE than in LOCO. Nevertheless, the pallet also dominates here, with over twice as many instances as the small load carriers. Stillages are the rarest while there are still twice as many forklifts. TOMIE has few instances per image, especially compared to LOCO, the majority of the images has no more than 10 annotations. The size of the annotations is more irregular compared to LOCO. This is because the camera distance to the respective objects remains virtually the same throughout the recordings. Furthermore, there are no annotations with a bounding box smaller than 0.1% of the image size.

4.1.3 SYNTH

Due to the scope of this paper, only one of the potential classes is considered. Pallets were chosen since they play the most elementary role and occur the most in the existing datasets. Thus, the performance of the synthetic data can be measured best.

To ensure data diversity, 13 different pallet and three different warehouse assets are used for the generation of SYNTH. The pallets are randomly spawned following various parameters which are randomly selected based on a self-defined range that can be changed before rendering. This includes the pose, texture, form and quantity. In addition to labelling full pallets, 2D front and side views of pallets were added to SYNTH. Camera position, orientation, and field of view were also randomized. Distractor objects with random attributes were placed in the foreground and background. The background was randomized by changing floor and wall textures. 3D assets from the logistics context were placed in the background. Random lighting was applied, including the use of a shadow thrower to simulate poorly illuminated pallets. Rendering quality was varied, including resolution and number of samples. After rendering, some sanity post-processing was applied, like excluding pallets which are barely visible in the image, either because they are placed at the image edges, or because they are occluded.

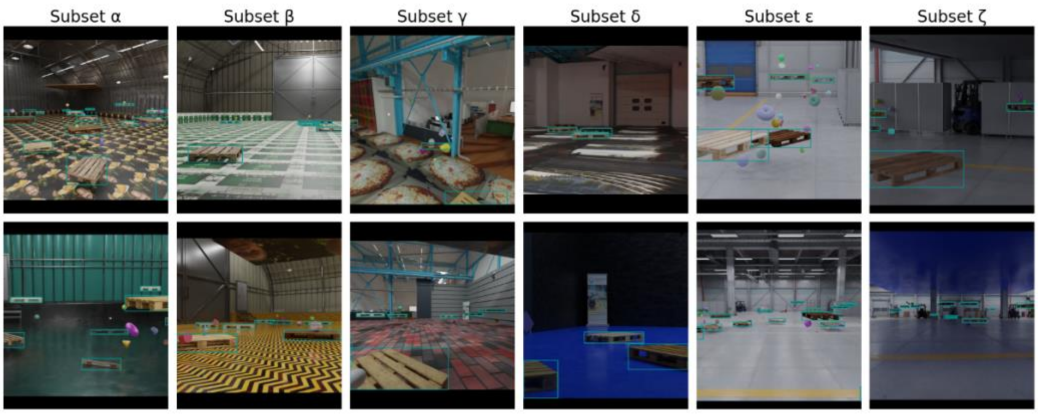


Figure 2: Examples of the different subsets of SYNTH.

About 18,000 images were rendered. with a total of 125,937 instances, divided into 6 subsets, all with slightly different parameters. Examples for images from the dataset can be seen in Figure 2. The annotations per image distribution is located between LOCO and TOMIE with the maximum of images having 1 to 5 pallets and no images with more than 50 pallets, with seven on average. The size of the bounding boxes is quite similar to LOCO. The composition of the dataset and the split into different subsets is shown in Table 1.

Table 1: Statistics of the SYNTH dataset.

Subset	Number of Images	Number of Pallets	Notes
α	2,992	25,279	Full randomization
β	3,017	15,926	Pallets only on floor level
γ	2,989	18,797	Full randomization
δ	3,006	15,109	Pallets only on floor level
ϵ	2,991	32,544	No texture change for floor and wall
ζ	3,035	19,625	No texture change for floor and wall More pallet front side instances

5. Experiments

5.1 Real Data

For the experiments with real data, the LOCO subsets (1-5) were split into training and validation sets, i. e. 2, 3 and 5 as training sets and subsets 1 and 4 as validation sets. Using TOMIE, we split the subsets (A - F) so that the training set contains A, B, E and the sets C and D as the validation set. We used an image resolution of 1120px, a batch size of 4, an IoU of 0.5 and a confidence of 0.001. For training, the standard YOLOv7 P5 parameters and pre-trained COCO weights were used.

5.1.1 LOCO Base Model

We trained the LOCO base model with Adam, a LR (Learning Rate) of 0.001 and 5 frozen layers. Inference was conducted with LOCO as well as TOMIE data on the weights of the best epoch. For LOCO and TOMIE the results are listed in Table 2.

Table 2: Inference results one the LOCO base model with LOCO and TOMIE.

Class Dataset	All	Small load carrier	Forklift	Pallet	Stillage	Pallet truck
LOCO	0.52	0.467	0.350	0.737	0.688	0.359
TOMIE	0.234	0.0	0.0	0.023	0.422	-

For fine-tuning with TOMIE, subset B was selected as training set and subset D as validation set. After conducting runs with several optimizer and freeze parameters (T), the best mAP@.5 reached was 0.67 using SGD and no frozen layers (T0). To prevent catastrophic forgetting, we applied mixed fine-tuning (M) and frozen layers: LOCO subset 1 was added to the training set, while subset 4 was added to the validation set, since both were not used to train the base model. The optimizer used was SGD and the LR was increased from 0.001 to 0.01 due to a higher number of and more diverse training data. Results are shown in Table 3.

Table 3: Inference results (mAP@.5) for TOMIE and LOCO with LOCO based model fine-tuned with TOMIE.

Inference results for TOMIE subsets A, C, E and F on the LOCO base model fine-tuned with TOMIE					Inference results for LOCO subset 4 on the LOCO base model fine-tuned with TOMIE			
Class	M T50	M T5	T0	T50	M T50	M T5	T0	T50
All	0.65	0.645	0.630	0.624	0.182	0.006	0.033	0.001
Forklift	0.35	0.289	0.293	0.338	0.057	0.001	0.002	0.001
Pallet	0.608	0.65	0.656	0.562	0.552	0.022	0.127	0.002
Stillage	0.993	0.995	0.995	0.972	0.036	0	0	0
Pallet truck	-	-	-	-	0.081	0	0.001	0

5.1.2 TOMIE Base Model

SGD was chosen, with an LR of 0.01 and five frozen layers as well as a resolution of 1152px. Subsets A, B, E and F served as the training set, while subset C and D were used for validation. After the 10th epoch a training mAP@.5 of 0.846 was reached, which was not surpassed after. Inference was first conducted with the LOCO benchmark (subsets 1 and 4) on the weights from the best epoch, which lead to an mAP@.5 of 0.002. On the TOMIE base model, fine-tuning with LOCO was conducted for 40 epochs while using SGD: once with 10, the other time with no frozen layers. The results are shown in Table 4.

Table 4: Inference results mAP@.5 for LOCO subsets 1 and 4 on the TOMIE base model.

Class Dataset	All	Small load carrier	Forklift	Pallet	Stillage
LOCO	0.002	0.0	0.0	0.001	0.005
TOMIE	0.839	0.826	0.613	0.937	0.977

The split and the other parameters are the same as before. The mAP@.5 inference results for both trained models are shown in Table 5, each for the weights of the best epoch.

Table 5: Inference results mAP@.5 on the TOMIE base model fine-tuned with LOCO.

Class	LOCO (T10)	TOMIE (T10)	LOCO(T0)	TOMIE(T0)
All	0.491	0.243	0.514	0.215
Small load carrier	0.379	0	0.485	0
Forklift	0.258	0	0.266	0
Pallet	0.737	0.011	0.745	0.019
Stillage	0.652	0.961	0.663	0.841
Pallet truck	0.431	-	0.411	-

5.2 Synthetic Data

In this section we analysed the quality of our SYNTH dataset by training models only with the pallet class. For this, we trained a SYNTH base model for 40 epochs with five frozen layers and SGD with a LR of 0.01. Subsets α and γ were used as training set, subset ϵ as validation set, the remaining data were used for inference testing. This way, the subsets with the most DR are used for training and the one closest to reality for validation. Proceeding with our SYNTH base model, we conducted additional experiments by fine-tuning the model with TOMIE and LOCO. We also trained a two staged fine-tuned SYNTH base model, which was first fine-tuned with TOMIE and LOCO afterwards. For inference testing we used subset 1 from LOCO. All experiment results are shown in Table 6.

Table 6: Inference results (mAP@.5) with LOCO subset 1 on different configurations.

Model	mAP@.5
SYNTH	0.096
LOCO fine-tuning on SYNTH	0.740
TOMIE fine-tuning on SYNTH	0.005
LOCO fine-tuning on TOMIE on SYNTH	0.724

In addition to our fine-tuned experiments we also tested all subsets from LOCO and TOMIE to determine how the inference with real data is when used only with models trained using SYNTH, which is shown in Table 7.

Table 7: Inference results on the SYNTH base model.

LOCO subset	1	2	3	4	5		all
mAP@.5	0.113	0.044	0.029	0.054	0.054		0.051
TOMIE subset	A	B	C	D	E	F	all
mAP@.5	0.718	0.263	0.416	0.003	0.752	0.015	0.343

6. Evaluation

6.1.1 Real Data

The LOCO base model shows an improved mAP compared to the original paper. However, while pallets and stillages produce reliable results, small load carriers, forklifts and pallet trucks perform poorly. For forklifts and pallet trucks, the low number of occurrences and variety of the objects are likely to be responsible for the model's poor performance. Delving deeper into LOCO, one reason is the annotation quality (see Figure 3). There are missing and faulty annotations, when comparing inference with ground truth. Also, the objects are in part difficult to recognise, be it due to their size or blur.

Figure 3: Comparison of the ground truth (left) and the predictions (right) in LOCO.

For the TOMIE base model, we discovered a fast training convergence. One possible reason for this is that the data is quite easy to learn on. The stillage class is detected well, which is because in all images it is the very same stillage instance. The performance for the forklift is, in comparison, rather poor. A reason for this might be the inconsistent annotations (see Figure 4) with sometimes the person dragging it being included and sometimes not. Annotation inconsistency also occur for other categories, which could lead to the notably fluctuation in training performance. Also, the model is overfitting on loaded pallets, which are sometimes detected even if they are occluded.

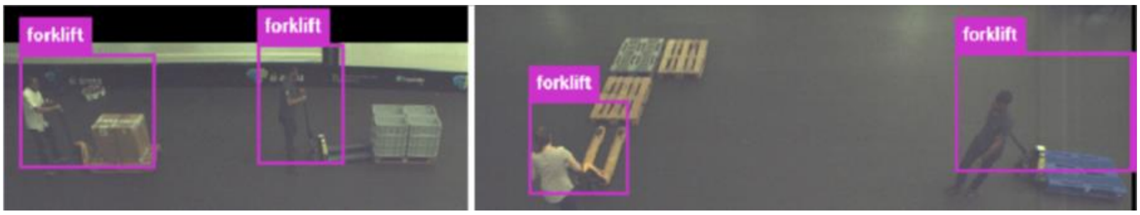


Figure 4: Examples of annotation inconsistencies of forklifts in TOMIE.

The performance of TOMIE data on the LOCO model is poor, except for the stillage class. Vice versa, performance is even worse. A central criteria is probably the camera perspective. In TOMIE it is almost a top-down, bird's eye view, whereas in LOCO the pictures were all taken relatively close to the ground. In addition, a model trained on LOCO mostly labels the visible part of loaded pallets. With TOMIE, the bounding box always covers the whole pallet. This leads to incorrect predictions due to low IoU, even though the pallet may have been recognised correctly (see Figure 5).

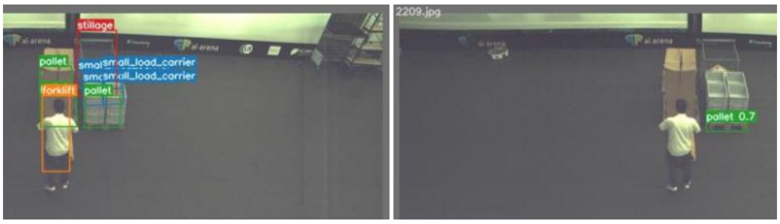


Figure 5: Pallet annotation compared to inference results with LOCO on the TOMIE dataset.

6.1.2 Synthetic Data

The SYNTH model performs much better on TOMIE than on LOCO, showing that the reality gap could be overcome with synthetic data. A deeper investigation of the LOCO dataset shows that pallets in shelves are rarely recognised, especially if the pallets do not face the camera or the instance is small (Figure 6, bottom left). The LOCO base model can recognise these objects much better. Stacked pallets are also problematic (Figure 6, top images).

Figure 6: Inference samples with LOCO subset 1 (dark green = ground truth, orange = LOCO base model, blue = SYNTH base model).

For pallets, in general it seems like fine-tuning with LOCO on a base model improves performance and again fine-tuning on SYNTH performs slightly better than fine-tuning on TOMIE. For fine-tuning with TOMIE on SYNTH, the inference with subset 1 performs very poorly as usual and as expected, fine-tuning on LOCO still brings a better performance. Finally, we analysed the combination of the SYNTH base model with LOCO and TOMIE data. For inference with subset 1 with LOCO fine-tuned model, a better performance can be achieved by fine-tuning.

7. Conclusion

In this paper, we conducted a thorough examination of two warehousing logistics datasets, LOCO and TOMIE. Our investigation not only involved a comparative analysis but also sought broader insights relevant to computer vision and logistics object detection. While first results demonstrated the superiority of our models on the LOCO benchmark, we identified inherent dataset limitations, including class distribution imbalances and annotation inaccuracies, particularly with pallets and small load carriers. TOMIE, with its consistent camera perspectives, presented challenges like label inconsistencies and fluctuations during training. These issues underscore the importance of robust dataset curation and annotation. Secondly, our analysis revealed substantial disparities between LOCO and TOMIE, spanning different camera perspectives, environmental conditions, and labelling approaches, shown by catastrophic forgetting during transfer learning. To bridge these gaps, we introduced a synthetic data generation pipeline, effectively leading to performance enhancements. In summary, our study not only offers insights into LOCO and

TOMIE but also underscores the broader relevance of robust dataset creation and domain adaptation challenges in logistics object detection. Bridging these gaps is crucial for enhancing model robustness and applicability in real-world logistics scenarios.

References

[1] Li, T., Huang, B., Li, C., Huang, M., 2019. Application of convolution neural network object detection algorithm in logistics warehouse. The Journal of Engineering 2019.

[2] Mayershofer, C., Ge, T., Fottner, J., 2021. Towards Fully-Synthetic Training for Industrial Applications, in: , LISS 2020, pp. 765–782.

[3] Mayershofer, C., Holm, D.-M., Molter, B., Fottner, J., 2020. LOCO: Logistics Objects in Context, in: 2020 19th IEEE International Conference on Machine Learning and Applications (ICMLA), pp. 612–617.

[4] Jérôme Rutinowski, Hazem Youssef, Sven Franke, Irfan Fachrudin Priyanta, Frederik Polachowski, Moritz Roidl, Christopher Reining, 2023. Semi-Automated Computer Vision based Tracking of Multiple Industrial Entities - A Framework and Dataset Creation Approach.

[5] Wang, C.-Y., Bochkovskiy, A., Liao, H.-Y.M., 2022. YOLOv7: Trainable bag-of-freebies sets new state-of-the-art for real-time object detectors. https://arxiv.org/pdf/2207.02696.

[6] Hafiz Mughees Ahmad, Afshin Rahimi, 2022. Deep learning methods for object detection in smart manufacturing: A survey. Journal of Manufacturing Systems 64, 181–196.

[7] Zaccaria, M., Monica, R., Aleotti, J., 2020. A Comparison of Deep Learning Models for Pallet Detection in Industrial Warehouses, in: 2020 IEEE 16th International Conference on Intelligent Computer Communication and Processing (ICCP), pp. 417–422.

[8] Manurung, P., Rusmin, P.H., Yusuf, R., 2022. Custom Pallet Detection Using YOLOv5 Deep Learning Architecture, in: 2022 International Symposium on Electronics and Smart Devices (ISESD), pp. 1–6.

[9] Li, Y., Ding, G., Li, C., Wang, S., Zhao, Q., Song, Q., 2023. A systematic strategy of pallet identification and picking based on deep learning techniques. Industrial Robot: the international journal of robotics research and application (ahead-of-print).

[10] Stefan Hinterstoisser, Olivier Pauly, Hauke Heibel, Martina Marek, Martin Bokeloh, 2019. An Annotation Saved is an Annotation Earned: Using Fully Synthetic Training for Object Instance Detection.

[11] Markus Knitt, Jakob Schyga, Asan Adamanov, Johannes Hinckeldeyn, Jochen Kreutzfeldt, 2022. Estimating the Pose of a Euro Pallet with an RGB Camera based on Synthetic Training Data.

[12] Sergey I. Nikolenko, 2019. Synthetic Data for Deep Learning.

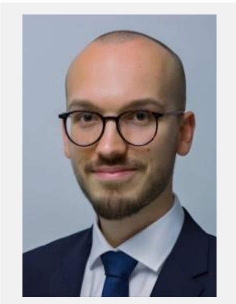
[13] Rutinowski, J., Vankayalapati, B., Schwenzfeier, N., Acosta, M., Reining, C., 2022. On the Applicability of Synthetic Data for Re-Identification. https://arxiv.org/pdf/2212.10105.

[14] Akar, C.A., Tekli, J., Jess, D., Khoury, M., Kamradt, M., Guthe, M., 2022. Synthetic Object Recognition Dataset for Industries, in: 2022 35th SIBGRAPI Conference on Graphics, Patterns and Images (SIBGRAPI), pp. 150–155.

Biography

Dimitrij-Marian Holm (*1990) studied Robotics at the University of Applied Science Munich. Since 2018 he is part of the Research Staff at the Chair of Materials Handling, Material Flow, Logistics, focusing on Machine Vision and Learning.

Philipp Junge (*1997) received a B.Sc. in Mechanical Engineering before completing the M.Sc. in Mechatronics & Robotics at the TU Munich in 2023. In his Master's thesis he worked at the Chair of Materials Handling, Material Flow, Logistics on the topic presented in this publication.



Jérôme Rutinowski (*1996) studied Mechanical Engineering at Ruhr-University Bochum. Since 2020 he is a researcher and PhD candidate at Prof. Dr. Dr. h. c. Michael ten Hompel's Chair of Material Handling and Warehousing at TU Dortmund University.

Johannes Fottner received a Dr.-Ing. degree in mechanical engineering from the Technical University of Munich (TUM), Munich, Germany in 2002. During the past 15 years, Johannes Fottner acted in different managing functions in the material-handling sector. Since 2016, he has been the head of the Chair of Materials Handling, Material Flow, Logistics with the TUM.

CPSL
CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
CPSL 2023-2

5th Conference on Production Systems and Logistics

Classification Of Flow-Based Assembly Structures For The Planning Of Flexible Mixed-Model Assembly

Nils Föhlisch[1], Peter Burggräf[1,2], Tobias Adlon[1], Verena Meier[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

The increasing product variance due to the growing individualization of customer requirements leads to smaller batch sizes and higher process time spreads in mixed-model assembly. The resulting decline in efficiency pushes conventional, less flexible assembly lines to the limits of their economic viability. Matrix assembly is an approach to increase flexibility and efficiency by decoupling workstations and dissolving cycle time constraints while maintaining flow. Both matrix and line assembly are flow-based assembly structures characterized by assembly objects moving according to the flow principle. Due to the numerous design options of flow-based assembly structures and the need to consider flexibility as a central decision criterion, the complexity of structural planning increases. The variety of the design options as well as their compatibility make it challenging for assembly planners to decide which configuration provides sufficient flexibility for their use case.

This paper presents a novel level-based classification for flow-based assembly structures that identifies the relevant configurations, ranks them according to provided flexibility, and breaks down the characteristics as well as their compatibility. The classification enables planners to efficiently compile, evaluate and select the flow-based structure configurations suitable for the individual use case during assembly structure planning. Planning efficiency and results are improved by transparently providing all configurations and their characteristics' compatibility to the planner without any research effort. The configuration selection focusing on flexibility by means of the classification can be the starting point of a subsequent simulation of the system behavior concerning efficiency.

Keywords

Mixed-Model Assembly, Matrix Assembly, Line Assembly, Flexibility, Efficiency, Assembly Planning

1. Introduction

In times of increasing individualization and diversification of customer requirements, the number of units per variant decreases and manufacturers use mixed-model assembly lines (MMAL) to minimize investments and associated risks [1, 2]. Different product variants with related characteristics are assembled in the same assembly line without retooling [3]. The different scopes in assembly stations make it increasingly difficult to maintain a uniform cycle time within the system [4]. Despite significant efforts for measures to reduce the cycle time spread and to optimize the variety of variants [4], conventional, clocked MMAL reach the limits of economic viability [5]. Therefore, companies are looking for assembly structures that are able to cope with the changing conditions in a short time and a paradigm shift towards more flexibility is emerging [2, 6, 7].

DOI: https://doi.org/10.15488/15252
ISSN: 2701-6277
publish-Ing.

Both line and matrix assembly form the flow-based assembly structures. Assembly objects move according to the flow principle through a series of assembly stations to be completed [8]. Matrix assembly makes use of the advantages of job-shop assembly regarding flexibility and of flow-line assembly regarding efficiency by decoupling workstations and dissolving the cycle time constraint [5]. Assembly objects each take an individual path through the assembly stations, which can be approached independently of each other [9]. In comparison to MMAL, matrix assembly is highly flexible and provides better efficiency for specific use cases [6]. In case of unforeseen events such as a disrupted or unavailable assembly station, it can easily be skipped by adjusting the path of an affected assembly object and the system can be changed proactively [10]. The significant advantages of matrix assembly go along with a higher control effort of the entire assembly and increased space requirements [11]. Currently, matrix assembly systems are not known to be fully deployed in series production, although the concept is broadly discussed in research and tested in prototype applications in practice [12]. Reasons for the slow introduction include companies' lack of experience in the use and planning of matrix assembly systems and the high planning complexity.

The majority of conventional approaches to assembly planning are based on the sequential phases *Formulation of the planning task, Rough planning, Detail planning* and *System implementation* [13]. After the formulation of the planning task and requirements regarding system adaptability, the rough planning is performed. In this, alternative characteristics are combined and thereby competing system configurations developed. After an evaluation, the superior configuration is selected, and the detailed planning is conducted.

When developing concepts during rough planning, planners are guided by classifications that differentiate assembly structures based on their constituting characteristics. Due to the increased planning scope in the structural planning of matrix assemblies, the known dimensions of those classifications do not describe the relevant characteristics with distinction. As a result, the system configurations of flow-based assembly structures are not transparent and structural planning becomes inefficient because planners must undertake research efforts to identify configurations. Hence a classification applicable for the structural planning of all flow-based assembly structures is required. In this paper, a novel classification for flow-based assembly structures to organize relevant configurations according to the provided flexibility is proposed. Therefore, the following research question is to be answered: *How can the cause-effect relationships of flow-based assembly structures be consolidated in a classification for efficient structural planning?*

2. Literature Review

The presented systematic literature review follows the approach described by VOM BROCKE ET AL. [14] and aims at identifying the key publications representing configurations of flow-based assembly structures and approaches to classify assemblies. The review scope and strategy were defined according to the taxonomy of literature reviews described by COOPER [15], extended by the Starlite mnemonic [16]. The concepts in the research field pursue the common goal of overcoming the challenges of multi-variant assembly, such as limited efficiency in particular, by increasing flexibility. This topic was conceptualized by iteratively identifying the main search terms for flexibilization and the domain. Accordingly, the search string (flexib* OR agil* OR matrix) AND ("assembly line" OR "assembly system" OR "mixed-model assembly") was applied for titles, keywords and abstracts resulting in 2,822 publications. These were analyzed using the PRISMA methodology [17] and 44 relevant publications remained after the screening process. A forward and backward citation search provided additional four publications. In the following, selected insights regarding concepts of flow-based assembly structures and classifications are presented.

2.1 Concepts of Flow-Based Assembly Structures

Flow-based assembly structures comprise both line and matrix assembly. The review results show that concepts to improve flexibility of conventional line assembly such as dynamic line balancing, sequencing, cycle time modifications, optimized system segmentation, flexible worker utilization and team work are already used in industrial practice and are therefore not presented in detail. However, these concepts reveal levers to improve flexibility like structuring in less dependent sub-systems, mitigating cycle time constraints and extending the utilization of workers' capabilities. In the following, the insights regarding matrix assembly structures are presented referring to these flexibility levers.

FOITH -FÖRSTER ET AL. investigate the productivity per area of assembly structures and show that it drops for line assemblies with a higher proportion of variants due to the cycle time spread, whereas modular structures such as matrix assembly roughly maintain their level [18]. GÖPPERT ET AL. develop a matrix assembly structure by dissolving the coupling of assembly stations established in assembly lines with the aim to increase the flexibility while maintaining efficiency [12]. This involves arranging self-adaptive and reconfigurable stations in the form of a grid within a segment of high flexibility requirements. MINGUILLON also uses a grid arrangement of stations that can perform multiple operations and have redundancy [19]. The assembly is cycle time-independent with individual processing times and unrestricted material flow. HOTTENROTT AND GRUNOW investigate the initial configuration of matrix assembly structures regarding mixed-model assembly of heterogeneous vehicles [6]. The authors show an average efficiency gain of 24.5 % using a matrix assembly compared to an assembly line if workers are not allowed to drift out of stations. The concepts share the same fundamental characteristics that the station coupling and cycle time constraint are dissolved but the authors provide negative definitions, i.e. it is shown which characteristics of a line assembly are omitted without naming the substituting mechanisms. The variety of similar, respectively synonymous terms, creates intransparency with respect to the central configuration characteristics.

By mitigating the cycle time constraint, its synchronization function needs to be substituted by means of planning and control. Although the analyzed publications do not explicitly refer to the applied extend of both, central concepts can be identified. GÖPPERT ET AL. describe an approach where individual order routes are controlled depending on the system status, such as resource availability, and a digital twin reacts to assembly progress at short notice [12]. BURGGRÄF ET AL. make use of a similar control approach that allows the assignment of assembly operations to stations without restrictions on fixed assembly sequences [9]. In contrast, the approach described by GRESCHKE ET AL. uses the same sequence of operations as in a line structure, so that the planning and control effort is reduced at the expense of flexibility [5]. HOTTENROTT AND GRUNOW allow a flexible operation sequence in the assembly precedence graph with focus on planning [6]. Orders are assigned to individual time periods in production and short-term planning includes the allocation of orders to AGVs. MINGUILLON develops a method for the control of a matrix assembly to increase the robustness against disturbances by means of predictive-reactive scheduling [19]. Scheduling comprises the temporal allocation of orders to stations and is carried out predictively on the basis of delivery dates. In addition, reactive rescheduling is used to respond in near-real time to disruptions that exceed anticipated levels. The approach combines planning and control scopes but is limited to cases with sufficient predictability of processes. In summary, concepts with a focus on planning, primarily controlling concepts and such with a combination of planning and control can be distinguished.

Different degrees of achieved flexibility can be distinguished regarding the utilization of workers' capabilities. FOITH-FÖRSTER ET AL. compare different structure types for assigning capabilities to assembly stations: universal structure, technology structure and single-process structure [18]. An assembly station of the universal type combines all assembly functions required to assemble the product in one single station. In contrast, the stations of a technology-based structure can just perform parts of the process (e.g. screw fastening). The highest specialization is realized within single-process stations designed for single operation only. In a matrix assembly, stations require multiple capabilities and redundancy is essential for flexibility according to several authors. In the concept according to GRESCHKE ET AL., the stations are equipped with multiple tools to perform various assembly operations [5]. KERN ET AL. make use of a flexible allocation of workers to stations so that capability profiles can be adapted [7]. The analysis of HOTTENROTT AND GRUNOW underlines that the mobility of workers has strong influence on efficiency [6]. SCHMITT ET AL. describe a matrix assembly concept, which is characterized by the fact that all assembly-relevant assets are mobilized and thus a maximum of flexibility is achieved [20]. In conclusion, the assignment and adaptability of the capabilities in a matrix assembly has strong influence on flexibility and efficiency. The concepts reach from fixed to fully adaptable capability profiles by using mobile production resources including workers and equipment. In case of mobile resources, the capability profile of a station results from the combination of the capabilities of the present workers and equipment. The mobility of resources enables the utilization of all available capabilities in a matrix assembly and is thereby key to maximum flexibility.

2.2 Approaches to Assembly Structure Classification

Classifications structure complex systems by differentiating the objects in the research field. In this chapter, useful approaches for the classification of assembly structures are introduced. LATOS ET AL. summarize eight conventional assembly structures by distinguishing the kinematic variables of stationary and moving assembly objects and workstations, as well as the direction and type of movement [21]. For example, stationary workstations characterize job shop assembly, where assembly objects are routed in an undirected and aperiodic manner. Moreover, a clocked line assembly considers stationary workstations and moving assembly objects, while its kinematics can be described as periodical due to the cycle time. Although this classification is a well-established concept in assembly planning, the level of detail regarding the kinematics parameters is insufficient to differentiate matrix assembly structures appropriately. The characteristic *undirected movement* is unspecific in the context of matrix assembly and *aperiodic movement* is also not further specified to match the variances of cycle time independence. Furthermore, the mobility characteristics are not intended to describe complex movement of production resources in a matrix assembly.

To the best of the authors' knowledge, there is no classification that can adequately describe line and matrix assembly structures simultaneously with specific dimensions applicable to assembly planning. The following classifications do not refer to assembly, but feature model structures that are beneficial for the classification of assembly structures. FROHM ET AL. present a classification for automation in manufacturing by breaking down activities into physical and cognitive tasks while acknowledging the cooperation between workers and technology [22]. The model contains seven levels of automation, from fully manual to fully automatic control, by which each manufacturing task can be classified. The level structure ensures easy usability for planners in automation planning and can be transferred to a classification for flow-based assembly structures to make different levels of flexibility transparent. Another level-based classification is SAE J3016 [23], which describes the degree of driving automation for on-road motor vehicle systems from no to full driving automation. This concept creates an easy-to-use methodology to allocate automation systems within six levels. The driving task is divided into its three main dimensions and characteristics are selected per dimension. Each level in the classification represents a relevant combination of characteristics. The model structure can be transferred to differentiate characteristics and classify configurations in the context of flow-based assembly structures by representing configurations as levels based on their constituent characteristics. Additionally, levels can be ranked according to their degree of provided flexibility.

In summary, the following conclusions regarding flow-based assembly structures and corresponding classifications can be derived. The characteristics applied in matrix assembly structures are only made transparent to a limited extent and it is uncertain which configurations exist for flow-based assembly structures. Furthermore, overall flexibility of structures remains unclear. Configurations cannot be distinguished by applying existing assembly classifications in the phase of structural planning and the entity of potential solutions cannot be identified efficiently during assembly planning with limited resources. From this, the following objectives are derived to answer the research question. The classification needs to represent the relevant configurations of flow-based assembly structures in a technology- and industry-independent way. Additionally, the level of detail of the classification is required to be adequate for the rough planning phase to enable the efficient identification of the suitable assembly structure for an application.

3. Morphology of Flow-Based Assembly Structures

The basis to identify the relevant assembly structure configurations for the classification are the concepts of flow-based assembly structures that emerge from the structured literature review. The methodological approach for the analysis is based on an empirically justified type determination according to KLUGE [24]. The morphology and classification were developed with regular involvement and systematic collection of feedback of an assembly expert panel. In addition to research institutes, the panel's consortium consists of automotive original equipment manufacturers and system enablers. In the first development phase (chapter 3), the relevant comparative dimensions are extracted that adequately capture both the similarities and differences between the concepts under investigation and finally characterize the types. For this purpose, the concepts are systematically abstracted and the relevant dimensions and their characteristics are distinguished with support of a morphological analysis according to ZWICKY [25]. Empirical regularity is analysed by means of iterative grouping. The second phase (chapter 4) focuses on the identification of the relevant types, respectively assembly structure configurations.

The resulting morphology of flow-based assembly structures contains the dimensions *Dimensionality of object routes, Synchronization principle of time* and *Mobility of production resources* in the columns (Tab. 1). Starting from the top, the characteristics in a column are ordered from high to low restrictions to adaption in an assembly structure and, by doing so, represent a ranking from low to high provided flexibility of the characteristics.

Table 1: Morphology of flow-based assembly structures

	Dimensions		
	Dimensionality of object routes	Synchronization principle of time	Mobility of production resources
Characteristics (Flexibility)	One-dimensional (Line)	Uniform cycle time	Stationary
	Two-dimensional (Matrix)	Average cycle time	Moving
		Expected operation time	
		Reaction to assembly progress	
		Expected operation time and reaction to assembly progress	

3.1 Dimensionality of Object Routes

The *Dimensionality of object routes* describes the degree of freedom of the routing of assembly objects between stations. *One-dimensional* and *two-dimensional* object routes are differentiated. One-dimensional routes correspond to the sequence and strict coupling of stations in a technological process direction which is the same for all assembly objects in the sense of a line assembly. All assembly objects take the same path through the assembly system. The flow is directional and objects cannot return to previous stations.

If stations are arranged in the form of a grid and assembly objects move freely without route restrictions, the object routes are considered *two-dimensional*. Accordingly, any other station in the system can be approached from each other and assembly objects can follow order-specific routes.

3.2 Synchronization Principle of Time

The dimension *Synchronization principle of time* describes the extent to which planning respectively control is used to coordinate work scopes between stations in the time dimension. A distinction is made between the five characteristics *Uniform cycle time, Average cycle time, Expected operation time, Reaction to assembly progress and Expected operation time and reaction to assembly progress*. These differ in particular concerning the degree of cycle time dependency, which in turn has a major influence on the amount of planning, respectively control, required during operation.

In an assembly structure with a *Uniform cycle time*, synchronization takes place using a cycle time, which is equal for all stations and after which the assembly object moves to the next station. The work scopes of an assembly station must be completed within the cycle time.

In an assembly structure with an *Average cycle time*, synchronization is achieved using a cycle time to be maintained on average over a defined number of cycles for all stations. The work scope of a product variant at a station may exceed the cycle time, provided that this time overrun is compensated in the subsequent cycles by variants with a smaller scope. This requires an appropriately coordinated sequencing of variants.

The third synchronization principle describes an assembly structure in which synchronization is achieved without cycle time constraint using planning based on *Expected operation times*. The expected operation time is an individual time slot per work scope for an assembly object, which is estimated based on available data such as MTM analyses and empirical values. Buffer times can be included in the planning to account for potential interruptions in the assembly process. The route through the assembly is pre-planned for each assembly object based on the distribution of operation times across stations for the planning period. The production resources in a station are bound to the predefined operation time when carrying out the work scope assigned to them.

In an assembly structure, which is synchronized by means of control in *Reaction to assembly progress*, the assembly progress is permanently monitored at all stations. When an assembly process is completed, the system reacts by assigning the next station to be approached by the assembly object in a situationally aware manner. No planning of the object route exists in advance. By doing so, there are fewer restrictions compared to a system based on an assembly schedule, such as synchronization using expected operation times.

An assembly structure can also be synchronized using a combination of planning in advance based on expected operation time and control in reaction to the assembly progress. In this case, the synchronization principle of *Expected operation time and reaction to assembly progress* is applied. As in the third characteristic, planning is carried out in advance according to the planning horizon. During operation, this plan is processed and, in parallel, the assembly progress is permanently monitored, as in the fourth characteristic. If deviations from the original plan occur, the system reacts by adapting control and, if the interruption is severe, the plan.

3.3 Mobility of Production Resources

The dimension *Mobility of production resources* describes the assignment of the resources assembly personnel and operating equipment to an assembly station differentiating between *stationary* and *moving*. If personnel and resources are *stationary*, they are permanently assigned to a specific station. Therefore, only the capability profile required at the respective station is used as a subset of the qualification matrix of the individual worker and the operating equipment.

The characteristic *moving* describes that the assembly personnel and/ or the operating equipment can move between assembly stations and thus change the place of use in the assembly system as required. In this way, the entire qualification matrix of the worker and/ or operating equipment can be utilized and capacities at stations can be varied. The capability of a station is thus determined by the capability profiles of the present worker and operating equipment.

4. Classification of Flow-Based Assembly Structures

In the second phase of the methodological approach, the classification is developed based on the morphology by means of an analysis of the cause-effect relationships. Initially, the model structure is developed based on the findings regarding the classifications leading to a chart with a stepwise increase of provided flexibility described by levels (Tab. 2). The classification uses dimensions as columns with characteristics represented in the cells. A configuration of a flow-based assembly structure, respectively a flexibility level, is determined by the combination of characteristics as a row in the chart. The analysis comprises the formation of all combinations of characteristics in the morphology and subsequent prioritization with regard to practical relevance by the expert panel. The priorities are assigned based on empirically found concepts and the experiences of the experts. Relevant combinations, respectively assembly structure configurations, are classified as flexibility levels from low to high provided flexibility in the classification. The levels are ranked according to provided flexibility by pairwise comparisons of the levels' characteristics combinations. A level has superior flexibility if the combination of characteristics provides fewer restrictions for adaption during operation (chapter 3).

Table 2: Classification of flow-based assembly structures

	Dimensions		
Levels / Flexibility	Dimensionality of object routes	Synchronization principle of time	Mobility of 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 usability and advantageousness of the developed classification in a practical context were reflected and evaluated by the 19-member panel of experts. By leveraging the expertise of the broad-based panel, an interdisciplinary evaluation including all disciplines involved in assembly planning was performed. The semi-structured reflection according to DÖRING AND BORTZ [26] was based on three assembly use cases and their products (chainsaw, automotive drive train and mobile crane assembly). The experts were asked to select the appropriate flexibility level for the individual application. The particular products were chosen due to their different requirements and each use case was described by crucial figures and properties relevant for planning. The chainsaw assembly was characterized by many variants in a single system (45 variants), a very high output quantity (30,000 pcs/year) and a long-term conversion of the shares from combustion engine variants to electric drive. The automotive use case contained five drive variants to be assembled in high output quantity (200,000 pcs/year) and with high volatility of variant shares. The use case with mobile cranes had a low output number (50 pcs/year) with only three main variants but with a wide variety of individualization options. Weighing the advantages and disadvantages of each level, the experts evaluated the extent to which a level was suitable for the particular use case. On this basis, the favored level was selected. For the chainsaw use case, the experts suggested splitting the system into a line segment (level 1 or 3), assembling the mostly variant independent base of the saw and a two-dimensional segment for the variant dependent assembly (level 9). A similar segmentation approach was considered for the mobile crane use case, but due to high operation duration and good predictability level 8 was favored for the overall structure. For the automotive assembly, the experts dismissed all levels with two-dimensional object routing due to too high expected effort for sequencing to re-establish the pearl chain for the following line segment and favored level 4. Finally, the experts evaluated the classification's advantages in such a planning situation.

All participating experts confirmed the classification's advantageousness for structural planning and its good usability in a practical context. The classification focuses on the aspects of an assembly structure that are essential in structural planning and reduces complexity by structuring the potential solutions. The experts noted that by using the classification, more attention is paid to the holistic view. This is particularly important when planning assembly structures with two-dimensional object routes. It was emphasized that an assembly could be segmented and the appropriate flexibility level is selected segment by segment. The classification structure supports the planning of such segment combinations and significantly reduces the required time to find an appropriate configuration as basis for more detailed analysis. Before planning an assembly structure, planners no longer have to laboriously search for dimensions, respectively characteristics, and analyze their compatibility. The classification also offers added value by being applicable for benchmarks by comparing the flexibility level of multiple assemblies. Additionally, it can be used to develop strategic target images and roadmaps by classifying the status quo of an assembly in the level structure and contrasting it to a target flexibility level or an evolution of levels in a schedule.

During the evaluation, interesting insights were obtained concerning the expected behavior of the levels. The experts confirmed that the flexibility grows with the levels while complexity also increases. Overall, it was seen as a prerequisite for the efficiency of two-dimensional levels that process times are sufficiently high or, in the case of low times, a correspondingly high work in process is kept in the system. To enable workers to move between stations, the number of stations or operating areas in the case of multiple workers per station needs to be higher than the number of workers. This applies analogously to moving operating equipment and the ratio is highly use case-dependent. In contrast, if workers and operating equipment are stationary, a significantly higher work in process at all stations is required to achieve maximum resource utilization. Overall, the achievable utilization of the system is determined by the interaction of the ratio of workers to stations, respectively operation areas, the mobility of resources and the amount of work in process.

Additionally, as the level increases, the order sequence, which is fixed in line systems, must become more flexible, or at least its dependence must be reduced. In the context of the use cases, the behavior of the systems in case of interruptions was discussed on the basis of the levels. It was underlined that for assemblies with a synchronization principle based on expected process times, higher planning reliability or lower susceptibility to interruptions is required than for primarily controlling systems. Especially for levels 5 to 8, good predictability of process times and limited fluctuation in the production program are essential. For these levels in particular, process times should not be too short and worker mobility is seen as an important enabler for high efficiency. Levels 11 and 12 were not favored because the expected effort measured against the benefit is still considered too high for the complexity described by the discussed use cases.

5. Conclusion and Outlook

This paper presents a classification that organizes all flow-based assembly structure configurations as foundation for structural planning in the rough planning phase. The classification contributes to improving planning efficiency and results by making configurations as well as their elements' compatibility transparent and thereby supports the planners. In summary, the formulated research question is answered by the flexibility levels including their characteristics combinations structured in the classification.

Extensions and possible classification improvements were identified for future research activities. For ease of use in practice, operationalization of the classification is desirable. A methodology that guides planners step-by-step through the process of structural planning using the classification needs to be developed. Ideally, this methodology is accessible to planners by utilizing a tool so that planner sonly need to enter input information of an use case and the appropriate flexibility levels are automatically prioritized. Furthermore, the knowledge of the implications of using a flow-based assembly structure for adjacent planning tasks needs to be extended for each level of the classification. This can further improve planning efficiency and counteract uncertainties during decision-making in interdisciplinary planning teams.

Acknowledgements

This research and development project is funded by the German Federal Ministry of Education and Research (BMBF) within *The Future of Value Creation – Research on Production, Services and Work* program in the *Industry 4.0 – Transformability of Companies in the Value Creation of Tomorrow (InWandel)* funding measure [02J21C130] and managed by the Project Management Agency Karlsruhe (PTKA). The authors are responsible for the content of this publication.

References

[1] Foith-Förster, P., Bauernhansl, T., 2016. Changeable Assembly Systems Through Flexibly Linked Process Modules. In: Procedia CIRP (41), 230–235. DOI: 10.1016/j.procir.2015.12.124.

[2] 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. In: Brecher, C., Klocke, F., Schmitt, R., Schuh, G. (Ed.): Internet of Production für agile Unternehmen. Aachen: Apprimus, 231–259.

[3] Gaal, A., Hofer, K., Ryback, T., Lingitz, L., Sihn, W., 2020. An agent-based approach to planning and controlling adaptable cell-oriented assembly systems. In: Procedia CIRP (93), 1158–1163. DOI: 10.1016/j.procir.2020.04.064.

[4] Kern, W., Rusitschka, F., Kopytynski, W., Keckl, S., Bauernhansl, T., 2015. Alternatives to assembly line production in the automotive industry. In: The 23rd International Conference on Production Research.

[5] Greschke, P., Schönemann, M., Thiede, S., Herrmann, C., 2014. Matrix Structures for High Volumes and Flexibility in Production Systems. In: Procedia CIRP (17), 160–165. DOI: 10.1016/j.procir.2014.02.040.

[6] Hottenrott, A., Grunow, M., 2019. Flexible layouts for the mixed-model assembly of heterogeneous vehicles. In: OR Spectrum 41 (4), 943–979. DOI: 10.1007/s00291-019-00556-x.

[7] Kern, W., Lämmermann, H., Bauernhansl, T., 2017. An Integrated Logistics Concept for a Modular Assembly System. In: Procedia Manufacturing (11), 957–964. DOI: 10.1016/j.promfg.2017.07.200.

[8] Bullinger, H. J., Rieth, D., Euler, H. P., 1993. Planung entkoppelter Montagesysteme - Puffer in der Montage. B.G. Teubner Verlag, Stuttgart.

[9] 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. In: Procedia CIRP (93), 1206–1211. DOI: 10.1016/j.procir.2020.03.079.

[10] Burggräf, P., Dannapfel, M., Adlon, T., Kahmann, H., Schukat, E., Holtwiesche, L., 2020. Multiagentensysteme in der Agilen Montage. Echtzeitfähige Ablaufplanung flexibler Operationsfolgen. In: wt Werkstatttechnik online 110 (4), 170–176.

[11] Burggräf, P., Dannapfel, M., Adlon, T., Schukat, E., Kahmann, H., Holtwiesche, L., 2020. Modeling and evaluating agile assembly systems using mixed-integer linear programming. In: Procedia CIRP (93), 1073–1078. DOI: 10.1016/j.procir.2020.04.072.

[12] 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.

[13] Bäumers, Y., 2017. Wirtschaftlicher Detaillierungsgrad der Montageablaufplanung. Dissertation, RWTH Aachen University.

[14] Brocke, J. Vom, 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.

[15] Cooper, H. M., 1988. Organizing knowledge syntheses: A taxonomy of literature reviews. In: Knowledge in Society 1 (1), 104–127. DOI: 10.1007/BF3177550

[16] Booth, A., 2006. 'Brimful of STARLITE': toward standards for reporting literature searches. In: Journal of the Medical Library Association 94 (4), 421–430.

[17] Moher, D., Liberati, A., Tetzlaff, J., Altman, D. G., 2009. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. In: Annals of Internal Medicine 151 (4), 264–269.

[18] Foith-Förster, P., Elsing, J.-H., Bauernhansl, T., 2017. Effiziente Montagesysteme ohne Band und Takt. Sind modulare Produktionsstrukturen eine konkurrenzfähige Alternative zur abgetakteten Linie? In: wt Werkstatttechnik online 107 (3), 169–175.

[19] Minguillon, F. E., 2020. Prädiktiv-reaktives Scheduling zur Steigerung der Robustheit in der Matrix-Produktion. Dissertation, Karlsruher Institut für Technologie (KIT).

[20] Schmitt, R. H., Hüttemann, G., Münker, S., 2021. A priori performance assessment of line-less mobile assembly systems. In: CIRP Annals – Manufacturing Technology 70 (1), 389–392. DOI: 10.1016/j.cirp.2021.04.059.

[21] Latos, B. A., Holtkötter, C., Brinkjans, J., Kalantar, P., Przybysz, P. M., Mütze-Niewöhner, S., 2018. Partizipatives und simulationsgestütztes Vorgehen zur Konzeption einer flexiblen und demografierobusten Montagelinie. In: Zeitschrift für Arbeitswissenschaft 72 (1), 90–98. DOI: 10.1007/s41449-017-0081-8

[22] Frohm, F., Lindström, V., Winroth, M., Stahre, J., 2008. Levels of Automation in Manufacturing. In: Ergonomia. International Journal of Ergonomics and Human Factors 30 (3), 1–28.

[23] Society of Automotive Engineers International: Standard J3016. 2021. Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles, SAE.

[24] Kluge, S., 2000. Empirisch begründete Typenbildung in der qualitativen Sozialforschung, In: Forum Qualitative Sozialforschung 1 (1), 2000.

[25] Zwicky, F., 1996. Entdecken, erfinden, forschen im morphologischen Weltbild. Droemer, Munich, 1966.

[26] Döring, N., Bortz, J., 2016. Forschungsmethoden und Evaluation in den Sozial- und Humanwissenschaften. Springer, Berlin. DOI: 10.1007/978-3-642-41089-5

Biography

Nils Föhlisch (*1992) received a M.Sc. degree in Business Administration and Engineering at RWTH Aachen University. Since 2019, he is a research associate and since 2022 group lead Digital Factory Planning at the Laboratory for Machine Tools and Production Engineering (WZL) of RWTH Aachen University.

Peter Burggräf (*1980) received the M.B.A., Dr.-Ing., and Professor degrees after studying Mechanical Engineering in Aachen and London. From 2011 to 2017, he was chief engineer with the Chair of Production Engineering at WZL. Since 2017, he holds the Chair of International Production Engineering and Management (IPEM) at University of Siegen, Germany.

Tobias Adlon (*1989) received a M.Sc. degree in Business Administration and Mechanical Engineering at RWTH Aachen University. Since 2015, he is a research associate at WZL and from 2018 to 2020, he was group lead Assembly Planning. Since 2020, he is chief engineer of the department Factory Planning.

Verena Meier (*1996) received a M.Sc. degree in Production Engineering from RWTH Aachen University. Her research focus are assembly planning procedures and the differentiation of flexible assembly structures.

5th Conference on Production Systems and Logistics

A Production Model That Combines Lean And Industry 4.0 Principles To Enhance The Productivity Of Small And Medium-Sized Enterprises (SMEs) In Peru's Food Manufacturing Sector

Adrian Ricardo Komori-Zevallos[1], Fernando Matias Montedoro-Garay[1], Yvan Jesus Garcia-Lopez[1], Juan Carlos Quiroz Flores[1]

[1]*Facultad de Ingeniería, Carrera de Ingeniería Industrial/ Universidad de Lima, Lima, Peru*

Abstract

New technologies, increasing competition, and changing consumer preferences in the food manufacturing sector have forced companies to generate customized products in dynamic demand and thus remain competitive in the market. As a result, companies have had to rethink their processes and product designs to optimize their manufacturing operations. In addition, moving from a conventional production model to processes supported by intelligent systems to generate efficiency improvements in the demand planning and productivity in their activities is necessary. This paper aims to introduce the development of an integrated model of lean 4.0 practices, demand forecasting using SARIMAX and DSS in a manufacturing SME. In addition, a literature review allowed identifying the variables that would be affected, such as inventory, waste, obsolete products, and productivity. Finally, a case study in the food manufacturing sector is considered to validate the model. The results will be presented through a visual analytics dashboard to streamline plant team decision-making.

Keywords

Lean 4.0; Demand Forecasting; Productivity; Machine Learning; Food Manufacturing Sector

1. Introduction

There is growing competition in the industrial sector, where companies are choosing to improve their production systems to make them agile, effective, and precise in the face of the constant changes in the modern world [1]. Bouchard et al. mentions that the emergence of new information technologies, the globalization of climate change, the lack of labor, and changes in consumer preferences have led to dynamic demands and the need for customized mass production systems [2]. With innovation and technological advancement, the increase in productivity has become the current focus, developing various ways of achieving this, but the practices of Lean Manufacturing are the most used [3]. According to INEI, Peru's manufacturing sector contributes 12% of the increase in production [4]. Applying VSM and other related techniques give visibility to the manufacturing production process and allow for balancing the workload, the achievements of which are mainly measured through utilization capacity [5]. In turn, food production in Peru increased (20.6%) during the first half of last year [6]. Food waste is a reality, and it is rare for companies in the sector to focus on reducing it, as it means adapting and modifying their processes [7]. Piras et al. mention that modern industrial food systems are characterized by overproduction, overabundance, and waste [8]. In this sense, it is relevant for companies to incorporate business intelligence tools that allow them to streamline and optimize decision-making through machine learning models to predict demand and, in this way, avoid

DOI: https://doi.org/10.15488/15256
ISSN: 2701-6277

costs by overestimating or underestimating demand [9]. Finally, several problems negatively affect companies' competitiveness and productivity.

1.1 Objective

This paper proposes a case study when applying the VSM tool with an integrated demand forecasting model with machine learning and DSS to optimize the production of an SME in the food manufacturing sector. In addition, the main objective will be to improve the productivity of a Peruvian food manufacturing company by improving demand forecasting and balancing the workload; in this way, waste will be reduced by overproduction, and loss of sales will be avoided. In addition, the research will conclude with the design of the DSS to monitor relevant KPIs by the plant team.

2. Literature review

This research developed a literature review to find studies related to Lean 4.0 and Machine Learning techniques, according to the research question: What consequences does the application of Lean 4.0 have for the planning of demand and productivity in the sector? In this way, prior knowledge is synthesized, and the state of the art in the food manufacturing sector is analyzed. The databases used to search for the terms were Scopus and Web of Science.

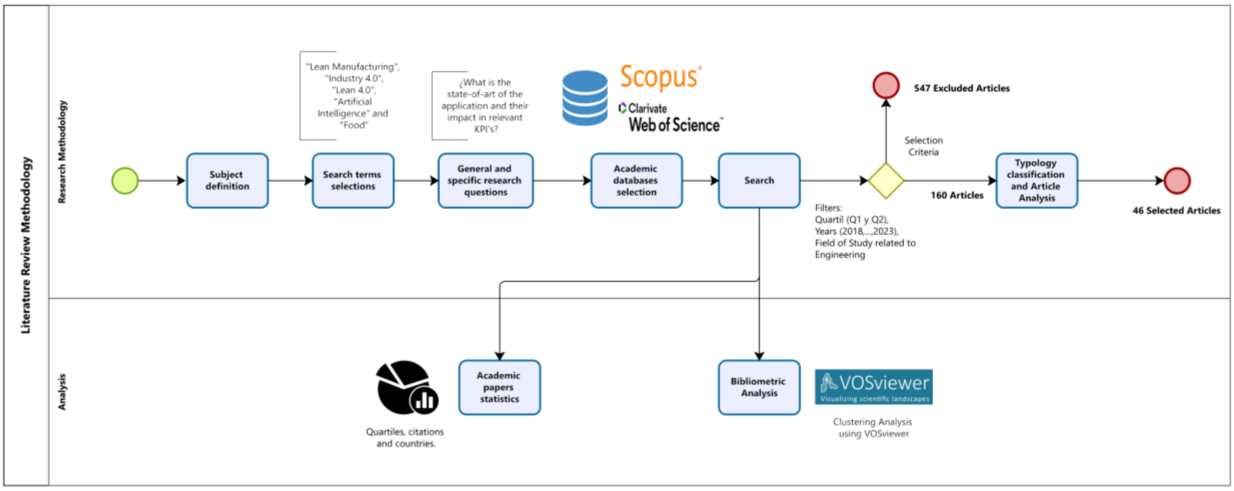


Figure 1: Literature Review Diagram

2.1 Demand forecast using Machine Learning

Using machine learning to make predictions in different business sector areas with a high degree of certainty is becoming increasingly popular. Companies must adapt to today's world, characterized by the need for personalized products, dynamic demand, and stock reduction [2]. In turn, authors Quiroz-Flores et al. implement a predictive demand model using machine learning to reduce the error metric by 9.7% in a poultry production company. In addition, another article identifies a case study in a manufacturing company with a manual process. It uses machine learning to predict the best baking temperature of its products, translating into a better quality of the final product. The results show increased productivity, efficiencies, and a decrease in the company's operating costs [10]. As we can see, there is a similarity between the authors' findings because they mention the advantages of generating a predictive demand model to achieve faster responsiveness to the market and being more accurate in production, better inventory management, and reduced costs due to overproduction or lack of stock.

2.2 Value Stream Mapping in the food manufacturing sector

Implementing production models based on Lean tools is an increasingly common practice. A study developed by Maalouf et al. shows that using the VSM technique allows identifying those productive process activities that are most important and add value, allowing a diagnosis to be made that serves as a basis for reorganizing the system and obtaining increases in productive capacity, reducing cycle times [11]. In turn, the VSM is used in another case study to analyze a company's conventional production system, finding that some activities can be omitted and restructuring the flow through a new map that allows for reducing waiting times and waste [12]. As can be seen, different authors agree that using Value Stream Mapping is adequate to identify those activities that provide value in a production process, being able to modify the sequence and reduce activities to optimize times.

2.3 Decision support system using Dashboards

The challenges of digitizing processes are mainly in using and visualizing large amounts of data collected. Lossie et al. report that Decision support systems (DSS) enable the plant team to be reached with accurate information at the right time. In this way, they designed, implemented, and validated context-sensitive dashboards for operators in production through expert evaluation [13]. In addition, another article presents the importance of giving the values of the most relevant key performance indicators (KPIs) for their monitoring and control. In this way, stakeholders can make better decisions and control actions in the face of changes in production and minimize negative impacts [14].

2.4 Lean 4.0

Lean 4.0 is an approach that combines tools from Industry 4.0 and Lean Production [15]. Although research continues, multiple studies have confirmed that integrating both favors a company's performance and helps reduce operating costs [16]. There is a positive correlation between Lean Production and Industry 4.0, where interaction impacts processes, workers, and organizational efficiency [17]. Approximately 76.3% of all possible pairings of different techniques between both domains have a positive correlation [18]. This makes it clear that it applies in most cases and that specific tools must be selected to improve performance. Research is ongoing, and technological advances will bring in-depth knowledge of the subject.

3. Methodology

In this point, considering the low productivity and level of planning, an inaccurate demand forecast and an insufficient control of the production by the production plant team. The following model is proposed and will assist us in the analysis, improvement, application and validation of the integration of VSM, Demand Forecasting and DSS. The variables to predict is the amount of sales of baked goods using the historical demand.

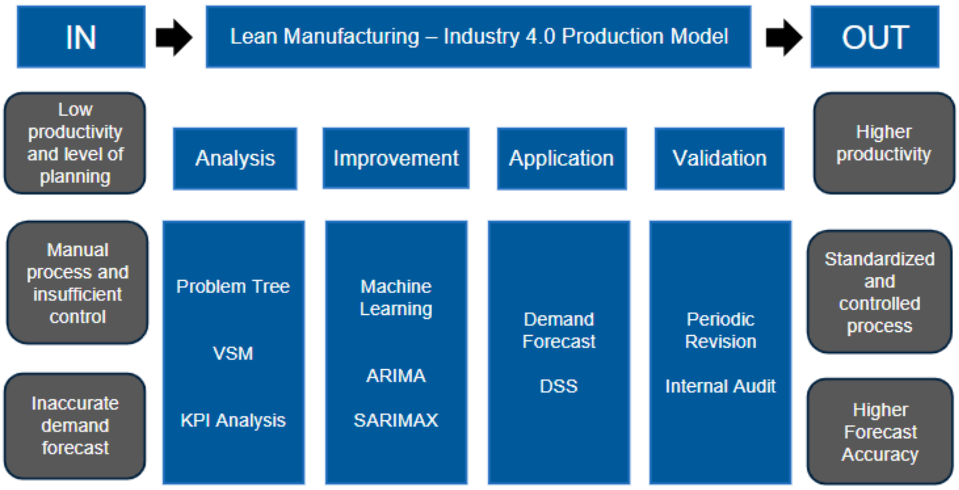


Figure 2: Integrated Model

3.1 Use of VSM for diagnosis in a production process and production of KPIs

Value Stream Mapping is a technique that separates the productive process from the good in all the activities to transform the raw material into the finished product. In this way, essential and critical activities can be separated from those that can be redistributed or eliminated as required. If information collection is appropriate, the time needed for each activity in the process will be provided. In this way, those that take longer are analyzed, being able to analyze the station and its elements to generate perspectives, redistributing space, and reducing or eliminating steps that do not add value to be more efficient [19]. The steps to implement it are Identifying activities and measurement of times, elaborating the map of the current sequence, analyzing the state before the improvement, and designing a future map and an implementation plan. For the present research, a VSM of the company's current state is developed as an analysis and a future VSM, including the proposal for change.

When it comes to baked goods, the main problems encountered are many manual jobs, excessively different times between activities, overproduction, and defective products, for which it is suggested to use the First in, First Out (FIFO) methodology, perform line balancing, automate processes such as cutting and manage inventory [20].

3.2 Demand Forecasting using Machine Learning

For the construction of the demand forecast, this paper follows the CRISP-DM methodology consisting of 6 iterative phases and is the industry standard process in machine learning projects [21]. These will be grouped into four steps, and the model will be built to predict monthly food production. Valuing their results by comparing performance metrics against the current company forecasting method is also essential. In addition, the Python programming language was used due to its open-source nature and the advantages of library availability for easy development.

3.2.1 Business Understanding & Performance Metrics Definition

A visit was made to the company's bakery production plant, and the problem of low productivity and its negative impact on lost sales was identified. In turn, through an analysis of root causes, it was identified that 22% of the problem is due to a poor estimate of demand. Its root is due to an outdated forecasting method by the company, directly affecting the production planning process since it is susceptible to the various variations that occur in demand generating losses and becoming obsolete. Indicators to measure the performance of the predictive demand model will be the coefficient of determination (upper case R squared mean absolute error (MAE), mean absolute percentage error (MAPE), mean squared error (MSE), and root mean squared error (RMSE) to evaluate the time series model. [9]

$$R^2 = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(\hat{Y}-\underline{y})^2}}{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i-\underline{y})^2}} \quad (1)$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|\hat{y}-y_i| \quad (2)$$

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{\hat{y}-y_i}{y_i}\right| * 100 \quad (3)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\hat{Y}-y)^2} \quad (4)$$

Where n is the number of observations of the sample of actual production data, capital Y unit vector is the predicted value, and subscript i. is the actual value of production in the period and bar below and unit vector, the final bar below the arithmetic mean of variable Y.

In turn, the Forecast bias [22] and Forecast accuracy [23] of the current demand forecast method will be compared against the suggested model according to the following equations 5 and 6, respectively.

$$Forecast\ bias\ \% = \frac{\sum Forecast}{\sum Sales} \quad (5)$$

$$Forecast\ accuracy = 1 - \frac{\sum Sales - \sum Forecast}{\sum Sales} \quad (6)$$

3.2.2 Data Understanding & Data Preparation

It should be ensured that the information does not have errors, null values, or missing data, ensuring that the data have the corresponding formats for processing through the open-source library of data analysis "pandas." Since it is a time series, the seasonality of the data prepared will be tested by the Augmented Dickey-Fuller unit root test (ADF), this statistical test is the extended version of Dickey-Fuller's simple test which eliminates autocorrelations between variables and formulates the following null and alternative hypothesis [24].

H0: No seasonality of the data sample

H1: Data sample presents seasonality

To reject the null hypothesis, the ADF test must have a p-value less than or equal to the level of significance used.

3.2.3 Model Construction and Selection

For the construction of the model, pre-processed data will be used. The ARIMA (Autoregressive Integrated Moving Average) algorithm will be evaluated and used for the construction of time series models combining the relationships of historical data with the analyzed observation and its residual error, and SARIMA (Seasonal ARIMA) to develop models considering seasonal and non-seasonal trend data in the time series [25]. The model will be trained with a quantity of historical data (Training data set) while predicting the future time series and evaluating the amount of remaining data (Test data set); in this way, the performance metrics of the model shall be obtained, and the most appropriate model shall be selected [9].

3.2.4 Deployment of the model

Once the trained model is selected with the best fit for the data type, it is executed in a cloud code editor with Python programming language, and the following periods expressed in months are forecast.

3.3 DSS using Dashboards.

A dashboard will be used to analyze indicators and summarize the company's information through the Power BI program. It is a visual tool that allows you to channel large volumes of data, being friendly to most users and facilitating the decision between alternatives. Lossie et al. mention that such a system aims to enable decision-makers to make decisions of the highest possible quality through collecting, processing, analyzing, and providing information and data; this is how large volumes of data can be automatically processed and displayed by the user [13].

4. Case study

On the one hand, the respective diagnosis was made using the Value Stream Mapping tool, which can be found in annexes. The results obtained are summarized in the following table:

Table 1: Value Stream Mapping Results

Category	Operation	Transportation	Inspection	Storage	Delay	Total
Value Added (VA)	10	-	-	-	-	10
Not Value Added (NVA)	-	1	-	-	-	1
Necessary but Not Value Added (NNVA)	-	1	3	2	3	9

As can be seen, there is an activity with the classification that does not add value, as it is not necessary or contributes significantly to the process. The current production situation in the company is characterized by a delay in waiting for cooling after frying. Here, the operators remain to move the product immediately after cooking, leaving it next to the fryers for a few minutes. Therefore, one of the proposed improvements is focused on the product's transport because if the frying is taken directly to the finishing area, physical space is released, and the filling and decoration process is expedited. In addition, a line balance will be made to redistribute and reorganize the workstations as part of the implementation plan. Thus, the time between stations will be as even as possible, increasing productivity. The demand forecasting model avoids overproduction, reducing waiting times and bottlenecks through more accurate projections.

Next, the new Value Stream Mapping is presented, pointing out the solutions to consider in the diagram.

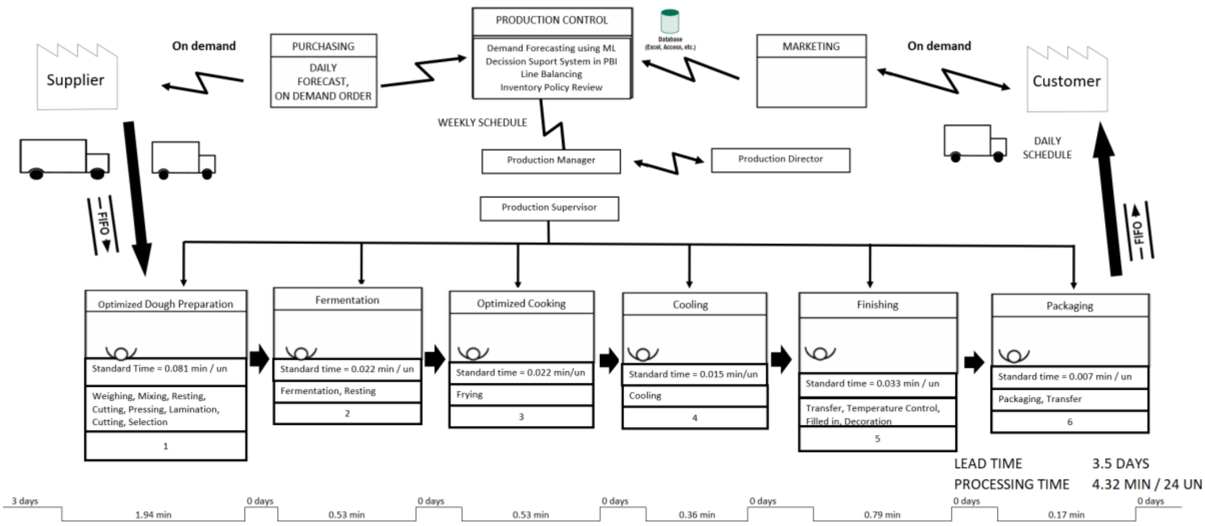


Figure 3: Future-state VSM

On the other hand, the test (ADF) is developed to determine the behavior of the historical production of the bakery product. The null hypothesis of the test states that the data are not stationary. Otherwise, for the data to be stationary, a p-value < 0.05 must reject the null hypothesis. Therefore, when obtaining a p-value of 0.98516, the null hypothesis is maintained; the demand is not stationary. As shown in Table 2.

Table 2: Augmented Dickey-Fuller test values (ADF)

Metrics	Operation
Test Statistic	0.509539
p-value	0.985160
#Lags Used	12
Number of Observations Used	63
Critical Value (5%)	-2.908645

The data set was partitioned into a set for training and validation following a ratio of 67% and 33%, respectively, as shown in Figure 2.

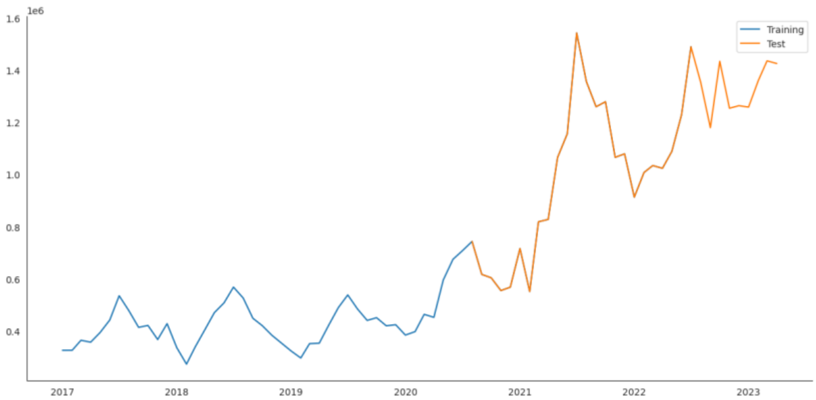


Figure 2: Train set and test set

The performance of the ARIMA vs. SARIMA algorithm is then evaluated, and as shown in Table 3, the prognostic model will be selected using SARIMA. It should be noted that when validating the model's performance using the graphs presented in Figure 3, many data adjusted to the Q-Q positive trend line can be observed.

Table 3: ARIMA and SARIMA Performance Metrics

Algorithm	R-squared	MAPE	MAE	MSE	RMSE
ARIMA	0.912174	0.120384	79891.5547	12753589839	112931.7928
SARIMA	0.922053	0.137624	75934.7801	11318930324	106390.4616

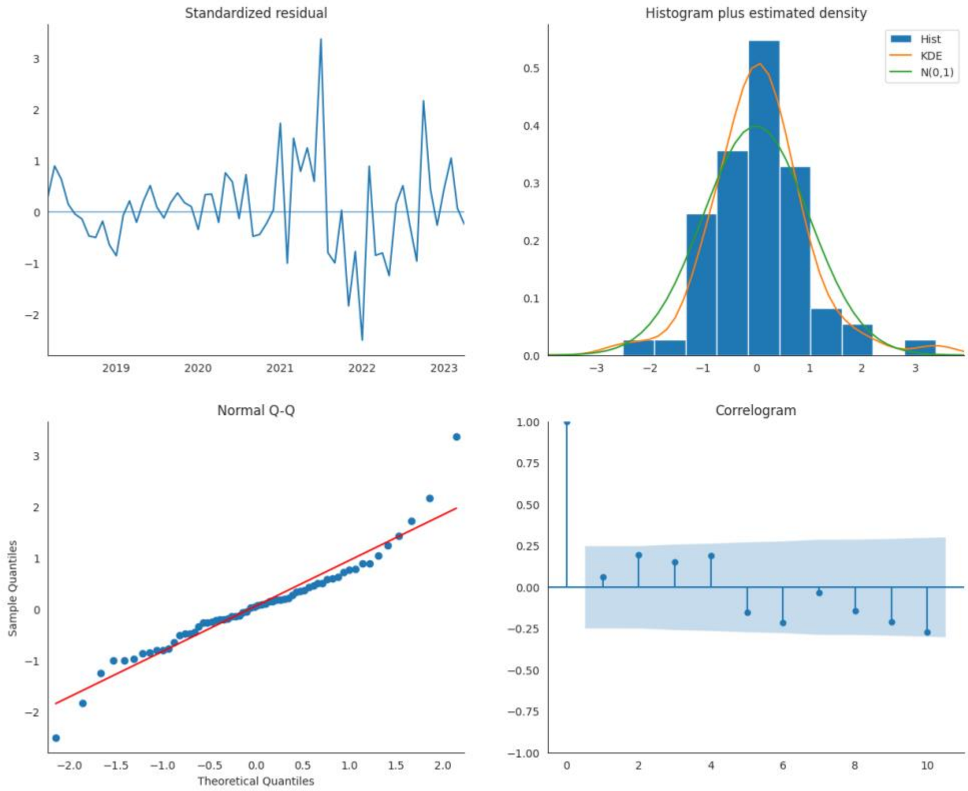


Figure 3: SARIMA model evaluation graphics

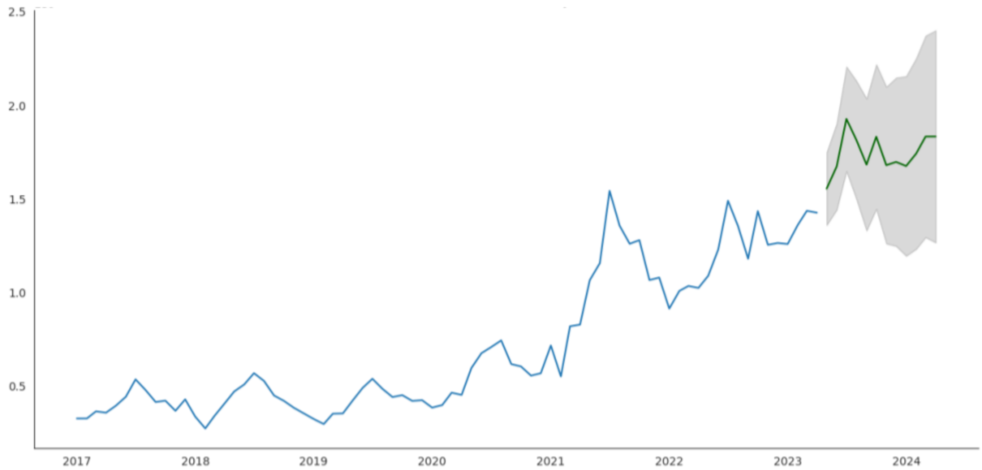


Figure 4: SARIMA – Forecast of Bakery Products

Finally, we evaluated the forecast of demand for the Bakery product of the case study for the next 12 months in units.

Table 4: SARIMA – Forecast of Bakery Products

Date	Forecast of Bakery
05/01/2023	1554093.38
06/01/2023	1672452.3
07/01/2023	1927182.61
08/01/2023	1813367.33

09/01/2023	1682587.07
10/01/2023	1831947.19
11/01/2023	1679416.94
12/01/2023	1697010.72
01/01/2024	1674892.54
02/01/2024	1741611.4
03/01/2024	1832730.78
04/01/2024	1832995.8

5. Results and conclusions

In conclusion, the proposed implementation of an integrated model of lean manufacturing, industry 4.0, and machine learning was validated by diagnosing the company's current situation through the lean VSM tool. In addition, it was identified the time it takes to carry out each activity of the productive process, which, added to the information obtained through the literature review, allowed proposing opportunities for improvement. A literature review was carried out that provided knowledge about the areas of the integrated model, facilitating the selection of tools.

In the case of the demand forecast model, a positive result was obtained with the SARIMA algorithm with a correlation coefficient of 0.922 and an absolute mean error of 75934. Also, it was discovered that the ARIMA model for the data set underestimated the demand value in most cases. Therefore, increasing the forecast accuracy of 93% to 97%. Finally, it is concluded with a dashboard designed with the requirements previously raised to monitor and streamline the decision-making of the plant team.

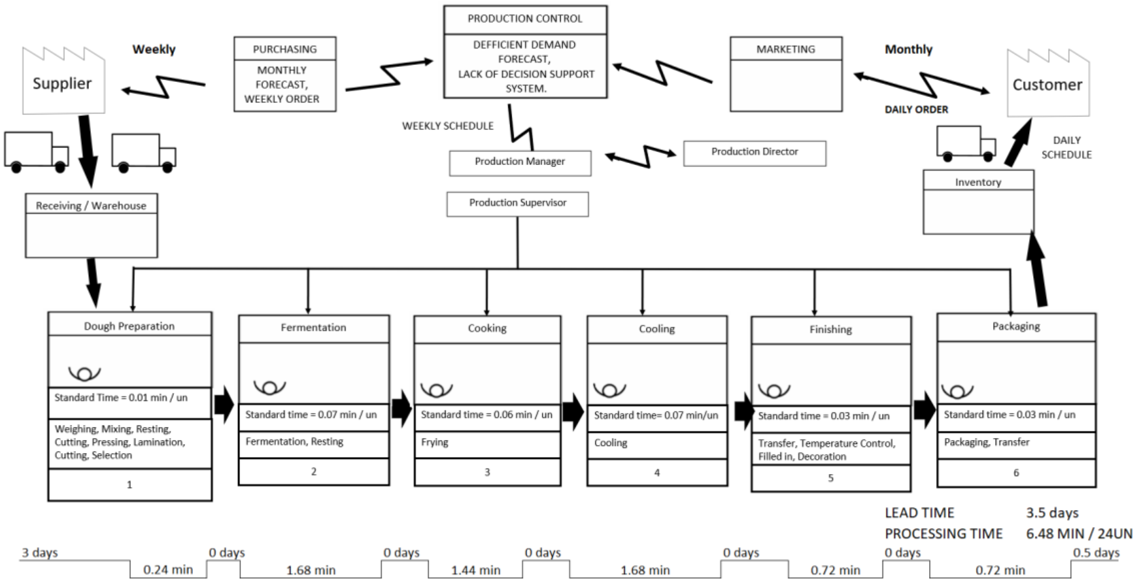
Moreover, VSM and Machine Learning tools have a positive correlation, so their work together allows to identify the current situation of the company and plan production more precisely, reducing waste and eliminating unnecessary activities to increase productivity.

Nevertheless, further research is necessary to improve the SME production process via Lean Manufacturing tools such as 5S and Standardized Work

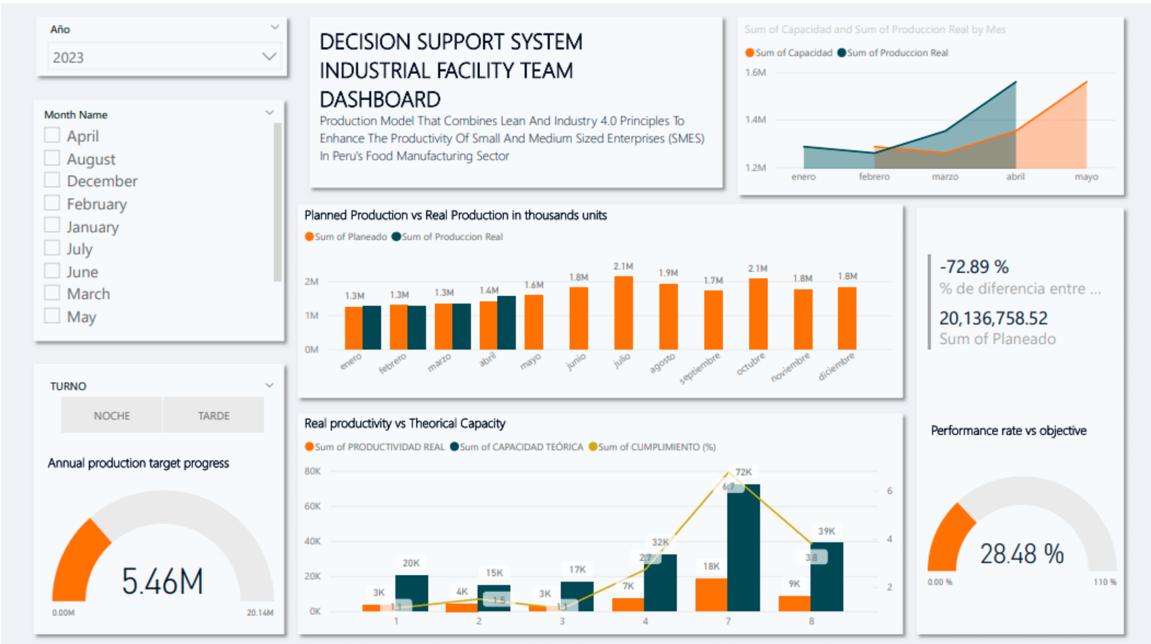
Acknowledgments

The authors state that the development of the academic article has been financed with personal sources and resources.

Appendix



Appendix 1: Current-State VSM



Appendix 2: Decision Support System, Industrial Facility Team Dashboard

References

[1] Akanmu, M., Nordin, N., 2022, "Hybrid Lean Practices Integrated with IR 4.0 and Sustainability in Malaysia Food and Beverages Companies: Conceptual Framework and Hypothesis Development", Pertanika J. Sci. & Technol, vol. 30, no. 3, pp. 2271-2293

[2] Bouchard, S., Abdulnour, G., Gamache, S., 2022, "Agility and Industry 4.0 Implementation Strategy in a Quebec Manufacturing SME", Sustainability, vol. 14

[3] Guzel, D., Asiabi, A., 2022, "Increasing Productivity of Furniture Factory with Lean Manufacturing Techniques" (Case Study). Technical Journal, vol. 16, no. 1, pp. 82 - 92

[4] INEI., 2023, "National Production Monthly Index February 2023"

[5] Hussain, D., Figueiredo, M., 2023, “Improving the time-based performance of the preparatory stage in the textile manufacturing process with value stream mapping,” Business Process Management Journal*,* vol. 29, no. 3, 801 - 837.

[6] SNI., 2022, “Industrial Situation – February 2022”

[7] Lutoslawski, K et al., 2021, “Food Demand Prediction Using the Nonlinear Autoregressive Exogenous Neural Network”, IEEE Access, vol. 9, pp. 146123 - 146136.

[8] Piras, S et al., 2021, “Community social capital and status: The social dilemma of food waste,” Ecological Economics, vol. 183

[9] Juan Carlos Quiroz-Flores et al., 2023, “Improving Demand Forecasting by Implementing Machine Learning in Poultry Production Company,” International Journal of Engineering Trends and Technology, vol. 71, no. 2, pp. 39-45

[10] Konur, S et al., 2021, “Towards Design and Implementation of Industry 4.0 for Food Manufacturing”, Neural Computing And Applications

[11] Maalouf, M., Zaduminska M., 2019, “A case of study of VSM and SMED in the food processing industry,” Management and Production Engineering Review, vol. 10, no. 2, pp. 60 - 68

[12] Wicaksono S., Setiawan, R., & Purnomo. (2019). Lean Manufacturing Machine using Value Stream Mapping. *Journal of Physics: Conference Series,* 1175, 012118. https://doi.org/10.1088/1742-6596/1175/1/012118

[13] Karl Lossie et al., 2023, “Lean Manufacturing Machine using Value Stream Mapping.” 4th Conference on Production Systems and Logistics, CPSL 2023 - 1

[14] Garcia-Garcia et al., 2021, “Business Process Re-Engineering to Digitalise Quality Control Checks for Reducing Physical Waste and Resource Use in a Food Company,” Sustainability, vol. 13

[15] Dillinger, F., Bergermeier, J., & Reinhart, G., 2022, “Implications of Lean 4.0 Methods on Relevant Target Dimensions: Time, Cost, Quality, Employee Involvement, and Flexibility”, 55th CIRP Conference on Manufacturing Systems, vol. 107, pp. 202-208.

[16] Dillinger, F., Kagerer, M., & Reinhart, G., 2021, “Concept for the development of a Lean 4.0 reference implementation strategy for manufacturing companies”, 54th CIRP Conference on Manufacturing Systems, vol. 104, pp. 330-335.

[17] Dillinger, F., Bernhard, O., & Reinhart, G., 2022, “Competence Requirements in Manufacturing Companies in the Context of Lean 4.0”, 9th CIRP Conference on Assembly Technology and Systems, vol. 106, pp. 58-63.

[18] Dillinger, F. et al., 2022, “A Systematic Approach to Identify the Interdependencies of Lean Production and Industry 4.0 Elements”, 14th CIRP Conference on Intelligent Computation in Manufacturing Engineering, vol. 112, pp. 85-90.

[19] Abdoli, S, 2019, “Digital Twin and Value Stream Mapping of Warehousing in Era of Industry 4.0”, Proceedings of the Conference on Production Systems and Logistics*,* CPSL 2023 - 1, pp. 823 - 832.

[20] Garg, H., Purohit, S. R., 2022, “Sustainable Value Stream Mapping in the Food Industry,” Smart and Sustainable Food Technologies, pp. 393 – 413

[21] Schöer et al., 2021, “A Systematic Literature Review on Applying CRISP-DM Process Model,” CENTERIS – International Conference on Enterprise Information Systems / ProjMAN – International Conference on Project MANagement / HCist – International Conference on Health and Social Care Information Systems and Technologies

[22] Resolutions, “Measuring Forecast Accuracy: The Complete Guide”

[23] Gartner, “Use Analytics to Improve Pipeline Management and Sales Forecasting”

[24] Rizwan Mushtaq., 2011, “Augmented Dickey-Fuller Test”

[25] Taha Falatouri et al., 2022, “Predictive Analytics for Demand Forecasting – A Comparison of SARIMA and LSTM in Retail SCM,” 3rd International Conference of Industry 4.0 and Smart Manufacturing, Procedia Computer Science vol. 200, pp. 993-1003

Biography

Adrián Komori (*2002) is a student of Industrial Engineering at the University of Lima since 2019, belonging to the tenth superior of the Faculty of Engineering and Architecture. He has interned at the Intercorp Corporate Leadership Center (Conglomerate of +50 companies and +100k collaborators in Peru), performing data analytics and management/process improvement—a candidate for a Business Engineering and Business Intelligence diploma from the University of Lima.

Fernando Montedoro (*2002) is a student of Industrial Engineering at the University of Lima since 2019, belonging to the tenth superior of the Faculty of Engineering and Architecture. He participated in the student exchange program of the University of Lima, studying subjects at the Faculty of Economics of the University of Salamanca. Pre-professional internship at Belcorp (Personal Care Products Company present in 16 countries), at Consumer Intelligence and Relationship Management.

Yvan Jesus Garcia-Lopez is a Ph.D. (c) in Engineering and Environmental Science, UNALM, “Master of Business Administration” from Maastricht School of Management, Holland, and a Master’s in Strategic Business Administration from Pontificia Universidad Católica del Perú. "Master of Science" in Computer Science, Aerospace Technical Center - Technological Institute of Aeronautic, Brazil. Stage in Optimization of Processes and Technologies, University of Missouri-Rolla, USA, and Chemical Engineer from the National University of Callao. Specialization Study in Digital Transformation, by Massachusetts Institute of Technology, Business Analytics, Wharton School of Management; Data Science by the University of California, Berkeley; Big Data and Data Scientist by MITPro, USA Postgraduate Professor: Specialized Master in IT, MBA Centrum Católica, MBA from Calgary, Canada, and Centrum Católica. Ex-Vice Dean of Information Engineering of the Universidad del Pacífico, He has over 25 years of extensive experience managing investment projects, execution, and commissioning in Peru, Colombia, USA, Brazil, and China.

Juan Carlos Quiroz-Flores holds an MBA from Universidad ESAN. He is an Industrial Engineer from Universidad de Lima, and Ph.D. in Industrial Engineering from Universidad Nacional Mayor de San Marcos, and Black Belt in Lean Six Sigma from Universidad Peruana de Ciencias Aplicadas. He is currently an undergraduate Professor and researcher at the University of Lima. He is an expert in Lean Supply Chain and operations with over 20 years of professional experience in operations management, process improvement, and productivity. He has published journal articles and conferences indexed in Scopus and Web of Science. He is a classified researcher by the National Council of Science, Technology, and Technological Innovation of Peru (CONCYTEC) and a member of ACM, IEOM, IISE, ASQ, IEEE, and CIP (College of Engineers of Peru).

5th Conference on Production Systems and Logistics

Local Manufacturing - Strategic Operationalisation Of Lean Methods In Manufacturing-related Small And Medium-sized Enterprises (SME)

Dominik Saubke[1], Fabian Ponert[1], Pascal Krenz[1], Jens P. Wulfsberg[1]
[1] *Helmut-Schmidt-University / University of the Federal Armed Forces Hamburg, 22043 Hamburg*

Abstract

The economic, social and ecological crises of recent years have shown that a change in our understanding of production and value creation is necessary. A more even distribution of production capacities can promote social and economic stability. The ability to produce locally unavailable products or spare parts at short notice (e.g. manufacturing medical-products during the pandemic) avoids CO_2 emissions due to transport and increases local production sovereignty and resilience. This means that production structures need to become more dynamic and responsive for spontaneous demand. Increasing local production at the place of need seems to be a solution that addresses the problems raised. When looking at currently available local production structures, small and medium-sized enterprises can be found at most locations. Unfortunately there is still a lack of productivity compared to industrial production in this enterprises. One form of overarching organisation and corporate culture that is largely established as standard in industry is the Lean Business Model. The introduction of such a strategy offers potentials for increasing the productivity and performance of a company regardless of its size. However, the methods and principles are not consistently applied in small and medium-sized enterprises. In the context of this work, studies were identified that deal with the feasibility of implementing Lean Methods in the manufacturing sector worldwide. The results were bundled into a new data model and subjected to a secondary analysis. The aim is to obtain a complete assessment of all lean implementation methods according to *VDI2870 Holistic Production Systems*. The suitability of the implementability in small and medium-sized enterprises is extended by an evaluation with regard to the target dimensions time, costs and quality. This creates a new possibility for strategic operationalisation of the Lean Methods for manufacturing companies.

Keywords

Lean Thinking; Local Manufacturing; Lean-Methods; Operational Strategy; Small and medium sized Enterprises

1. Introduction

Our way of life, politics and economy have been affected by numerous crises in recent years [1]. The CO_2 concentration in the atmosphere worldwide has increased by about 44 percent in the last 150 years and industrialisation has made a major contribution [2]. Manufacturing companies bear a great responsibility in overcoming theses Problems [3]. Furthermore, the Covid 19 pandemic has exposed the vulnerability of our global linear supply chains [4,5]. The war in Ukraine also demonstrates the challenge that manufacturing companies face in times of crisis. In Ukraine, for example, a massive shift of companies from eastern to western Ukraine is currently being observed. These often small and medium-sized enterprises (SMEs) face

DOI: https://doi.org/10.15488/15272
ISSN: 2701-6277
publish-Ing.

the challenge of reorganising all relevant means of production in a new environment within a very short time. The multiple crises call for a structured response. A more distributed and local form of manufacturing close by the point of need could help to change the production sector [6] by making it more resilient, helping to achieve ambitious climate targets and creating an appropriate degree of production sovereignty. Today local production is represented by SMEs in a high degree [7]. In addition to the industrially driven value creation in large companies, SMEs have a major impact on the production sector, with about 99.4% of all private sector companies belonging to this category in 2018 in Germany [8]. A similar distribution can be found in all major economies [7,9]. The integration of local SMEs into dynamic manufacturing networks might be a way to promote production at the place of need. An essential aspect of economic efficiency for manufacturing companies is their own productivity. The Lean Business Model an ubiquitous standard of highly productive and industrial manufacturing according to current estimates, is still not being applied to the necessary extent in SMEs [10]. The orientation of the approach is still industrial. In Germany, for example, the understanding of the Lean Business Model for manufacturing companies is represented by a uniform standard. This is a guideline of the *Verein Deutscher Ingenieure (VDI)* called *VDI2870 Holistic Production Systems* [12,11]. Within the framework of *VDI2870*, 35 Lean Methods are assigned to the seven principles of lean. [13, 10, 14]

A common international understanding of the Lean Business Model exists only to some extent; the international studies consulted later show this clearly. Individual principles are missing or others appear, and the catalogue of Lean Methods also varies in length [7]. The principles and methods listed in *VDI2870* are therefore not part of a general understanding of lean [15]. Improvement potentials and possibilities for increasing productivity through the implementation and integration of the Lean Business Model have been proven in numerous case studies [16].

2. Objective of Research and Current Status

2.1 Objective of Research

SMEs are part of the economic success in many countries. Increasing productivity could be achieved by implementing a Lean Business Mode'. At the operational level, this requires an understanding of Lean Methods. For this, every company needs a specific strategy to fulfil their needs. [14, 17]

SMEs usually do not have the necessary resources (time, personnel and costs) to deal with the possibilities and potentials of a Lean Business Model as intensively as they would like and to design a strategy that is suitable for the company [18]. This problem is to be countered by developing an overarching picture of the feasibility of implementing the 35 Lean Methods in SMEs in the manufacturing sector. By combining and systematising results from several studies, a new data basis is created for conducting a secondary analysis. Only companies in the manufacturing sector are included in the analysis. The results of this overarching analysis on the measure of feasibility will be expanded to include an aspect of strategic operationalisation. In VDI2870 *'Holistic Production Systems'* the methods are sorted according to design principles, the syntax presented here leaves this sorting and follows a problem-oriented approach in the form of the division into the three target dimensions according to McKinsey: costs, quality and time. [19,11]. The research question answered in this paper is,

> *which Lean Methods are particularly suitable for strategic operationalisation in the target variables of costs, quality and time when implemented in small and medium-sized enterprises (SMEs)?*

The aim is therefore to create opportunities for the better implementation of Lean Methods in SMEs, based on an international and transparent data basis. At the same time, an overview for easier method selection with regard to a chosen target dimension is to be made possible.

2.2 Current Status

This literature study was preceded by an initial research on the topic of lean method implementation in SMEs, which showed that there is no internationally uniform understanding of the adaptation of Lean Methods in SMEs, while on the other hand there is a broad understanding of the industrial lean process. In particular, some older scientific contributions do not adapt the Lean-Method Model introduced in *ISO 9000 Series Quality Management Principles* and *ISO 9001:2015 Quality Management Systems – Requirements* [20], [17]. The first surveys on this topic can already be found before the turn of the millennium. In 1998, for example, Voss et. al. described for the first time in "Made in Europe: Small Companies" methods or principles which, from today's perspective, can be assigned to the international understanding of the Lean Business Model. With the *Areas of Practice* mentioned there, there are two similarities to the Lean Methods defined according to *VDI2870*. In his work SMEs from all sectors were considered [21]. Another overview is provided by Kennedy et. al. 2003 in *"A comparison of manufacturing technology adoption in SMEs and large companies"*, where 19 production-relevant variables are listed, three of which clearly coincide with Lean Methods. These are analysed in terms of implementation in SMEs in the manufacturing sector [22]. Matt et. al. published a comprehensive overview of the implementation of lean production methods in 2013, which includes 14 of the 35 Lean Methods according to *VDI2870* and 19 other lean production methods some of which are now considered part of the seven basic lean principles or are assigned to other concepts of production organisation. Some of the Studies do not have a transparent presentation of the data or there was no differentiation with regard to the production sector. [17]

3. Introducing Lean Methods for Strategic Operationalisation

3.1 Method Catalogue of Lean Principles According to Guideline VDI2870

The Lean Business Model is a business ideology that is a pervasive standard of the global corporate world involved in manufacturing [23,24]. It was designed to avoid waste of resources through organisational means and changes in Toyota's Production System (TPS). At the same time, increasing quality was a primary goal of this management orientation [25]. Today, there is still international ambiguity regarding the methodological conceptualisation in relation to the Lean Business Model and a generally accepted definition. While there is consensus on the fundamentals, opinions become more fragmented the closer one gets to practical implementation. In the following, the understanding of the Lean Business Model in terms of Holistic Production Systems (GPS) according to *VDI2870* will be taken as a basis [12,11]. The aim is to organise and structure production to exclude activities that do not add value. Instead, processes are aligned with the needs of the customers.

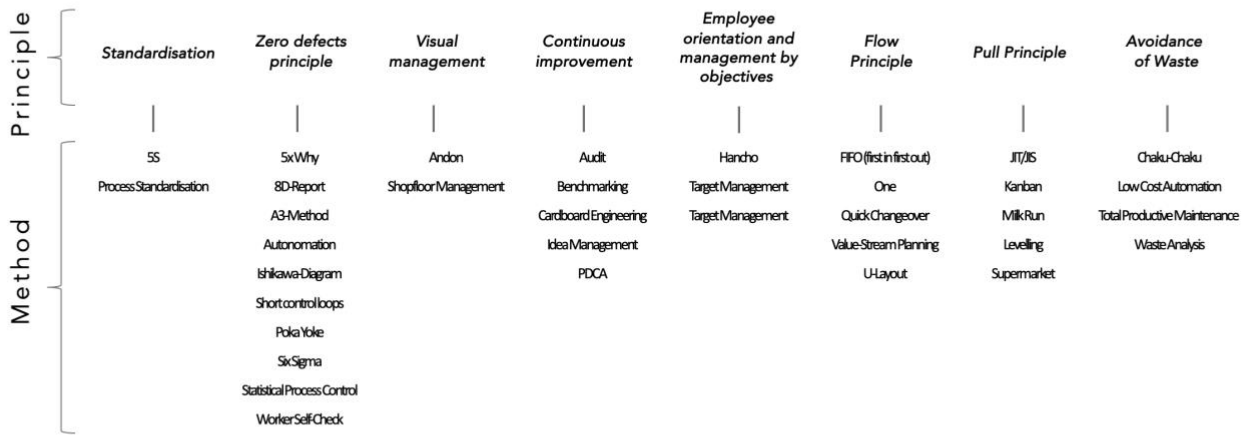


Figure 1: Lean Methods Assigned to the Lean Flow Principles.

According to *VDI2870*, the Lean Methods of GPS are subdivided as shown in Figure 1. The diagram shows the seven basic lean flow principles according to *VDI2870*, which are defined as Standardisation, Zero Defects Principle, Visual Management, Continuous Improvement, Employee Orientation and Management by Objectives, Flow Principle, Pull Principle and Avoidance of Waste. A total of 35 different Lean Methods are assigned to these lean principles. In the following, the extent to which these have already been implemented in SMEs is examined.

3.2 Classification of small and medium-sized Enterprises (SME) and Producing Enterprises

The secondary analysis presented later deals with the implementation of Lean Methods in SMEs in the manufacturing sector. These will first be defined, using the classification of enterprise categories introduced by EU Recommendation 2003/361/EC. Micro, small and medium-sized enterprises are defined as all enterprises that employ no more than 249 persons, have an annual turnover of less than 50 million euros or an annual balance sheet total of no more than 43 million euros. Furthermore, no more than 25 % of the voting rights in the company may be held by a government agency or a public corporation. At the same time, only companies from the manufacturing sector should be considered. The term manufacturing industry comes from the German Classification of Economic Activities (WZ) and is a generic term for five economic sectors. Subordinate to the manufacturing industry is the processing industry (classification WZ08-C). All industrial enterprises that convert raw materials and/or intermediate products are assigned to the manufacturing industry. This includes the manufacture of basic and production goods as well as capital goods. The manufacturing sector can be equated with industry or with the industrial sector. The manufacturing sector is characterised by machine production, a structured division of work steps and production in production facilities. For the analysis, the study data primarily (>90%) used was collected from SMEs that can be assigned to the manufacturing sector. [8]

4. Methodical Approach

4.1 Literature Review

The literature search was conducted with the help of the portal *Web of Science*, the search portal *Scopus* and the *Online Library of the Helmut Schmidt University*. First, the *Scopus* database was searched for all publications with the keyword "Lean" in the title that were published after 2011. By limiting the year, the necessary topicality can be guaranteed. As a result of the search, 18,026 titles were identified. The search results were therefore narrowed down by including the terms "manufacturing or management or thinking" and the number of titles was reduced to 3628. In a next step, the search was restricted further by adding the terms "small or medium or enterprise or enterprises or SME". With the search performed in this way at Scopus, 142 sources were finally identified. In the next step the same search was carried out in *Web of Science*. The adjusted literature corpus from the two searches resulted in a total of 155 titles, meaning 30 titles were listed twice. Three further sources were identified via the web search of the library of Helmut Schmidt University, so that a total of 158 could be considered. The publications were then pre-screened. Based on the titles and abstracts, the literature corpus was reduced to a pre-selection of 33 publications for further consideration. These were analysed in more detail (reading abstracts, methodology, scope, etc.) to identify all studies that deal with the implementation of Lean Methods. In the same process, the trustworthiness of the reports was checked on the basis of the authors and the publisher. All sources of the pre-selection could be viewed in full text. The list of sources and the pre-selection can be found at the following link DOI: 10.17632/hhsf7hgmck.1.

In the next step, the sources were classified and systematised with regard to the characteristics of the data used. In the corpus of literature defined during the literature search, nine scientific studies were identified that conducted data surveys among small and medium-sized enterprises (SMEs) in the manufacturing sector in various countries. A selection of the studies shown in Table 1 was used for the secondary analysis [23,26]. Some studies mainly consider lean principles in their surveys of companies, while the authors only partially address the methods listed in VDI 2870 [24,27]. In order to facilitate the development of customised operationalisation strategies, only studies that deal in detail with the implementation of methods and distinguish between at least ten different methods are considered.

Table 1: Overview of the Relevant Studies.

RELATED STUDIES	AUTHOR	MENTIONED METHODS	CONSIDERED SME'S	REFERENCE
Lean Implementation in SME in Less Developed Countries - Some Empirical Evidences From North Africa	**Belhadi (2017)**	**18 (51%)**	**84**	**[28]**
Lean manufacturing in Brazilian small and medium enterprises-implementation and effect on performance	Godhino (2016)	<10	N/A	[29]
Validity and reliability of lean enterprise frameworks in Indian manufacturing industry	Jasti (2014)	<10	N/A	[30]
Application of lean thinking in supply chain management by the small and medium sized manufacturers in China - A status survey	Lau (2013)	<10	N/A	[31]
Enterprises Characteristics And Lean Outcome - An Empirical Evidence From Vietnam Manufacturing Enterprises	**Nguyen (2022)**	**15 (43%)**	**6**	**[32]**
Lean implementation in small- and medium-sized enterprises An empirical study of Indian manufactures	**Sahoo (2017)**	**12 (34%)**	**24**	**[33]**
A review on issues of lean manufacturing implementation by small and medium enterprises	Shirmali (2017)	<10	N/A	[34]
Implementation of Lean Six Sigma in small- and medium-sized manufacturing enterprises in the Netherlands	**Timans (2011)**	**11 (31%)**	**51**	**[35]**

4.1 Secondary Analysis: Data Structure and Evaluation Criteria

The literature research shows that there is already some work on the degree of implementation of the Lean Business Model in SMEs, by combining the results of the studies an improved data basis can be created. The greatest challenge here is the harmonisation of data. The evaluation criteria of the individual studies were analysed and systematically combined by defining a Likert scale. For this rating, scale values from one to five were used. A rating of "one" means that only an insufficient implementation of the method under consideration can be determined and less than 20% of the companies have engaged with the method. A rating of five on the Likert scale means that an implementation of the method could be determined across the board in more than 80% of the companies considered and that it is particularly suitable for use in SMEs. The existing evaluations of the individual studies were successfully synchronised through our processing.

Figure 2 shows the distribution of companies in different major regions of the world that were considered. In total, 165 companies from the three regions mentioned could be considered in the following assessment. During the processing of the studies, it became apparent that there are different designations for the individual methods within the studies; this was taken into account in the synchronisation of the data. The distribution graph on the left in Figure 2 shows how many of the companies of the total number of 165 were surveyed in the evaluation of a method. A closer look at the map shows that there are no recent studies on the implementation of Lean Methods in the major business locations of the USA and China. Existing studies either do not distinguish between manufacturing and other types of companies or they are outdated. There was a research peak on the topic of lean in the 1990s; in the course of digitalisation and concepts such as Industry 4.0, it may be interesting to gain a current overview here.

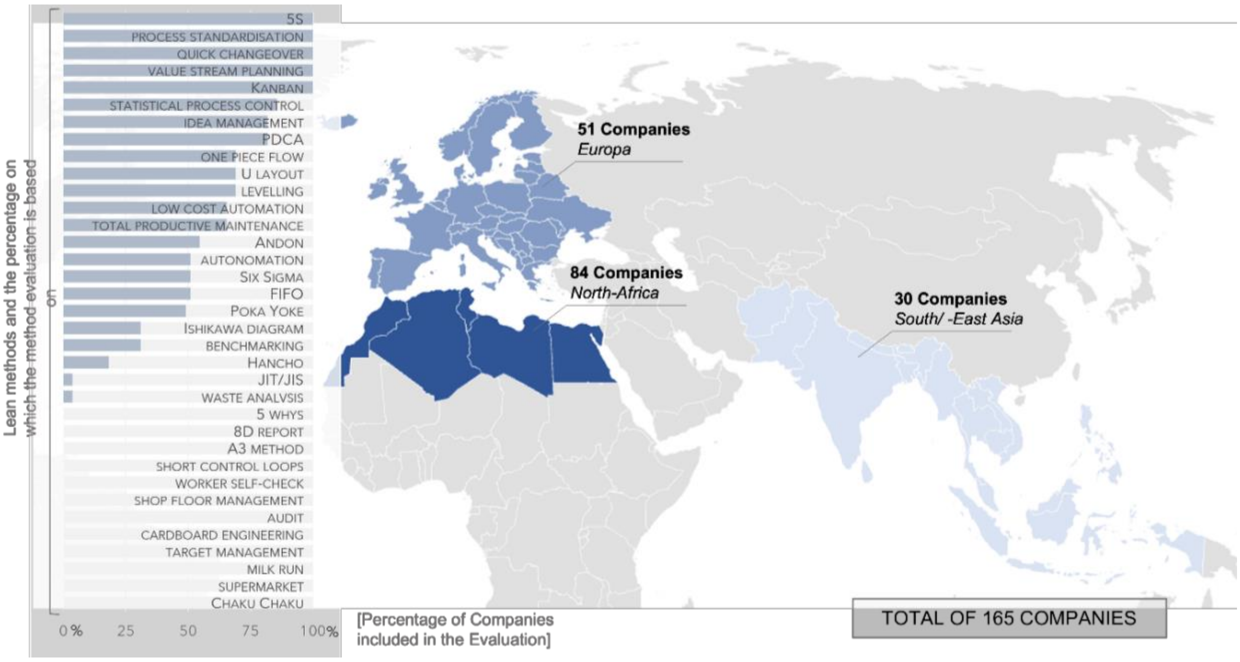


Figure 2: Distribution of Studies and Share of Companies Surveyed.

5. OUTCOME OF THE ANALYSIS

5.1 Presentation of the Results

By combining the various studies on the implementation of Lean Methods in SMEs, it was possible to improve the validity of a methods implementability in a first step. While only one study took more than 50% of the Lean Methods into account, when looking at the studies individually, a statement on 66% of the methods can be made by combining the data. In addition, the significance was improved by cumulating the number of companies surveyed on which the individual methods rating is based on.

Table 2: Lean-methods and their evaluation in terms of suitability and target variables.

Lean Methods and Principles according to VDI2870																																			
Lean Principle	*STD*	*ZDP*	*ZDP*	*ZDP*	*VM*	*CI*	*ZDP*	*CI*	*CI*	*AW*	*FP*	*OM*	*CI*	*ZDP*	*PP*	*PP*	*PP*	*AW*	*PP*	*FP*	*CI*	*ZDP*	*STD*	*FP*	*VM*	*ZDP*	*ZDP*	*ZDP*	*PP*	*OM*	*AW*	*FP*	*FP*	*AW*	*ZDP*
Lean Method	5S	5x Why	8D report	A3 method	Andon	Audit	Autonomation	Benchmarking	Cardboard Engineering	Chaku-Chaku	FIFO (first in first out)	Hancho	Idea managment	Ishikawa diagram	JIT/JIS (just in time/)	Kanban	Leveling	Low Cost Automation	Milk Run	One Piece Flow	PDCA	Poka Yoke	Process Standardisation	Quick Changeover	Shopfloor management	Short control loops	Six Sigma	Statistical Process Control	Supermarket	Target Management	Total Prod. Maintenance	U-Layout	Value Stream Planning	Waste Analysis	Worker Self-Check
Overall Suitability	4				4		4	3			5	2	4	3	3	3	2	3		2	3	1	3	3			2	3			2	2	3	5	
Quality	8				11		12	6			9	7	12	6	3	3	2	3		7	7	4	9	3			5	9			2	2	3	5	
Cost	4				4		8	6			5	4	12	6	5	9	2	9		7	7	2	6	7			3	3			7	2	7	15	
Time	8				7		8	6			5	4	12	6	5	9	4	6		7	7	2	9	10			3	3			2	7	10	10	

Continuous improvement = CI   *Standardisation* = STD   *Visual management* = VM   *Flow Principle* = FP

Employee orientation and management by objectives = OM   *Zero defects principle* = ZDP   *Avoidance of Waste* = AW   *Pull Principle* = PP

Table 2 shows the values assigned to the methods in the column *Overall Suitability*. The general evaluation was combined with an assessment of each method on the three target variables of cost, time and quality. The evaluation of the effect of the individual methods on the target variables was carried out in analogy to *VDI2879*. By combining the two evaluation systems, it was possible to define an assessment for each method on a scale of 1-15, which allows a direct assessment of whether a method is suitable for achieving the selected objective when used in SMEs. Assessments with a very high value were additionally coloured darker in the table. For example, the method *Waste-Analysis* was evaluated in all studies with a high degree of implementability combined with is effect on the *Reduction of Costs* the total rating get the maximum number of 15. The introduction of an Idea Management is considered a suitable method for positively influencing all three target dimensions to a high degree according to *VDI2879*. In accordance with this, our evaluation found a high degree of implementation of the method, which indicates that the introduction an *Idea Management* in SMEs is possible to a higher degree, despite known limitations, such as fewer specialist departments, more diffuse individual employee workload, lack of resources. In general, the table shows the scores of all methods for achieving the optimisation one of each target variable. In the next step, therefore, a possibility for the strategic operationalisation of the methods in the three target variables will be presented.

5.2 Strategic Operationalisation Regarding Three Target Factors: Quality, Time and Cost

To better align production in one of the target variables, a new rating for each Lean Method was introduced before. Normally the methods are combined by focussing the Lean-Principles. The introduced overview now gives the opportunity to expand the approach of designing a lean Strategy for a producing SME. In the next step, a possibility for the strategic operationalisation of the methods in the three target variables is presented. For this purpose, the methods and their evaluation have been visualised in Figure 3. The Lean Methods were presented in a Web-Diagram. The Diagram has two coloured areas, in each half of the Lean-Methods are listed. The separation occurs at a value of 8.

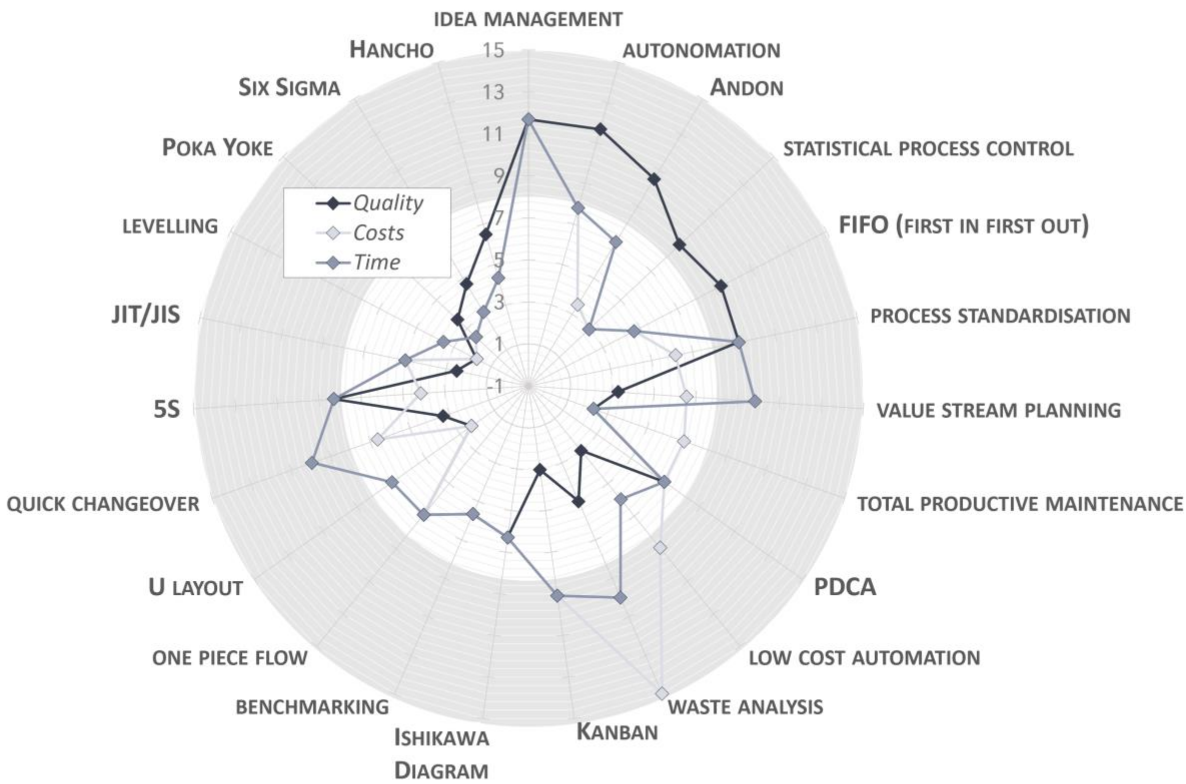


Figure 3: Illustration of the Lean Methods in the Target Variables of Time, Quality and Costs.

In order to achieve optimisation of the target variable T***ime***, the Lean Methods of *Waste Analysis*, *Idea Management, Process Standardisation*, *Kanban*, *Quick Changeover* and *Value Stream Planning* should be focused on. It should be taken into account that some of the Methods are usually introduced together with other Methods of the Lean principle as you see in Figure 1 - here it should be critically questioned in each case, whether or not other additional Lean Methods should be considered as well.

The sustainable orientation of the organisation of production towards the target quantity of ***Quality*** can be positively influenced to a particularly high degree by taking into account the Lean Methods of *Idea Management*, *Autonomation*, *Andon*, *Statistical Process Control*, *5S* and *FIFO.* Here, too, the introduction of individual Lean principles, such as *Standardisation,* would usually be accompanied by a general *Process Standardisation* in addition to the *5S* method.

The introduction of lean manufacturing, optimised for the target parameter of ***Costs,*** should place particular emphasis on the methods of *Waste Analysis* and *Low Cost Automation* for SMEs. In addition, the introduction of a *Kanban* system and *Idea Management* could be suitable for achieving the goals. Again, some Lean methods should be introduced in combination with other methods of the corresponding Lean principle. When introducing the pull principle, methods such as a supermarket are also suitable for optimising one's own production.

6. Discussion and Future Research

The distribution of the companies involved shows that there is a deficit of modern and up-to-date studies on the implementation of Lean at the operationalisation level in SME; there is a need for further research action here. It is also critical to see that economically strong regions of the world are not represented by corresponding studies. With regard to the data itself, it must be critically assessed that data could not be found for all methods. In the case of methods for which no data could be found, this does not mean that they cannot be of use to SMEs, it simply means that none of the companies surveyed have tried it yet. By combining the studies, it was possible to generate a more comprehensive statement on the various methods. The evaluation is based on the fact, that the suitability of Lean Methods can be assessed at the degree of implementation, which leaves out the fact that some methods may not be promoted strongly enough or that there are gaps in knowledge. In addition, the synchronisation of the data was done in some cases by deriving a suitable Likert scale based on the number of mentions found in the survey, so minor deviations must be assumed. Nevertheless, with the results of the secondary analysis the use of Lean Methods for SMEs is getting easier. The new evaluation was combined with an available evaluation to assess the suitability of a method for improving a production system in the target variables of time, costs and quality. This results in the possibility of targeted operationalisation of Lean Methods in the target variables mentioned. Through the integration of multiple investigations regarding the integration of lean methodologies in SMEs, an initial enhancement in validity was achieved. While individual studies considered only a fraction, the new data allows for conclusions to be drawn on approximately 66% of the methods. Furthermore the evaluation of individual methods could be placed on a better evaluation basis (increased number of surveyed companies) by combining the studies. The distribution of the companies involved shows that there is a deficit of modern and up-to-date studies on the implementation of Lean at the operationalisation level. By extending the analysis to other regions and by specifying the approach to synchronising the data even better results could be achieved. It could be interesting to add further data in the future, if necessary, to compare the data with studies from before 2011 or to compare the data according to the OECD economic ranking.

Acknowledgements

The Project 'Production Next Door' at the Helmut-Schmidt-University, University of the Federal Armed Forces Hamburg is funded by the Center for Digitization and Technology Research of the Federal Armed Forces (dtec.bw) - dtec.bw is funded by the European Union - NextGenerationEU.

References

[1] Umweltbundesamt, 2022. Trends der Lufttemperatur. https://www.umweltbundesamt.de/daten/klima/trends-der-lufttemperatur#fruhling-und-sommer-signifikant-warmer. Accessed 1 November 2022.

[2] NDR, 2019. Klimawandel: Daten, Fakten, Quellen. NDR, September 6.

[3] Welthungerhilfe.de - Für eine Welt ohne Hunger und Armut, 2022. Klimawandel – Folgen & Ursachen | Welthungerhilfe. https://www.welthungerhilfe.de/informieren/themen/klimawandel.

[4] Kohtala, C., 2015. Addressing sustainability in research on distributed production: an integrated literature review. Journal of Cleaner Production 106, 654–668.

[5] Pinkwart, A., Schingen, G., Pannes, A.-T., Schlotböller, D., 2022. Improving Resilience in Times of Multiple Crisis: Commentary from a German Economic Policy Point of View. Schmalenbachs Zeitschrift fur BWL Forschung = Schmalenbach journal of business research 74 (4), 763–786.

[6] Krenz, P., Stoltenberg, L., Markert, J., Saubke, D., Redlich, T., 2022. The Phenomenon of Local Manufacturing:, Towards Sustainable Customization: Bridging Smart Products and Manufacturing Systems. Springer International Publishing, Cham, pp. 1014–1022.

[7] Bunderministerium für Wirtschaft. Kleine Anfrage zu KMU: Bunderministerium_Wirtschaft(2018)KMU_Fakten.

[8] Rauch, E., Dallasega, P., Matt, D.T., 2017. Critical Factors for Introducing Lean Product Development to Small and Medium sized Enterprises in Italy. Procedia CIRP 60, 362–367.

[9] Krenz, P., Saubke, D., Stoltenberg, L., Markert, J., Redlich, T., 2022. Towards Smaller Value Creation Cycles: Key Factors and their Interdependencies for Local Manufacturing. Hannover : publish-Ing.

[10] Büdenbender, J., 2018. Lean Management. Herkunft, Inhalt und kritische Beurteilung, 1. Auflage, digitale Originalausgabe ed. GRIN Verlag, München, 21 pp.

[11] Verein Deutscher Ingenieure. Ganzheitliche Produktionssysteme Methodenkatalog.

[12] Verein Deutscher Ingenieure, 2012. VDI-Richtlinie 2870 'Ganzheitliche Produktionssysteme': Methodenkatalog.

[13] Dombrowski, U. (Ed.), 2015. Ganzheitliche Produktionssysteme: Aktueller Stand und zukünftige Entwicklungen. Springer Vieweg, Berlin, Heidelberg, 330 pp.

[14] Helmold, M., 2021. Kaizen, Lean Management und Digitalisierung: Mit den japanischen Konzepten Wettbewerbsvorteile für das Unternehmen erzielen. Springer Gabler, Wiesbaden, [Heidelberg], 261 pp.

[15] Timans. Implementation of Lean Six Sigma in small- and medium-sized manufacturing enterprises in the Netherlands.

[16] Oliveira, A.L.G. de, Da Junior, W.R.R., 2019. Productivity Improvement Through The Implementation Of Lean Manufacturing In A Medium-Sized Furniture Industry: A Case Study. Sajie 30 (4).

[17] Matt, D.T., Rauch, E., 2013. Implementation of Lean Production in Small Sized Enterprises. Procedia CIRP 12, 420–425.

[18] Alefari, M., Almanei, M., Salonitis, K., 2020. Lean manufacturing, leadership and employees: the case of UAE SME manufacturing companies. Production & Manufacturing Research 8 (1), 222–243.

[19] McKinsey & Company, 1993. Einfach überlegen: Das Unternehmenskonzept, das die Schlanken schlank und die Schnellen schnell macht. Schäffer-Poeschel, Stuttgart, 203 pp.

[20] Thomas, A., Barton, R., 2006. Developing an SME based six sigma strategy. Journal of Manufacturing Technology.

[21] Voss, C., Blackmon, K.L., Cagliano, R., Hanson, P., Wilson, F., 1998. Made in Europe: Small Companies. Business Strategy Review 9 (4), 1–19.

[22] Kennedy, J., 2003. A comparison of manufacturing technology adoption in SMEs and large companies. 16th Annual Conference of Small Enterprise Association of Australia and New Zealand.

[23] Prof. Günter Mey, Paul Sebastian Ruppel & Rubina Vock, 2023. Forschungsmethode Sekundäranalyse (Definition, Einordnung, Vorteile …). https://studi-lektor.de/tipps/qualitative-forschung/forschungsmethode-sekundaeranalyse.html. Accessed 2 January 2023.

[24] Verein Deutscher Ingenieure e.V., 2012. VDI 2870 - Ganzheitliche Produktionssysteme Grundlagen: Einführung und Bewertung. Beuth Verlag GmbH. https://perinorm-s.redi-bw.de/perinorm/fulltext.ashx.

[25] Jauregui-Becker, J.M., Perry, N., 2014. Lean Design, in: Produ, T.I.A.f., Laperrière, L., Reinhart, G. (Eds.), CIRP Production Engineering. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 1–5.

[26] Schryen, G., 2015. Writing Qualitative IS Literature Reviews—Guidelines for Synthesis, Interpretation, and Guidance of Research. CAIS 37.

[27] Verein Deutscher Ingenieure e.V., 2013. VDI 2870 - Ganzheitliche Produktionssysteme Grundlagen: Methodenkatalog Blatt2. Beuth Verlag GmbH. https://perinorm-s.redi-bw.de/perinorm/fulltext.ashx.

[28] Belhadi, A., Touriki, F.E., El Fezazi, S., 2018. Lean Implementation in Small and Medium-Sized Enterprises in Less Developed Countries: Some Empirical Evidences From North Africa. Journal of Small Business Management 56, 132–153.

[29] Godinho Filho, M., Ganga, G.M.D., Gunasekaran, A., 2016. Lean manufacturing in Brazilian small and medium enterprises: implementation and effect on performance. International Journal of Production Research 54 (24), 7523–7545.

[30] Jasti, N.V.K., Kodali, R., 2016. Validity and reliability of lean enterprise frameworks in Indian manufacturing industry. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 230 (2), 354–363.

[31] Lau, K.H., Wang, J., 2013. Application of Lean Thinking in Supply Chain Management by the Small and Medium Sized Manufacturers in China. International Journal of Information Systems and Supply Chain Management 6 (4), 1–17.

[32] Nguyen, D.-M., Duong, T.-K., 2022. Enterprises Characteristics and Lean Outcome: An Empirical Evidence from Vietnam Manufacturing Enterprises. Management Systems in Production Engineering 30 (2), 98–108.

[33] Sahoo, S., Yadav, S., 2018. Lean implementation in small- and medium-sized enterprises. BIJ 25 (4), 1121–1147.

[34] Shrimali, A.K., Soni, V.K., 2017. A Review on Issues of Lean Manufacturing Implementation by Small and Medium Enterprises: Arvind Kumar Shrimali. International Journal of Mechanical and Production 2017.

[35] Timans, W., Antony, J., Ahaus, K., van Solingen, R., 2012. Implementation of Lean Six Sigma in small- and medium-sized manufacturing enterprises in the Netherlands. Journal of the Operational Research Society 63 (3), 339–353. Zeitung, S., 2020. Wie der Bundestag über Klimapolitik spricht. Süddeutsche Zeitung, March 5.

Biography

Dominik Saubke, M.Sc. (*1989) has been a research assistant at the Institute of Production Engineering (LaFT) of Helmut-Schmidt-University in Hamburg since 2021. With several years of experience in Product Engineering and Product Development his current research focus is production-readiness in collaborative crowd design processes.

Fabian Ponert, B.Sc. (*1996) has been a undergraduate assistant at Institute of Production Engineering (LaFT) within the Department of Mechanical Engineering and a graduate of economic engineering at the Helmut-Schmidt-University in Hamburg.

Pascal Krenz, Dr.-Ing. (*1983) has been a research assistant at the Institute of Production Engineering (LaFT) within the Department of Mechanical Engineering of Helmut-Schmidt-University in Hamburg since 2011. He leads the research area on local production at the Institute and related research projects.

Univ.-Prof. Dr.-Ing. Jens P. Wulfsberg (*1959) is head of the Chair of Production Engineering in the Department of Mechanical Engineering at Helmut-Schmidt University in Hamburg since 2001. The main research areas at the Manufacturing Technology Laboratory (LaFT) are value creation systems, robotics, micro manufacturing as well as additive manufacturing and lightweight construction.

5th Conference on Production Systems and Logistics

Improving OEE in a Peruvian SME: A Case Study on the Application of Lean Manufacturing Tools in the Metalworking Sector

Carlos Mundaca-Lopez[1], Christopher Villar-Farfan[1], Juan Carlos Quiroz-Flores[1*] and Yvan J. García-Lopez[1]

[1]*Facultad de Ingeniería, Carrera de Ingeniería Industrial,Universidad de Lima, Perú*
**Corresponding author: jcquiroz@ulima.edu.pe*

Abstract

In Peru, SMEs have been affected by the crisis that caused the COVID 19 pandemic. Likewise, the hard competition with Asian countries like China has been a reason for Peruvian SMEs deciding to work with high-quality products. However, poor machine and maintenance management, high percentage of rework, and excessive downtime are frequent problems faced by SMEs in the metalworking sector. For this reason, the bending area was identified as the most critical. In this study, the case of a Peruvian SME that produces air conditioning products was studied. In this case, the bending area was the most critical. Therefore, the main objective of this study is to prove how the use of lean manufacturing tools can impact the productivity of the bending area, thereby improving indicators such as OEE, cycle time, unnecessary routes, and space reduction.

Keywords: Lean Manufacturing; 5S; SLP; TPM; Standardized Work, OEE, Metalworking Sector.

1. Introduction

At present, SMEs are important in our economy because they represent 90% of all formal companies. In addition, they provide jobs to many people since they generate approximately 70% of employment. [1]. In 2021, approximately 2.1 million SMEs Will be registered in Peru. These SMEs represent a significant percentage (99.5 %) of all registered companies [2]. One of the most important sectors in Peru is the manufacturing sector, which accounts for 12.7 % of the country´s GDP. In addition, it generated a large number of jobs for people, accounting for 8.8% of the national employment. Similarly, the manufacturing sector registered 15.4 % of the total tax collection in 2021[3]. The metalworking sector is one of the most important branches of the manufacturing sector. In 2022, this sector registered more than $ 264 million in exports between January and May. This sector began to expand worldwide, with sales in 89 markets. Among the countries to which exports were made in 2022, Chile, Australia, and Argentina [4].

The main problem of low production is the low availability of machinery. Likewise, It is also due to poor machine maintenance management and poor quality products that generate low profitability for the business [5]. Most companies in the metalworking sector suffer drastic problems related to the poor use of resources, which decreases the productivity and quality of products due to poor process management [6]. Peruvian companies from the metalworking sector suffer from low production due to high set-up times and low machine availability [7].

DOI: https://doi.org/10.15488/15320
ISSN: 2701-6277

It is very important that Peruvian companies in the metalworking sector improve their productivity to meet national and international demand. For this reason, this case study chose the problems of this sector in terms of low productivity and low machine availability. Because of this problem, an improvement model has been implemented using tools such as SMED, inventory control, and work standardization [8].

This scientific article is divided into the following parts: State of the Art, Which Will show the background to the problem from the perspective of different authors. Contribution: The theoretical basis of the model is presented, and the proposed model is described with the indicators used. Validation, which describes the results before using the model, implementation of pilots and simulation, and results. Finally, conclusions are presented.

2. State of the Art

2.1 Metalworking sector

There is a lot of competitiveness in the metalworking sector, which motivates companies to use tools to increase efficiency and continually improve competitiveness [9,10]. Quality is one of the most important factors to be more efficient because consumers seek high-quality products to feel safe and satisfied [11].

For this reason, it's important to apply a tool to achieve the objective of increasing efficiency and reduce costs in the production process for SMEs in metalworking sector, therefore a new model of operational efficiency has been implemented using tools from lean manufacturing such as the 5S, SLP, Standardized Work and TPM [12, 13, 14, 15].

In agreement with the foregoing, the application of these tools in this sector results in better efficiency. However, it can sometimes be improved by a large percentage or just a small percentage, so it is not always possible to reach an acceptable percentage. [16, 17]. In addition, lean tools are not the only way to improve efficiency; there are other case studies that apply DEA (), which have achieved positive results. [18].

2.2 5S Methodology

5S is a Japanese methodology derived from 5 word: Seiri (sort), Seiton (set in order), Seiso (clean), Seiketsu (Standardise) and Shitsuke (Sustain) [19]. The 5S tool has the objectives of cleanliness and order of the workplace and standardization of the area. The integration of 5S motivates employees and improves process efficiency [20].

On the other hand, the implementation of the 5S tool and other lean tools has improved efficiency, reduced operating costs, and substantially increased quality in the metalworking sector, as they address common industry problems such as long production times, late deliveries, and low productivity, highlighting the relevance of the 5S tool in this sector [21].

However, not always 5S brings impressive results; as expected, sometimes the company has little or no improvement. For example, a Peruvian company did not achieve its goals using the 5S tool because the performance was affected by the human factor focused on organizational culture and the standardization of its processes [22].

2.3 SLP – Systematic Design Planning

Systematic design planning (SLP) is a methodology that allows the observation and identification of different scenarios to determine the one that best fits the requirements of the plant. This tool contributes to reducing the bottleneck rate, reducing the cost of material handling, reducing downtime, and optimizing labor to reduce costs and optimize the plant [23,24].

Likewise, the application of the SLP tool provides positive results, such as a decrease in the flow of material, cost reduction with respect to material handling, shortening the effort of the operators, and reducing the time to search for materials, since everything was assigned in the correct place [25, 26, 27].

On the other hand, the SLP tool is very versatile and can be applied not only in the manufacturing sector, but also in other sectors such as the textile and food industries. [28, 29, 30].

2.4 TPM – Preventive Maintenance

The objective of Total Productive Maintenance (TPM) is to improve the productivity and quality of products, as well as increase employee satisfaction at work. It reduces breakdowns, eliminates losses, and thus reduce costs [31]. One of the pilars of TPM is preventive maintenance, which consists of not waiting for failure to occur but performing maintenance to avoid it [32].

In addition, the implementation of the TPM methodology led to the recognition of the importance of good maintenance management and the continuous improvement of production processes to reduce breakdowns, increase availability, and improve operational performance, supporting the effectiveness of this tool in the industrial sector for global competitiveness [33, 34].

However, this tool has also been applied to the metalworking sector in other countries. A Brazilian company implemented TPM practices and increased the MTBF indicator by more than 700%, had an MTTR reduction of more than 40%, and increased availability by more than 5% [35].

2.5 Standardized work

Standardized work is a tool for lean manufacturing that seeks to reduce variability and waste based on three elements: talk-time, sequence of operations, and work-in-process [36].

Likewise, Standardized work allows procedures and operations to be produced efficiently, seeking a minimum amount of waste. For this purpose, efficient methods and standards are used. [37].

On other hand, the application of this tool resulted in improvements in an SME in the manufacturing industry, because the percentage of reprocessing was reduced from 20.14% to 2.1% and the talk time indicator was reduced from 5.64% to 3.84%. [38].

3. Contribution

3.1 Fundamentals of the contribution

The proposed model is developed based on work management. It can be validated through its use in different studies that sought organized practice but had limited application in companies specialized in ventilation systems, contributing to the state of the art or knowledge by validating its success in increasing efficiency. Figure 1 shows the proposed model.

In this case, the 5s tools of lean manufacturing methodology were considered to focus on the organization and cleanliness in the workstation, contributing to the PDCA (PLAN-DO-CHECK-ACT) improvement cycle. These tools allow diagnostic control with different formats, 5S sequences, standard audits, and continuous improvements [39]. In addition, work standardization improves the training of operators to optimize and formalize work methods by identifying and analyzing activities that do not generate value [40].

Furthermore, it is important to consider the proposed structure when implementing the Total Productive Maintenance (TPM) strategy. It seeks the main definition of maintenance and coordination for intervention at critical points by applying the preventive maintenance plan to control and evaluate different phases [41].

Finally, the systematic layout planning (SLP) tool is of great importance as it contributes to identifying different scenarios to choose the correct sequence for the areas and optimal material transportation, storage, and operational services [42].

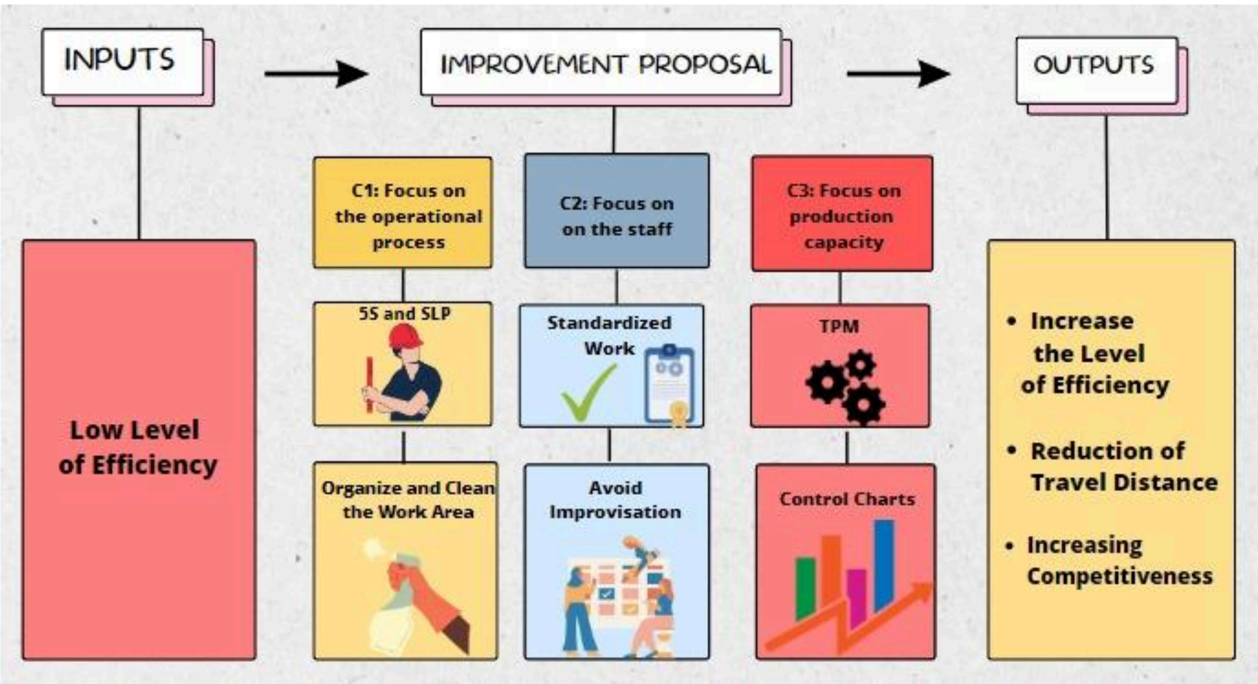


Figure 1: Basis of the Model

3.2 Proposed model

The study revealed that a singular Peruvian company in the metal-mechanical sector had the main issue of low efficiency. This situation was primarily caused by the impact of unproductive time, where the analysis showed that there were three root causes of these problems: machine failures, stoppages due to the absence of operators, and unnecessary displacements.

The first component of the model was problem analysis. In this section, the identification of different problems in the current situation is possible by applying value stream mapping to identify the operational efficiency, performance, cycle times, and others. Additionally, the structure of the layout diagram is used to record the proposed plant layout in the initial situation. Moreover, a route diagram was created to verify all activities involved in the process and find the best way to reduce time and distance. Finally, specific indicators are proposed for the four tools:5S, standardized work, SLP, and preventive maintenance, with the purpose of identifying the necessary methodologies for making the necessary changes (Figure 2).

The second component focuses on the operational process, proposing the implementation of tools that reduce no-value activities in production. For this situation, the 5s methodology will be sequentially implemented, involving sorting, organizing, cleaning, standardizing, and sustaining to improve the working conditions. Additionally, systematic layout planning will help reduce the workflow by eliminating unnecessary movements during productive activities. The main tools in this component are summarized in the next section.

- Red card to identify useless items.
- 5S schedule.
- 5S Waste notification report.
- Process for 5S audits.

- Code for reasons and order of proximity.
- Correlation and thread diagrams.
- Procedure for implementing Standardized Work (SLP).

In addition, the focus on personal will be maintained, utilizing a standardized work tool to enhance their performance and capacity by primarily selecting methods, procedures, and work practices to reduce variability. The main tools in this component are summarized in the next section.

- Standard Work Diagram.
- Standardized Work Combination Table (SWCT).
- Training Record.
- Standardized Activity Plan.

Then, the focus on production capacity will be to implement Total Productive Maintenance (TPM), primarily through preventive maintenance, to solve critical points within the production areas by conducting maintenance activities on each machine and defining the times, resources, and frequencies involved in reducing operational issues. The main tools in this component are summarized in the next section.

- Failure mode and Effects Analysis (AMEF)
- Maintenance control for continuous improvement
- Preventive maintenance training plan

Finally, the third component verifies objective compliance to ensure that the developed model achieves increased operational efficiency. Additionally, audits will complement it to maintain activities according to the production standard by comparing before and after implementation. Figure 2 illustrates the implementation of the proposed model.

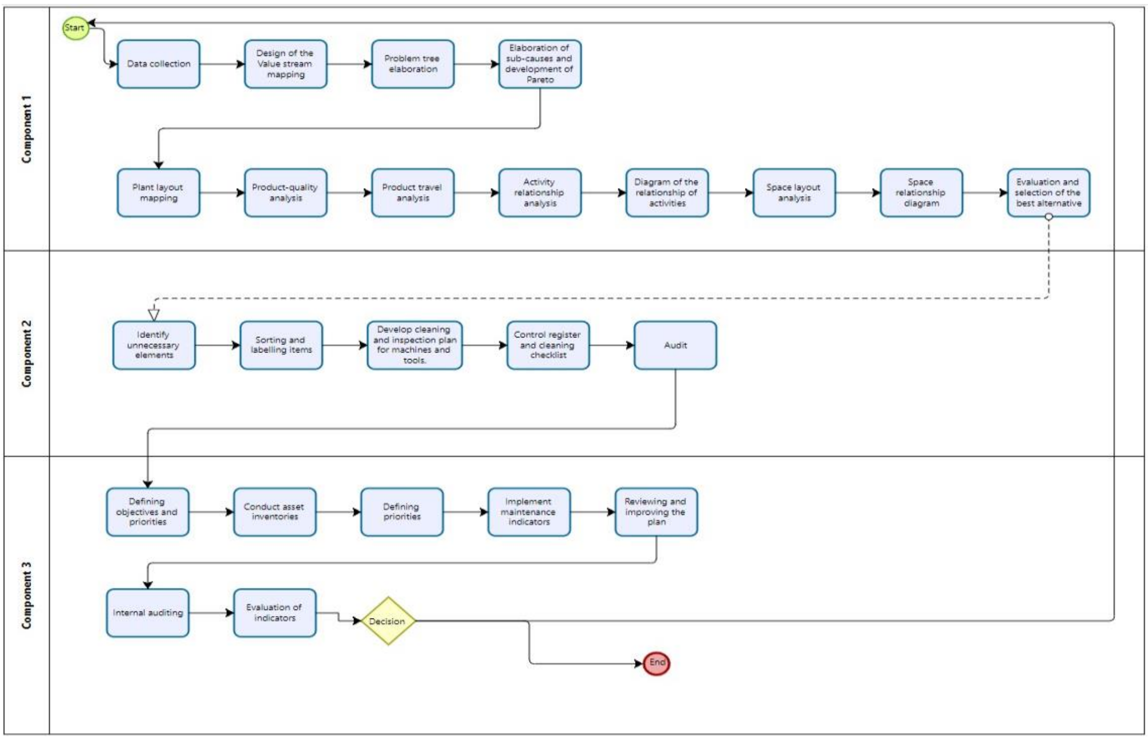


Figure 2: Proposed Model

3.3 Model indicators

To evaluate the enhancements brought about by the proposed model, the following indicators must be used:

Overall Equipment Effectiveness (OEE)

These investigations indicate that lean manufacturing tools can increase the OEE indicator by 3.75% [43].

$$OEE = A\ x\ P\ x\ Q$$

$$Availability\ (A) = \frac{Run\ Time}{Planned\ Production\ Time}$$

$$Performance\ (P) = \frac{Ideal\ Cycle\ Time\ x\ Total\ Count}{Run\ Time}$$

$$Quality\ (Q) = \frac{(Units\ Produced - Defects)}{Units\ Produced}$$

Mean time between failures (MTBF)

A study demonstrated that a 15% increase in MTBF can be achieved by improving the level of availability [44].

$$\beta = \frac{Operating\ Time}{Number\ of\ faults}$$

Cycle time

Several studies have mentioned that the implementation of standardized work can improve the cycle time indicator by 9% [45].

$$\gamma = \frac{Available\ Work\ Time}{Units\ of\ work}$$

Unnecessary travel routes

Many studies have indicated that the implementation of SLP can lead to an approximately 22 % reduction in unnecessary travel [46].

$$\delta = \left(\left(\frac{Final\ Total\ Distance}{Initial\ Total\ Distance}\right) - 1\right) x\ 100$$

Tool search time

Using the 5S tool, the search time indicator was reduced by 30.27% [47].

$$\theta = \left(\left(\frac{New\ Area}{Current\ Area}\right) - 1\right) x\ 100$$

4. Validation

4.1 Initial Diagnosis

The case study presents a technical gap related to low operational efficiency in production, which is below the 85% standard. This is because the current production model achieved only 64% efficiency. In this structure for the diagnosis data collection, it was found that the main cause of the problem was machine breakdown, representing 86.38%. The primary causes arise from machine issues (51.41%) due to a lack of maintenance plans, downtime due to the absence of operators (15.14%) as the company undergoes personnel changes that are inexperienced in machine operation, and unnecessary displacements (6.62%) as the layout of the machinery results in long travel distances due to a lack of organization and cleanliness. Figure 3 summarizes the problem tree based on the technical diagnosis conducted during 2022.

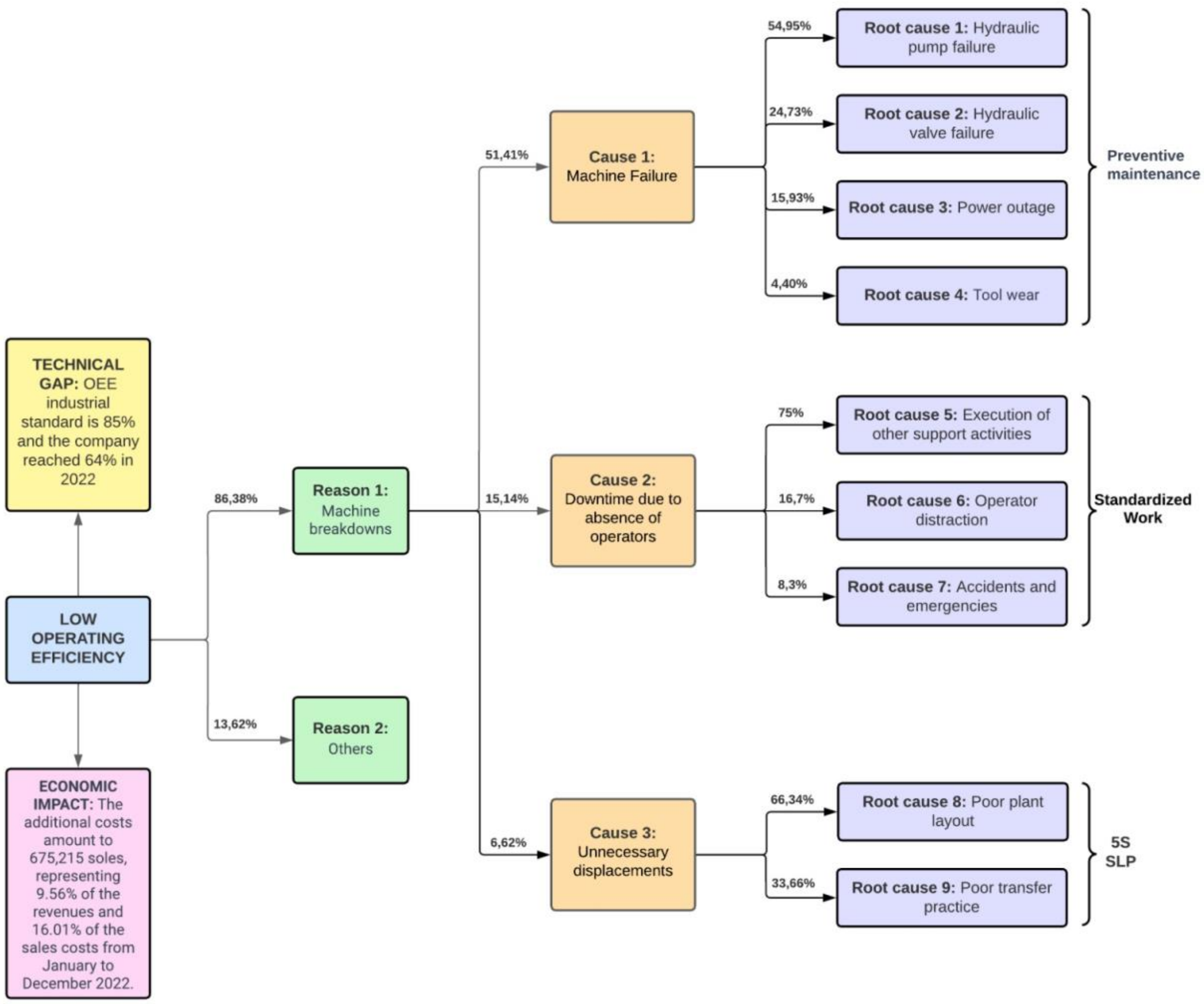


Figure 3: Problem Tree

4.2 Implementation for the pilot plan in 5s and SLP

First, the tools were classified using a control card to group all objects in the warehouse, count them, identify their respective purpose, frequency of use, necessity in production, and observation of their condition. Additionally, unnecessary items were removed if they were damaged, non-functional, or not in the warehouse.

Second, signs were placed on the shelves and labels were attached to each item. These items were grouped based on their frequency of use, with those used most frequently being placed closer to the main door.

Third, the entire warehouse and the instruments or tools inside were thoroughly cleaned. To establish better cleanliness control, a brief talk was given to explain the benefits of cleanliness, and a registration form was created for each operator to complete on the day they performed the cleaning.

Next, the number of maintenance inspections was monitored to confirm the effectiveness of the work. Subsequently, a procedure was implemented to maintain order in the warehouse, which was posted outside the main door for all employees.

Finally, a daily cleaning control sheet was developed. It is important to remind all company employees about the philosophy of the 5S tool and strive to achieve its objectives. Therefore, a panel was placed on the wall, indicating the meaning of the 5S, the objectives, and the steps to follow in this philosophy. These actions were undertaken to motivate operators and enable them to perform their tasks correctly. Table 1 shows the initial 5S audit.

Table 1: Initial 5S audit

Phases of 5S	**Start**	**Objective**	**Percent**
Seiri - Sort	3	10	30%
Seison – Set in order	3	10	30%
Seiso - Shine	5	10	50%
Seiketsu - Standardize	4	10	40%
Shitsuke - Sustain	3	10	30%

An analysis of the current workshop layout and optimized plant layout design was proposed. The effort was then calculated to compare it with the current situation, previously determined during the company diagnosis, resulting in the measurement of the productivity variation. Figure 4 illustrates the proposed layout.

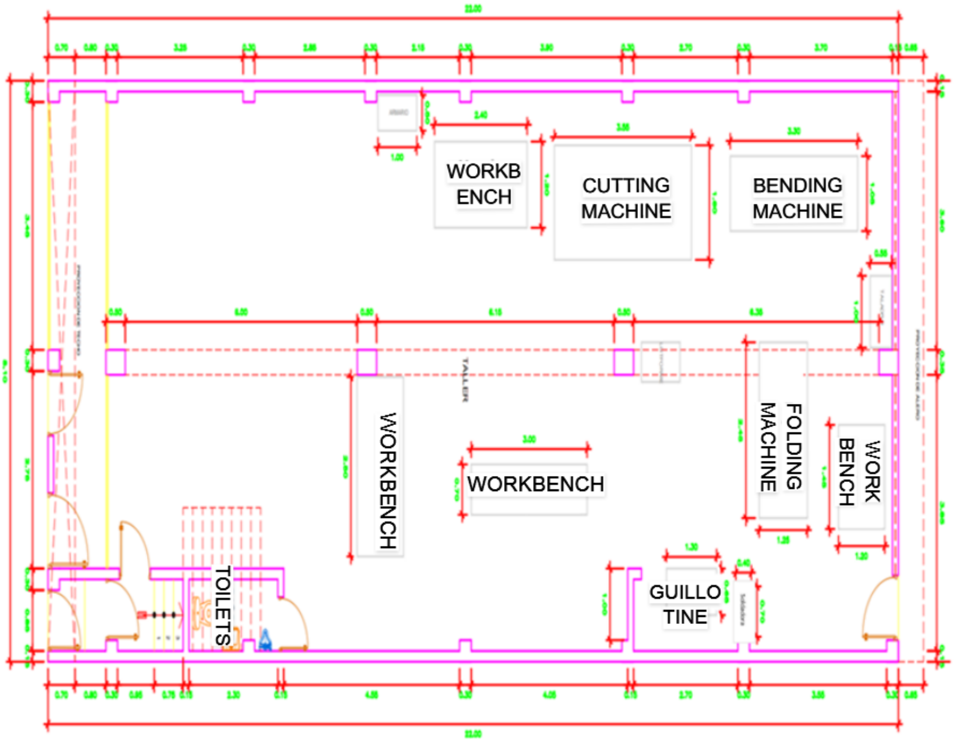


Figure 4: Improvement proposal for Workshop Layout.

4.3 Simulation improvement proposal

The simulation started after the 5S and systematic layout planning implementations using the Arena software, where the main problems identified were the excessive times in the bending activity and the different unproductive times owing to constant machine breakdowns. The figure shows the improved system, starting from order arrivals, where the ventilation system design was specified, to storage and dispatch. Changes were made by increasing resources with the support of an assistant in bending and shearing, specializing in work activities, and implementing a maintenance plan to reduce machine breakdowns and minimize downtime. An input of 40 samples was implemented to increase the accuracy of the values, considering a confidence level of 95% and margin of error of 5%. This resulted in an optimal value of 95 repetitions with confidence intervals of [1.94, 3.29]. The distributions were adjusted using the input analyzer, where only values with a chi-square greater than 0.15 were accepted. Figure 5 shows the simulation of the process using the Arena Simulator software.

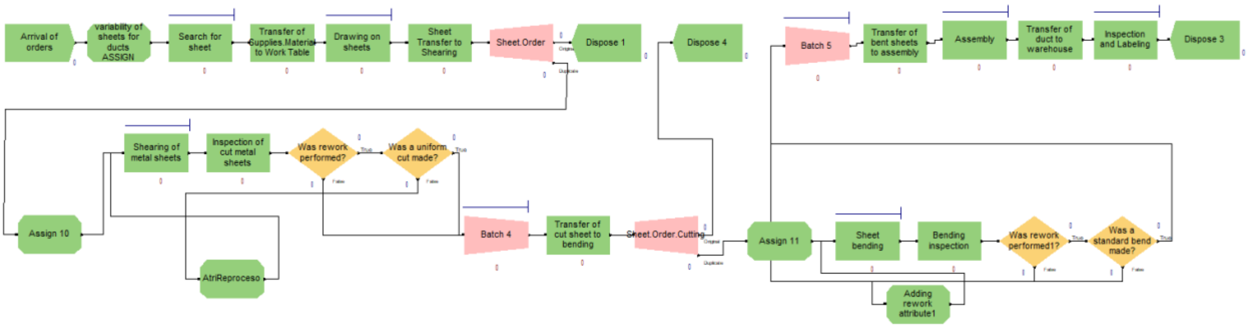


Figure 5: Simulation model in Arena

Table 2 lists the results of the in-house application and the simulation.

Table 2: Model Indicators

Problem	As is	Objective	Results	Cause	Indicator	Actual	Improved
Low Efficiency	64%	85%	72%	Machine Failure	MTTR	1.32 days	5.1 days
				Downtime due to absence of operators	Cycle time	2.69 hr	2.27 hr
				Unnecessary displacements	Unnecessary travel routes	43 m	21 m
					Tool search time	5 min	3 min

5. Results and Discussion

The proposed model, based on increasing efficiency in a company specializing in the production of industrial ventilation systems, utilized 5S, SLP, Standardized Work, and Preventive Maintenance tools. These tools address issues related to machine failures, operator absences, and unnecessary displacements. The results from Table 2 are interpreted in this section, starting with the company's efficiency not reaching the acceptable minimum of 85%; however, the trend shifted from poor to fair, ranging between 65% and 75%. In fact, the 5S tool enabled a 66.67% reduction in the tool search time by maintaining order and cleanliness in the work environment. The SLP achieved a 104% reduction in unnecessary displacements between different areas by redistributing the areas for better flow. The implementation of standardized work in machine operations resulted in a 15.61% reduction in cycle time, as the standardization of machine functioning was established owing to technical operator **inexperience.** Finally, the preventive maintenance program ensured that the Mean Time to Repair (MTTR) remained above the optimal level by approximately 200%. This was achieved by scheduling complete operation shutdowns on Saturdays for equipment repair and maintenance, allowing them to remain operational during the workweek. These methods have an impact on the standard deviation by reducing the variation compared with the others. However, it is important to note that the mean value indicates a different situation in terms of maintaining wide ranges, especially when compared to the results from the reviewed studies for MTTR (Mean Time to Repair) and SLP (Service Level Performance).

6. Conclusion and outlook

This study presents a model composed of the use of four tools (Standardized Work, 5S, SLP, and Preventive Maintenance), which achieved an efficiency level of 72%, an acceptable level when seeking improvement, although it has not reached the global standard. The improvement was achieved through the reorganization of work areas by reducing distances using SLP, where the organization and cleanliness provided by the 5S tool were key to maintaining commitment to the objective. Additionally, machine downtime was reduced owing to stoppages caused by poor maintenance, which was addressed through a structured preventive maintenance plan tailored to the type of industrial machinery. The variability in equipment handling by the staff was also reduced by maintaining standards in work activities. Future studies should delve deeper into this research to verify its long-term effectiveness as this is a prototypical review of the model.

References

[1] U. Nations, "Día de las Microempresas y las Pequeñas y Medianas Empresas | Naciones Unidas," United Nations, 2023. https://www.un.org/es/observances/micro-small-medium-businesses-day (accessed Jul. 14, 2023).

[2] Ministerio de producción. "Produce impulsa la industrialización y lanza la primera política nacional de desarrollo," Www.gob.pe, 2022. https://www.gob.pe/institucion/produce/noticias/667576-produce-impulsa-la-industrializacion-y-lanza-la-primera-politica-nacional-de-desarrollo (accessed Jul. 14, 2023).

[3] Redacción Gestión, "Participación del sector manufacturero en PBI nacional cayó 2.5% en los últimos ocho años," Gestión, Nov. 08, 2022. https://gestion.pe/economia/participacion-del-sector-manufacturero-en-pbi-nacional-cayo-25-en-los-ultimos-ocho-anos-rmmn-noticia/ (accessed Jul. 14, 2023).

[4] D. Bonett, A. Aguilar, L. Montoya Sánchez, M. Maza, and M. Rosado, "Créditos." Available: https://www.inei.gob.pe/media/MenuRecursivo/boletines/05-informe-tecnico-produccion-nacional-mar-2022.pdf

[5] X. Cusihuallpa Vera, E. Suarez Montes, J. Quiroz Flores, and J. Alvarez, "Improvement of the Manufacturing of Aluminum Pots Using Lean Manufacturing Tools," Human Interaction, Emerging Technologies and Future Applications III, pp. 499–505, Aug. 2020, doi: https://doi.org/10.1007/978-3-030-55307-4_76.

[6] J. Angulo Alva y D. Rodriguez Gonzales." Aplicación de Lean Manufacturing para mejorar la productividad de la empresa metalmecánica Promet E.I.R.",tesis bachiller, UCV, Trujillo, Perú, 2019. [En línea]. https://repositorio.ucv.edu.pe/handle/20.500.12692/47968.

[7] A. Lopez Osorio, N. Vila Moretti, A. Flores Perez, J. Quiroz Flores, and M. Collao Diaz, "Production Model Integrating TOC and Lean for Lead Time Reduction in Chemical Manufacturing: An Empirical Research in Peru," Jan. 2022, doi: https://doi.org/10.1145/3523132.3523140.

[8] J. Padilla Triveno and J. Quiroz Flores, "Lean Production Model to Increase Equipment Availability in the Manufacturing Process of Gas Hose Connectors in Metalworking SMEs," Sep. 2022, doi: https://doi.org/10.1145/3568834.3568893.

[9] K. Sanchez, Jenner, Yeimy Salvatierra Garcia, and W. Quispe, “Lean Manufacturing Application in the Laminating Machine Manufacturing Process in a Metalworking Company,” Dec. 2020, doi: https://doi.org/10.1007/978-3-030-57548-9_42.

[10] E. Capcha Huamali, W. Vila Huaman, G. Viacava Campos, and L. Cardenas, “A Lean Manufacturing and RCM-Based Production Process Improvement Model for Increasing the Production...,” ResearchGate, Jul. 2021. https://www.researchgate.net/publication/352992008_A_Lean_Manufacturing_and_RCM-Based_Production_Process_Improvement_Model_for_Increasing_the_Production_Capacities_of_Carbonated_Beverage_Bottling_Companies (accessed Jul. 15, 2023).

[11] S. Singh, A. Agrawal, D. Sharma, V. Saini, A. Kumar, and Seepana PraveenKumar, “Implementation of Total Productive Maintenance Approach: Improving Overall Equipment Efficiency of a Metal Industry,” vol. 7, no. 4, pp. 119–119, Dec. 2022, doi: https://doi.org/10.3390/inventions7040119.

[12] R. Esteban and A. Paula, “Modelo de producción Lean Manufacturing para incrementar la eficiencia de una línea de producción continua en una empresa del sector metalmecánico,” Sunedu.gob.pe, 2020, doi: https://doi.org/0000%200001%202196%20144X.

[13] B. Bringas Fernandez, M. Carrion Reyes, E. Altamirano Flores, and G. Viacava Campos, “Model to Increase the Production Efficiency of Low-Pressure Regulators through the Combined Use of Lean...,” ResearchGate, Mar. 2022. https://www.researchgate.net/publication/362604525_Model_to_Increase_the_Production_Efficiency_of_Low-Pressure_Regulators_through_the_Combined_Use_of_Lean_Tools_at_a_Metalworking_SME (accessed Jul. 15, 2023).

[14] D.Enrique, Y. Salvatierra Garcia, W. Quispe, and E. Castañeda, “Optimization Model to Increase the Productive Flow, Applying SLP, 5s and Kanban-Conwip Hybrid System in Companies of the Metalworking Sector”, 2022, doi: https://doi.org/10.1109/icim56520.2022.00041.

[15] J. Kaneku and J. Martinez. “Propuesta de mejora para reducir el índice de mudas en una empresa metalmecánica mediante el uso de herramientas lean manufacturing,” Upc.edu.pe, 2020, doi: http://hdl.handle.net/10757/654963.

[16] L. Del Rosario Malasquez, E. Dulce Meneses, G. Viacava Campos, and L. Cardenas, “A production process efficiency improvement model at a MSME Peruvian metalworking company,” Jan. 2023, doi: https://doi.org/10.1063/5.0119648.

[17] N. M. Canahua Apaza, “Implementación de la metodología TPM-Lean Manufacturing para mejorar la eficiencia general de los equipos (OEE) en la producción de repuestos en una empresa metalmecánica,” Industrial Data, vol. 24, no. 1, pp. 49–76, Aug. 2021, doi: https://doi.org/10.15381/idata.v24i1.18402.

[18] Roma Mitra Debnath and V.J. Sebastian, “Efficiency in the Indian iron and steel industry – an application of data envelopment analysis | Emerald Insight,” Journal of Advances in Management Research, vol. 11, no. 1, pp. 4–19, 2013, doi: https://doi.org/10.1108//JAMR.

[19] J. Arrieta, “Las 5s pilares de la fábrica visual,” Revista Universidad EAFIT, vol. 35, no. 114, pp. 35–48, 2021, Accessed: Jul. 15, 2023. [Online]. Available: https://publicaciones.eafit.edu.co/index.php/revista-universidad-eafit/article/view/1073

[20] Quiroz-Flores, J. C., Chavez-Osorio, G., & Guillen-Valdivia, S. (2023). Increased service level in environmental consulting SMEs through a collaborative model between Data Analytics and PDCA. 1–10. https://doi.org/10.18687/leird2022.1.1.18.

[21] A. Peralta, L. Valverde, R. Salvador, G. Quispe, F. Dominguez, and C. Raymundo, “Application of Lean Manufacturing to Improve the Duct Production Process of an Air Conditioning Company in the Year 2021,” vol. 71, no. 3, pp. 46–58, Mar. 2022, doi: https://doi.org/10.14445/22315381/ijett-v71i3p206.

[22] Y. Nunez-Castaneda, M. Moreno-Samanamud, M. Shinno-Huamani, F. Maradiegue-Tuesta, and J. Alvarez-Merino, “Improvement of Warehouses of Distribution Companies through Lean Warehouse and an Allocation Algorithm,” Oct. 2019, doi: https://doi.org/10.1109/iestec46403.2019.00091.

[23] G. Anchayhua, S. Cevallos, J. Jorge, and C. Raymundo, “Production Management Model Based on Lean Manufacturing and SLP to Increase Efficiency in the Tapestry Manufacturing Process in Lima Manufacturing SMEs,” pp. 589–596, Sep. 2021, doi: https://doi.org/10.1007/978-3-030-85540-6_74.

[24] S. Kawakami Arevalo, M. Veliz Torres, J. Quiroz Flores, and M. Noriega Araníbar, “Increased Productivity through a Production Model Based on Lean Manufacturing and SLP Tools in Small Furniture Manufacturing Workshops,” Sep. 2022, doi: https://doi.org/10.1145/3568834.3568873.

[25] A. Watanapa and W. Wiyaratn, “Systematic Layout Planning to Assist Plant Layout: Case Study Pulley Factory,” vol. 110–116, pp. 3952–3956, Oct. 2011, doi: https://doi.org/10.4028/www.scientific.net/amm.110-116.3952.

[26] D. Cordova-Pillco, M. Mendoza-Coaricona, and J. Quiroz-Flores, “Lean-SLP production model to reduce lead time in SMEs in the plastics industry: A Empirical Researh in Peru,” Jan. 2022, doi: https://doi.org/10.18687/laccei2022.1.1.151.

[27] D. Álvarez-Arias, Jeniffer De Ávila-Moore, and Josué Hurtado–Rivera, “Aplicación de Metodología SLP para Redistribución de Planta en Micro Empresa Colombiana del Sector Marroquinero: Un Estudio de Caso,” vol. 4, no. 1, Jun. 2022, doi: https://doi.org/10.17981/bilo.4.1.2022.11.

[28] A. Lista, G. Tortorella, M. Bouzon, S. Mostafa, and D. Romero, “Lean layout design: a case study applied to the textile industry,” vol. 31, Jan. 2021, doi: https://doi.org/10.1590/0103-6513.20210090.

[29] L. Casallo, E. Lucero, F. Maradiegue, and D. Ruiz, “Proposal of Work Standardization to Improve a Metal-mechanical Process,” Dec. 2021, doi: https://doi.org/10.1109/ieem50564.2021.9673052.

[30] V. Paucar, S. Munive, V. Nunez, G. E. Marcelo, D. Ruiz, and S. Nallusamy, “Development of a Lean Manufacturing and SLP-based System for a Footwear Company,” Dec. 2020, doi: https://doi.org/10.1109/ieem45057.2020.9309667.

[31] P. Marinho, D. Pimentel, R. Casais, and Luís Pinto Ferreira, “Selecting the best tools and framework to evaluate equipment malfunctions and improve the OEE in the cork...,” ResearchGate, Dec. 30, 2021. https://www.researchgate.net/publication/357431187_Selecting_the_best_tools_and_framework_to_evaluate_equipment_malfunctions_and_improve_the_OEE_in_the_cork_industry (accessed Jul. 15, 2023).

[32] C. Flores, Y. Gastelu, G. Mendez, C. Minaya, B. Pineda, K. Prieto and K. Ríos. “ Gestión de mantenimiento preventivo y su relación con la disponibilidad de la flota de camiones 730e Komatsu-2013 ”, Jul. 2016.

[33] Fagner, Juliana Valença Sousa, J. Tomaz, and T. de, “Utilizando o AHP para melhoria de processos de fabricação em TPM em um complexo industrial e portuário,” Exacta, vol. 19, no. 3, pp. 523–549, 2023, Accessed: Jul. 15, 2023. [Online]. Available: https://periodicos.uninove.br/exacta/article/view/16693/8930

[34] S. Singh, A. Agrawal, D. Sharma, V. Saini, A. Kumar, and Seepana PraveenKumar, “Implementation of Total Productive Maintenance Approach: Improving Overall Equipment Efficiency of a Metal Industry,” vol. 7, no. 4, pp. 119–119, Dec. 2022, doi: https://doi.org/10.3390/inventions7040119.

[35] N. Carvalho Biehl and M. Afonso Sellitto, “TPM e manutenção autônoma: estudo de caso em uma empresa da indústria metal-mecânica,” ResearchGate, Dec. 15, 2015. https://www.researchgate.net/publication/287375150_TPM_e_manutencao_autonoma_estudo_de_caso_em_uma_empresa_da_industria_metal-mecanica (accessed Jul. 15, 2023).

[36] W. Fazinga, F. Saffaro, E. Isatto and E. Lantelme, “Implementación del trabajo estandarizado en la industria de la construcción,” Revista de ingeniería de construcción, vol. 34, no. 3, pp. 288–298, Dec. 2019, doi: https://doi.org/10.4067/s0718-50732019000300288.

[37] S. Bragança and E. Costa, “An application of the Lean Production tool Standard Work”, Sep. 2015. https://www.researchgate.net/publication/281447644_An_application_of_the_Lean_Production_tool_Standard_Work.

[38] A. Patiño and M. Quispe, “Implementación de trabajo estandarizado, SMED y mantenimiento autonomo para reducir reproceso en la fabricación de zunchos en una mype del sector plástico,” Upc.edu.pe, 2021, doi: http://hdl.handle.net/10757/659636.

[39] I. Nathaly, E. Yorch, E. Altamirano, and Christian del Carpio, "Improvement Model Based on Four Lean Manufacturing Techniques to Increase Productivity in a Metalworking Company," Jan. 2021, doi: https://doi.org/10.1145/3447432.3447442.

[40] A. Huertas-Reyes, S. Quispe-Huerta, C. Leon-Chavarri, and J. A. Velasquez-Costa, "Increased efficiency of a metalworking SME through process redesign using SMED, Poka Yoke and Work Standardization," Proceedings of the 2nd LACCEI International Multiconference on Entrepreneurship, Innovation and Regional Development (LEIRD 2022): "Exponential Technologies and Global Challenges: Moving toward a new culture of entrepreneurship and innovation for sustainable development," 2022, doi: https://doi.org/10.18687/leird2022.1.1.69.

[41] Teonas Bartz, Julio Cezar Mairesse Siluk and Ana Paula Barth Bartz, "Improvement of industrial performance with TPM implementation | Emerald Insight," Journal of Quality in Maintenance Engineering, vol. 20, no. 1, pp. 2–19, 2014, doi: https://doi.org/10.1108//JQME.

[42] J. Arias-Castañeda, R. Condori-Gonza, V. Aparicio-Lora, A. Barbachan-Callirgos, and Wilder Namay, "Process Improvement Model Based on Lean Manufacturing and Plant Distribution to Reduce Production Times," pp. 455–463, Jan. 2021, doi: https://doi.org/10.1007/978-3-030-80462-6_55.

[43] S. Imam Shakil and M. Parvez, "Application of Lean Manufacturing in a Sewing Line for Improving Overall Equipment Effectiveness (OEE)," vol. 08, no. 09, pp. 1951–1971, Jan. 2018, doi: https://doi.org/10.4236/ajibm.2018.89131.

[44] S. Aisyah, H. Hardi Purba, and S. Setiaji, "Analysis Work Standardization Using The Standardized Work Combination Table on CNC of Mission Case Line Process at PT Astra Otoparts, Tbk - Nusametal Division," vol. 1003, pp. 012044–012044, Dec. 2020, doi: https://doi.org/10.1088/1757-899x/1003/1/012044.

[45] Roncal-Coronel, M., Tarazona-Ballon, F., & Quiroz-Flores, J. C. (2023). Warehouse Management model to reduce return rate applying Lean Manufacturing Techniques and Multicriteria ABC in a SMEs in the textile sector. In ACM International Conference Proceeding Series (Vol. 1, Issue 1). Association for Computing Machinery. https://doi.org/10.1145/3587889.3587913.

[46] K. A. Bonilla-Ramirez, P. Marcos-Palacios, J. C. Quiroz-Flores, E. D. Ramos-Palomino and J. C. Alvarez-Merino, "Implementation of Lean Warehousing to Reduce the Level of Returns in a Distribution Company," 2019 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), Macao, China, 2019, pp. 886-890, doi: 10.1109/IEEM44572.2019.8978755.

[47] Pacheco-Colcas, F. A., Medina-Torres, M. P., & Quiroz-Flores, J. C. (2022). Production Model based on Systematic Layout Planning and Total Productive Maintenance to increase Productivity in food manufacturing companies. In ACM International Conference Proceeding Series (Vol. 1, Issue 1). Association for Computing Machinery. https://doi.org/10.1145/3568834.3568854.

Biographies

Carlos Mundaca (*1999) is a student of Industrial Engineering at the University of Lima since 2018, belonging to the tenth superior of the Faculty of Engineering and Architecture. He is a professional trainee in the quality domain of the ASA. He was also interested in areas such as purchasing, demand, and planning. For this reason, he is studying postgraduate courses in supply chain management, with a focus on demand planning.

Christopher Villar (*2000) is a student of Industrial Engineering at the University of Lima since 2018, belonging to the upper middle of the Faculty of Engineering and Architecture. He is a professional trainee in the Bimbo group (with +145,000 collaborators and +1,500 sales centres strategically located in 34 countries in the Americas, Europe, Asia, and Africa), participating in the Revenue Growth Management area. He also studied specialization courses in Business Intelligence and Data Analytics.

Juan Carlos Quiroz-Flores holds an MBA from Universidad ESAN. He is an Industrial Engineer from Universidad de Lima and a Ph.D. in Industrial Engineering from Universidad Nacional Mayor de San Marcos and Black Belt in Lean Six Sigma from Universidad Peruana de Ciencias Aplicadas. He is an undergraduate professor and researcher at the University of Lima. He is an expert in lean supply chains and operations with over 20 years of professional experience in operations management, process improvement, and productivity.

Yvan Jesus Garcia-Lopez is a Ph.D. (c) in Engineering and Environmental Science, UNALM, MBA from Maastricht School of Management, Holland, MSc in Computer Science, Aerospace Technical Center - ITA, Brazil. Stage in Optimization of Processes and Technologies, University of Missouri-Rolla, USA, and Chemical Engineer from the National University of Callao. He has over 25 years of extensive experience in managing investment projects, execution, and commissioning in Peru, Colombia, the USA, Brazil, and China.

CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
CPSL 2023-2

5th Conference on Production Systems and Logistics

Improvement Proposal To Increase Productivity Of A SME In The Primary Manufacturing Sector Using Standardized Labor and TPM Tools

Diego Niño De Guzmán-Lunarejo [1], Dahana Anthuanet Obregon-Leon [1] and Alberto Flores-Perez [1*]

[1]Facultad de Ingeniería, Carrera de Ingeniería Industrial,Universidad de Lima, Perú
[*] Corresponding author: alflores@ulima.edu.pe

Abstract

The case study is situated in a SME in the primary manufacturing sector and focuses on increasing its productivity using lean manufacturing tools. First, productivity was identified at 15%, while the average for the sector was 25%, causing a negative economic impact of approximately U$301,309 per year. Through the diagnosis, it was found that the main reasons were machine downtime, caused by various factors such as unplanned downtime and maintenance; the second reason was inadequate sorting of raw material, due to the lack of standardized procedures, lack of protocols and disorder in the sorting area. To address these problems, an improvement model was developed based on 5S tools, standardized work and TPM (autonomous and preventive maintenance). To validate the model, a pilot project of 5S tools and standardized work was carried out through an internal audit conducted before implementing the tool and after its application, an increase in 5S compliance from 29% to 84% was evidenced. Likewise, the standardized work pilot reduced the cycle time of the raw material classification activity from 708 to 539 seconds thanks to the implementation of a procedures format that standardized the process and eliminated activities with no added value. Regarding TPM, it was validated using Arena software, achieving a 2% improvement in OEE and therefore a 19.4% increase in productivity.

Keywords

Productivity; TPM; Preventive Maintenance; Standardized Work; 5S.

1. Introduction

The manufacturing sector is made up of those economic activities that transform the chemical or physical composition of raw materials into new products. It is subdivided into two: manufacturing, which corresponds to the production activities of primary products that are generally used as raw materials, and non-primary manufacturing, which is made up of food and beverages; textiles, leather and footwear; chemicals, rubber and plastics; and non-metallic minerals, among others [1]. Peru is one of the world's largest producers of fishmeal, which is used to formulate balanced feed for activities such as aquaculture, poultry farming, livestock, etc [2].

Fishmeal production has been increasing by 19% on average since 2019, in addition, the contribution of the manufacturing GDP until 2021 had a growing trend reaching up to 13%, likewise it is considered of great importance in the generation of employment since until 2021 it has represented approximately 8.75% of the national Economically Active Population (EAP) [3][4][5]. The present case study has analyzed the non-

DOI: https://doi.org/10.15488/15322
ISSN: 2701-6277
publish-Ing.

primary manufacturing subsector because it studies the production of fishmeal from hydrobiological resources.

According to the literature reviewed, it was found that the main problem lies in low productivity due to various factors such as raw material selection, quality, equipment operation, reprocessing, among others. A case study identified as the main problem the amount of waste in the process, due to the lack of quality controls and inadequate transportation of raw material, which was countered with their proposal to apply lean tools such as VSM, Standardized Work and 5S, which reduced on average 33% the cycle time [6]. Similarly, in another case study, they found that their main problem was low productivity due to quality and waste or MUDAS throughout the process, once the waste and its causes were identified, it was proposed to organize the plant and reduce material search times, apply 5S. To achieve a continuous flow in the processes, minimize overproduction and reduce in-process inventories, the Heijunka tool was proposed [7]. Finally, the use of Jidoka was proposed to reduce quality problems and reduce costs due to defective products. In addition, a case study on an SME producer of giant squid concluded that its low productivity was directly related to plant downtime, so it sought to implement the TPM tool to reduce machine breakdowns and improve its production capacity, then apply the tool resulted in the reduction of such times by 39%, increased machine availability by 14% and improved the time between failures by 40% [8].

This case study presents a study carried out in a company that produces waste flour for export from hydrobiological residues. The company's main issue was low productivity, which is present in a similar way in other companies of the Peruvian manufacturing sector. According to a diagnosis carried out, the high number of machine failures, lack of standardized procedures and lack of organization at the workstation were identified as causal factors. These factors caused a slowdown in the production flow, resulting in less production than planned. Productivity was determined throughout the year by the ratio between the tons of finished product and the amount of raw material used, obtaining an average value of 0.15 (Tons of Finished Product / Tons of Raw Material). This value was contrasted with the ratio obtained by the leading company in the sector, which was 0.25 (Tons of Finished Product / Tons of Raw Material). In this way, a technical gap of 0.10 was obtained, thus demonstrating a significant difference in productivity. Additionally, it was identified that the economic impact amounted to U$301,309 per year, primarily due to the unproduced tons of finished product and excessive labor time paid.

This article is composed as follows: introduction, which presents the situation of the sector with emphasis on the main problems, literature review to verify success cases related to the proposal, the methodology of the contribution, validation and finally conclusions.

2. Literature Review

2.1 Improved productivity in the manufacturing sector

Within the manufacturing industry, several improvement models have been developed, applying different methodologies and tools, with the objective of increasing productivity and reducing waste in the different stages of the process. In this sector, low productivity caused by a high level of waste and machine stoppages is recurrent. Therefore, among the solution alternatives, tools such as TPM can be implemented to reduce the frequency of machine stops and tools such as standardized work and SLP to reduce production cycle times, thus increasing productivity and reducing economic losses [9]. On the other hand, a study conducted in the food industry shows as a result a reduction of waste to optimal levels for the industry, thanks to the application of a model based on lean manufacturing tools such as 5S, Standardization and Kanban [10]. In another case study, a low production capacity and the disorder in different areas of the company were evidenced. After implementing the SMED, TPM and 5S tools, the model allowed a reduction of 25% in maintenance times and, at the same time, the training of more qualified personnel to deal with the problem, thus achieving a higher production capacity [11].

2.2 5S

The implementation of the 5S tool promotes cleanliness and order, which has a positive impact on work quality and efficiency. In addition, it helps reduce waste generated during manufacturing processes. By implementing 5S effectively and efficiently, organizations experience significant improvements in productivity. Also, this implementation results in higher profits and increased competitiveness globally in both manufacturing and non-manufacturing sectors [12]. A case study developed in an assembly line, presents the implementation of the tool, where it was possible to reduce the search time from 8.6 h to 3.1 h, thus improving the total process cycle efficiency [13]. Similarly, the 5S were applied with the objective of improving the organization of consumables, which caused a great impact on the efficient operation of workshops and maintenance activities. Thanks to it, a 70% reduction in the time required to locate materials was achieved, which went from 45 seconds to 15 seconds [14].

2.3 Standard Work

Standardized work is a tool used to improve the overall productivity of a company, since it helps to identify areas for improvement by highlighting waste in a process and specifies exactly how work can be performed to gain a competitive advantage [15]. A study conducted in the automotive sector focused on standardizing operations, reducing or eliminating the number of activities that do not generate added value and increasing productivity. Thanks to the implementation of this tool, it was possible to balance the activities, achieving similar execution times. In addition, the new operating methods made it possible to reduce the number of workers required and shorten the distance between operations on the line [16]. Similarly, in another investigation, the tool was applied for reducing activities that do not add value to the product, managing to increase the workstation's capacity, saving 31.6 seconds per cycle, and increasing process productivity by up to 6.5 [15]. In another study, this tool was applied in an assembly line of agricultural machinery, resulting in an improvement in the continuous flow of materials and a significant increase in speed and quality in meeting the assembly line's needs [17].

2.4 Total Productive Maintenance

The TPM tool is defined by some authors as a system designed to eliminate waste such as downtime, unscheduled stops, production slowdowns and defective products [18]. A study conducted in an auto parts machining line implemented TPM in the bottleneck, where a reduction of lost hours due to unplanned maintenance, a 33.21% reduction in lost production and a 10.7% increase in production capacity were achieved [19]. Similarly, the productivity level of an organization was improved by applying a methodology based on the Autonomous Maintenance pillar, with which it managed to reduce the MTTR from 17 to 9 hours and maximize the OEE by 30% [20]. On the other hand, it was designed and applied a sequential scheme to implement TPM in a bottling line, which allowed increasing OEE by 62.6% during after 9 months [21]. Another relevant study, a training plan was carried out to improve workers' skills, resulting in the increase of the MTBF value from 124 to 155, the reduction of MTTR from 5.26 to 4.56 and a remarkable increase in OEE from 95.9% to 97.1% [22]. This tool also allowed the absolute increase in yield by 6.83% and OEE by 6.45% [23]. Finally, a 23% decrease in breakdowns was obtained in the CNC lathes sector and there was an increase in machine availability and OEE of approximately 5% [24].

3. Contribution

To develop an improvement model, a literature review was conducted to find case studies covering problems related to machine downtime, lack of standardized procedures and lack of organization. Unlike other research, the present model applies the TPM, Standardized Work and 5S tools. These tools were selected with the objective of covering some of the main problems of the sector. Likewise, it was identified that there are no studies applied to fishmeal processing SMEs. Table 1 shows the articles selected and the tools used to solve the problems identified.

Table 1: State of the art vs. main problems comparison matrix

Authors	Unplanned shutdowns	Maintenance shutdowns	Lack of standardized procedures
Coppo et al. (2022)	Preventive and Autonomous Maintenance		
Mor et al. (2018)			Standardized Work
Bataineh et al. (2019)	Autonomous Maintenance		
Pinto et al. (2020)	Autonomous Maintenance	Preventive Maintenance	
Santos et al. (2021)			Standardized Work
Rojas et al (2021)			Standardized Work
Proposal	**Autonomous Maintenance**	**Preventive Maintenance**	**Standardized Work**

3.1 Proposed Model

Based on the literature review, an improvement model was proposed to increase productivity in a company of the primary manufacturing sector through the use of three lean manufacturing tools: 5S, Standardized Work and TPM. These tools will be implemented together, with the objective of obtaining a greater impact on productivity improvement, reducing the time lost due to machine stoppages and inadequate raw material classification. As can be seen in Figure 1.1, the proposed model consists of 3 components: Execute protocols and order in the organization, implement standardized procedures and Reduce machine stoppages.

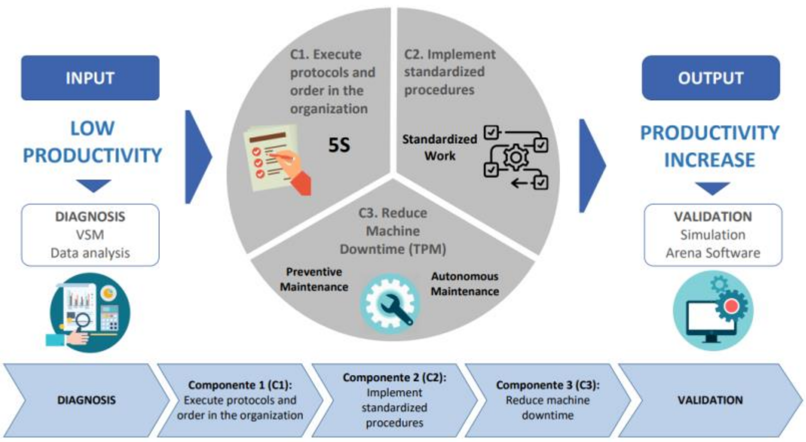


Figure 2: Proposed model

3.2 Model components

The proposed model consists of three components, which are clearly related to the tools to be used for the improvement proposal as shown in Figure 1, each of these will be detailed in greater depth for its subsequent application.

3.2.1 Component 1: 5s

The first phase consists of implementing the 5S tool in the raw material selection area, since it became evident that the operators do not have an adequate and clean space in which they can carry out their activities.

Also, this tool will be used as a basis for implementing the following tools in a more orderly and efficient manner, since, according to the literature reviewed, 5S is responsible for laying the groundwork for applying other tools that can have a greater impact on improving processes.

3.2.2 Component 2: Standardized Work

In this second component, it is proposed to implement Standardized Work, which is one of the tools that allows increasing productivity in companies and is defined as the specific instructions that help to make a product in the most efficient way [15]. This tool consists of elaborating determined procedures, to standardize the execution of operations and previous activities, with the objective of improving the productivity of the operators. At the beginning of this phase, the operations to be improved must be identified and a work sequence must be established so that the operators have a single way of working, as well as determining the standard time and carrying out a continuous control to validate compliance.

3.2.3 Component 3: TPM (preventive and autonomous)

The TPM tool will be implemented with the objective of having an established procedure for the prevention of equipment failures to foresee losses that will affect productivity in the future. From this tool, only 2 of the TPM pillars will be implemented, which are preventive maintenance and autonomous maintenance. For the first pillar, it is necessary to evaluate the equipment in question and diagnose the current situation of them, what they need and identify the causes of this problem. Then the operators will be helped to restore the deterioration of the equipment, correct design weaknesses and extend the life of the equipment through good planning and scheduling of maintenance, schedules for spare parts, lubrication, and the necessary technical information such as data sheets, operating manuals, types of materials and lubricants used by each equipment, etc. Finally, the aim is to standardize maintenance techniques to reduce the frequency of failures of equipment and its parts in order to extend its useful life and make the best possible use of it without losing the quality of the final product.

3.3 Model indicators

To measure the results of the implementation with respect to the initial state of the company, the following indicators will be used.

Productivity: Used to evaluate the number of tons of finished product obtained for each ton of raw material used.

Objective: To increase the productivity level by at least 10%.

$$Productivity = \frac{Metric\ Tons\ of\ Residual\ Flour}{Metric\ Tons\ of\ Hydrobiological\ Residues} \tag{1}$$

OEE: Used to evaluate the overall efficiency of the machines involved in the production process.

Objective: To achieve an OEE of at least 85%.

$$OEE = Availability\ x\ \%\ Yield\ x\ \%\ Quality \tag{2}$$

Cycle time: Used to measure the time it takes to classify a batch of residual flour.

Objective: Reduce cycle time by at least 30%.

$$CT = \sum(\ Total\ Classification\ Time) \tag{3}$$

4. Validation

This chapter will show the results obtained throughout the realization of the case study. First, after a diagnosis of the current situation of the company, the productivity was 15%, which was below the productivity of the sector obtained from the ratios of a leading company in the sector that has a productivity of 25%, which shows the existence of improvements. After implementing the proposed tools, a productivity ratio of 19.3% was obtained, which translates into a productivity increase of 4%. On the other hand, the factors that were related to low productivity were machine stoppages and deficient classification of raw material.

4.1 Initial Diagnosis

Regarding the diagnosis made, Figure 1 shows the trend of the productivity indicator of the case study throughout the year 2022, which was between 10% and 15%, a result below the sector value of 25%, which shows the existence of a technical gap to be improved. The following are the first results to be improved for the identified causes: Deficient classification of raw material and machine stoppages.

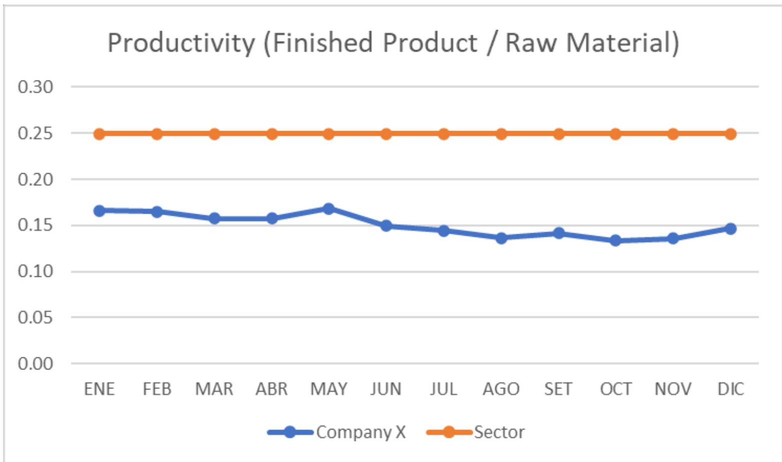


Figure 2. Technical gap in productivity

Table 2 details the activities sequentially for the selection and classification of raw material, which has a cycle time of 708 seconds.

Table 2. Activities of the raw material classification process

N°	Activity	VA/ NVA	Cycle time per operator (seconds)				
			1	2	3	4	Average
1	Receive raw material	VA	304	365	258	350	48.75
2	Load the raw material into the hopper	VA	22	26	19	25	23.034
3	Visually inspect and remove contaminants and unsuitable material.	VA	260	242	299	312	278.2
5	Dispose of contaminants and unsuitable material in the deposition area	NVA	40	38	51.2	36	41.3

6	Collect waste from deposition area and place in container	NVA	160	184	144	200	172.0
7	Take waste to disposal area	VA	167.5	116.58	134	160.8	144.72
Total:							708.00

On the other hand, in the case of machine stoppages, a record of the frequency of failures was obtained for each piece of equipment over the course of a year, as shown in Table 3, which provided a clearer view of the availability and operability of the equipment.

Table 3. Machine stoppages in a year

Equipment	Frequency
Mixed stove	40
Rotary pre-strainer	40
Double screw press	40
Wet grinding mill	44
Rotary tube dryer	100
Purifier	32
Dry grinding mill	44
Antioxidant hopper	44
Bagging machine	37

Finally, Table 4 shows the OEE calculation made to verify the current situation of the equipment in use, with a result of 64% below the recommended OEE.

Table 4. OEE case study

Productive hours 2374	Available hours 2880	Availability index 82%
Designed production 2883.65	Produced capacity 3351.62	Yield index 86%
Good production 2595.29	Designed production 2883.65	Quality index 90%
	OEE	**64%**

4.2 Implementation for the pilot plan

According to what was previously described, with respect to the proposed model, it is known that 3 lean tools have been implemented, which are 5S, standardized work and TPM. For the 5S tool, an internal audit was conducted on the current situation of the raw material reception and selection area, which allowed measuring the degree of opportunity for improvement in the mentioned area. It is evident that there is an improvement in the order of the area together with improvements to identify the tools that should be used in the process, since the tool has not been implemented, it can be observed that the organization has a 5S score of 29%, which is very low compared to other companies. Likewise, a minimum score of 85% was defined to be reached after its implementation, however, it reached a value of 84% after applying each one of the 5S in the organization, a training program was carried out for all the collaborators, a team was formed in charge of the implementation and the pilot test was started with the elimination of everything that was not used in that area and occupied space that it should not, A general cleaning of the area was carried out in order to have a cleaner and more hygienic environment, and the health of the workers was also prioritized by placing trash cans that are constantly changed so that waste does not accumulate. The company also seeks to implement measures to ensure that organization and order are complied with following the 5S methodology, which is why a checklist will be used to validate implementation. Finally, activities were established to verify that the 3S already implemented persist over time and reinforce good habits when necessary, through the last 2S.

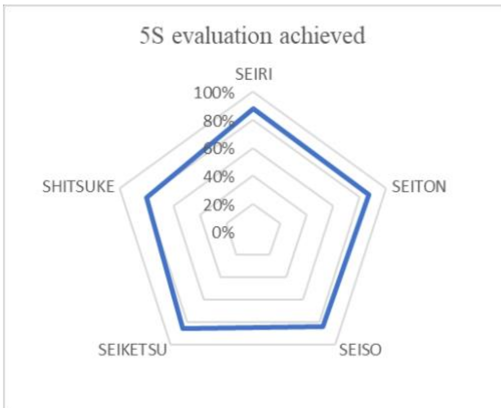


Figure 3. Qualification achieved after implementation

For the standardization of the work, the steps for the selection of raw material were identified, as well as the activities without added value that proceed to be eliminated to speed up the process, without altering the quality of the raw material that will enter the production. In addition, a document was designed to provide a visual presentation of the procedure, facilitating understanding by the operators, and always guaranteeing the application of the new procedure. Figure 4 shows the mentioned document.

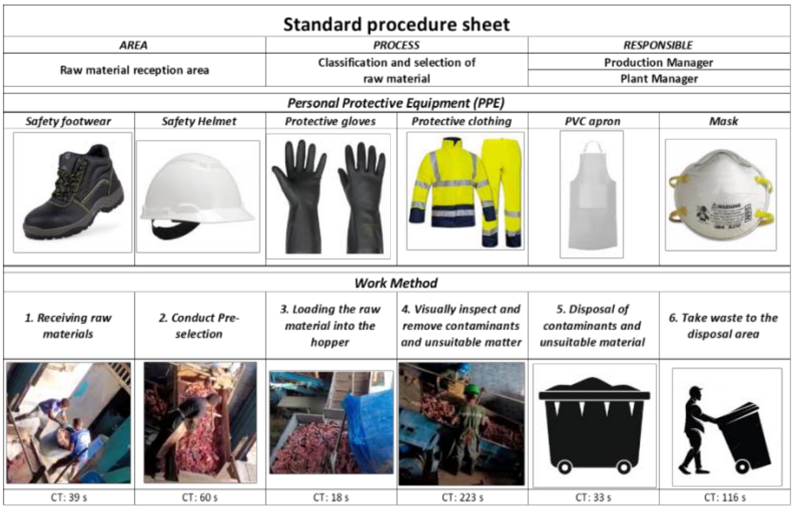


Figure 4. Procedure for raw material classification

Based on the document, the activities were carried out as a pilot test, omitting those that have no added value, thus reducing the initial cycle time. Table 5 shows the most efficient activities and their respective time.

Table 5. Implementation of the standardized procedure

No.	Activity	VA/NVA	Average observed time (seconds)
1	Reception of raw material	VA	44.35
2	Preselection	VA	69.43
3	Load Raw Material into hopper	VA	26.47
4	Visually inspect and remove contaminants and unsuitable material	VA	235.24
5	Deposit contaminants and unfit material in container	VA	36.1
6	Take waste to disposal area	VA	127.37
		Total	538.96

Regarding the improvement proposal for recurring machine stoppages, the TPM tool is implemented in the autonomous and preventive pillars, firstly, the autonomous pillar aims to train operators so that they can perform inspections and adjustments of the equipment when required and have a faster response capacity to any eventuality, A training session was held to introduce the employees to the principles of autonomous maintenance and explain its importance for maintaining high levels of productivity, after which theoretical and practical training is provided in a more specialized way and focused on each of the equipment used in the production process.

Table 6. Autonomous Maintenance Training Program

AUTONOMOUS MAINTENANCE TRAINING	
User profile	**Methods**
Aimed at all production and maintenance related workers: production manager, plant supervisor, maintenance manager, technicians, and operators.	Lectures, slide presentations, videos, group dynamics, presentation of success stories, question and answer session.
Objectives	
1. To introduce the concepts and principles of autonomous maintenance. 2. To raise awareness of the benefits and advantages of autonomous maintenance in the improvement of production efficiency. 3. To learn the steps and activities to be performed for the implementation of the autonomous maintenance program. 4. To learn how to inspect and detect machine failures. 5. Acquire knowledge about corrective actions for the solution of failures. 6. Understand the critical success factors in the implementation of Autonomous Maintenance.	
Description of contents	
1. **Introduction and awareness:** • Concept of autonomous maintenance • Characteristics of an AM program • Benefits of its application • Objectives of the program • Show success stories 2. **Program implementation** • Description of the detailed steps for implementation • Define the tasks of the operators 3. **Technical training** • Fault detection • Root cause analysis • Corrective Actions • Training in equipment cleaning, lubrication, adjustments, and calibration activities.	4. **Audit of the AM program** • Evaluation of standards and procedures • Program performance indicators and metrics. • Checklist to measure compliance with activities. 5. **Actions to sustain the AM** • Evaluation and follow-up of activities • Development of corrective actions • Ongoing establishment of clear goals and objectives. 6. **Success factors of the AM** • Explain the importance of leadership and commitment. • Promote active participation of operators • Establishment of clear standards and procedures
Program duration	
From 06/01/2023 to 06/30/2023	

The procedure detailed in Table 6 will allow the operators to be able to solve any unforeseen failure, to the extent that they can solve it by verifying everything that is stated in the form. Otherwise, the maintenance team should be called to solve major failures.

On the other hand, the preventive pillar of TPM was implemented, with the objective of reducing the frequency of failures so that they operate in the best conditions and do not cause production stoppages, in the same way as for the autonomous pillar, all operators must be trained, and a team must be formed to follow the schedule that will be established. In addition, operating manuals and instructions are required so that operators can detect small failures in time and even act in advance. After implementing these pillars, a 38% reduction in machine stoppages was estimated, an average calculated from a review of case studies where the tool was applied [6][25], so Table 7 shows the new data to be used in the simulation on the reduction of machine stoppages.

Table 7. Machine stops after pilot test

Equipment	Frequency
Mixed stove	24
Rotary pre-strainer	25
Double screw press	24
Wet grinding mill	27
Rotary tube dryer	62
Purifier	19
Dry grinding mill	27
Antioxidant hopper	27
Bagging machine	22

4.3 Simulation improvement proposal

To validate the model proposed in the previous chapters, the simulation software Arena was used to run the results obtained in the pilot test and see the impact it would have on the main indicators which are productivity and OEE. The simulation shown in Figure 5 was designed for the entire production process, from raw material to the production of 50 kg bags of fishmeal. In the first instance, the Input Analyzer software was used to determine the number of samples necessary for the replications in the simulation, of which 30 were used since it is the minimum recommended value for case studies, using a confidence level of 95% and a percentage of error of 10%, and allows obtaining the adjusted distribution for the duration time of each of the operations. On the other hand, two scenarios were considered for the development of the simulation, firstly, with the current machine stops and secondly, the number of stops and repair time reduced after the pilot plan, the purpose of being able to simulate both scenarios is to see the impact on productivity and availability in the mype, as well as to obtain an improvement in the OEE result.

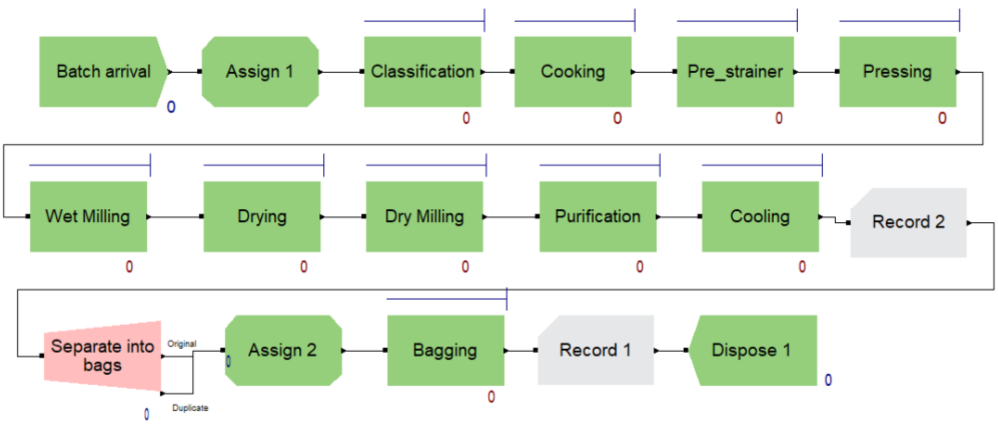


Figure 5. Simulation model of the process in Arena

Next, Table 8 will present the indicators proposed to measure the impact of the implementation of the tools used, with the objective of making a more precise comparison between the initial situation and the scenario obtained after having implemented the proposed tools, through pilot tests for the case of the 5S tools and standardized work and simulation for the TPM tool.

Table 8. Results metrics

Measurement of the improvement project							
Problem	Current	Objective	Enhanced	Indicators	Current	Objective	Enhanced
Low Productivity	15%	25%	19.3%	OEE	64%	85%	66%
				Cycle Time	708 sec.	489 sec.	538.96 sec.
				5S compliance level	29%	85%	84%

5. Discussion

From the literature reviewed it has been possible to verify the existence of various problems in the sector, however a problem constantly mentioned is the amount of wastage [6], in the present case study it is not supposed to be a problem since the case study company manufactures the product from hydrobiological resources therefore, the wastes can be reprocessed in the next batch as raw material.

To develop the proposal, case studies were investigated where the problems present in the sector have been solved and have had quantitative and significant improvements in the companies. Such is the case of a Peruvian company that used the TPM tool to reduce machine stops, managing to reduce the frequency of these stops by 40%, managing to increase OEE by 4%, and improve productivity by 4.3% [23]. Furthermore, in a plastic company, the 5S tool was applied on the assembly line, which allowed them to improve the efficiency of the activities involved and increase the 5S score, from 20% to 80% [13]. Finally, with the objective of eliminating activities that do not generate value in the system, the Standard Work tool was used, where study cases were identified that validate an improvement in their activities after applying it, the case of a line of pre- assembly in a gearbox manufacturing company managed to reduce its total cycle time from 67.53 to 64.69 hours for demand per day [26]. Based on the studies reviewed, it was possible to identify that the results obtained both in the literature and in the present research are consistent, obtaining favorable results in improving productivity. These findings demonstrate the importance of implementing lean tools in the peruvian manufacturing sector to overcome the recurring problems of the sector. In this way, the proposed model can serve as a framework for the application of these tools in other MSEs in the sector.

The research project has proposed the use of TPM tools (preventive and autonomous pillars) and standardization of work to increase productivity, although it is true that a slight improvement was obtained, it is recommended to maintain and further investigate the other problems that occur in the case study company and make use of other Lean tools such as Kaizen to work together with those already proposed. In a case study it could be evidenced that the use of TPM plus Kaizen contributed to reduce the number of losses due to machine stoppage, with this, the OEE increased by more than 10%, this tool would allow to maintain a culture of continuous improvement in the company and thus greater commitment to comply with the standardized work procedures and TPM that were applied in the improvement project [27].

Likewise, one of the main limitations in developing the proposal was the implementation of a lean culture within the case study company because it involved a new way of working and changing the traditional methods to which the workers were accustomed. Often, they tend to resist changes due to uncertainty and lack of confidence in the new methodologies, especially when the workers are not familiar with the benefits that the application of new tools would bring. To counteract this obstacle, training was developed regarding the lean tools to be implemented so that they feel involved and part of the project.

Another significant limitation of this study is that the validation of the TPM was based on a simulation to evaluate and compares the initial and final scenario. However, this could have limited the ability to obtain results that accurately reflect the actual conditions and challenges that could arise during TPM implementation in an everyday work context. Therefore, it is recommended that future research delve into the empirical evaluation of the application of TPM, through its step-by-step implementation and the recording of the corresponding indicators for impact assessment.

6. Conclusion

This study proposes the use of lean tools such as Standardized Work and TPM (autonomous and preventive) to mitigate the identified problem of low productivity. The main causes were identified through engineering tools such as Ishikawa diagram, Pareto diagram and TIS analysis to know them in detail and directly attack each of them. Therefore, a literature review related to the proposed topic was carried out to validate the use of the proposed tools. Based on the improvement model, the tools specified therein were applied.

First, it was possible to demonstrate that the application of 5S allowed to improve order and cleanliness in the area, obtaining a substantial improvement in the level of compliance with 5S, which went from 29% to 84%, since at first the lack of order in the space could be observed with the naked eye. However, thanks to an initial audit it was possible to specifically detect which areas were causing the greatest problem, to be solved and finally evaluated in a final audit. In addition, this tool made it possible to lay the foundations for the implementation of the Standardized Work and TPM tool. Subsequently, a standardized procedure was implemented that detailed the steps to be followed to perform the activity correctly and in the shortest possible time, thus eliminating downtime, thus reducing the cycle time by 23. 88%. Finally, the TPM tool was implemented in the autonomous and preventive maintenance pillars, resulting in a 38% reduction in the number of machines stops.

Regarding the validation of the results, the Arena software and the pilot test allowed the comparison of the results before and after its application. It was also possible to verify that the reduction of machine failures generated an impact on the increase of OEE indicators of 2% and an increase of 4. 3% in productivity.

References

[1] La crisis de la covid-19 y su impacto en la manufactura. (2020, 9 de noviembre). La Cámara. Available: https://lacamara.pe/la-crisis-de-la-covid-19-y-su-impacto-en-la%20manufactura, Accessed on Mar 11, 2023.

[2] Sociedad Nacional de Pesquería. (s.f.). Harina de Pescado: Perú lidera su producción mundial. https://www.snp.org.pe/industria-pesquera/harina-de-pescado/#:~:text=El%20Per%C3%BA%20es%20el%20principal,al%20grado%20de%20una%20harina.

[3] Instituto Nacional de Estadística e Informática. (2023). Población económicamente activa ocupada, según principales características. https://www.inei.gob.pe/estadisticas/indice-tematico/ocupacion-y-vivienda/

[4] Instituto Nacional de Estadística e Informática. (2023). Producto Bruto Interno según Actividad Económica (Nivel 9) 1950 - 2021 (Valores a precios constantes de 2007). https://www.inei.gob.pe/estadisticas/indice-tematico/economia/

[5] Instituto Nacional de Estadística e Informática. (2023). Transformación de productos pesqueros, según giro industrial. https://www.inei.gob.pe/estadisticas/indice-tematico/economia/

[6] Siriban-Manalang, A. B., Brillante, J. B., Cabahug, F. I. V., & Flores, R. P. (2019). Clean & Lean Production in Fish Canning Industry—A Case Study. In Lean Engineering for Global Development (pp. 191–223). Springer International Publishing. https://doi.org/10.1007/978-3-030-13515-7_7

[7] Jimenez, G., Santos, G., Sá, J. C., Ricardo, S., Pulido, J., Pizarro, A., & Hernández, H. (2019). Improvement of Productivity and Quality in the Value Chain through Lean Manufacturing – a case study. Procedia Manufacturing, 41, 882–889. https://doi.org/10.1016/j.promfg.2019.10.011

[8] 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 Conference Series: Materials Science and Engineering, 796(1), 012006. https://doi.org/10.1088/1757-899X/796/1/012006

[9] Pacheco-Colcas, F. A., Medina-Torres, M. P., & Quiroz-Flores, J. C. (2022). Production Model based on Systematic Layout Planning and Total Productive Maintenance to increase Productivity in food manufacturing companies. Proceedings of the 8th International Conference on Industrial and Business Engineering, 299–306. https://doi.org/10.1145/3568834.3568854

[10] Rojas-Benites, S., Castro-Arroyo, A., Viacava, G., Aparicio, V., & del Carpio, C. (2021). Reduction of Waste in an SME in the Meat Sector in Peru through a Lean Manufacturing Approach Using a Model Based on 5S, Standardization, Demand Forecasting and Kanban. The 2021 7th International Conference on Industrial and Business Engineering, 279–285. https://doi.org/10.1145/3494583.3494592

[11] Valverde-Curi, H., De-La-Cruz-Angles, A., Cano-Lazarte, M., Alvarez, J. M., & Raymundo-Ibañez, C. (2019). Lean Management Model for Waste Reduction in the Production Area of A Food Processing and Preservation SME. Proceedings of the 2019. 5th International Conference on Industrial and Business Engineering, 256–260. https://doi.org/10.1145/3364335.3364378

[12] Chandrayan, B., Solanki, A. K., & Sharma, R. (2019). Study of 5S lean technique: a review paper. International Journal of Productivity and Quality Management, 26(4), 469. https://doi.org/10.1504/IJPQM.2019.099625

[13] Makwana, A. D., & Patange, G. S. (2022). Strategic implementation of 5S and its effect on productivity of plastic machinery manufacturing company. Australian Journal of Mechanical Engineering, 20(1), 111–120. https://doi.org/10.1080/14484846.2019.1676112

[14] Pombal, T., Ferreira, L. P., Sá, J. C., Pereira, M. T., & Silva, F. J. G. (2019). Implementation of Lean Methodologies in the Management of Consumable Materials in the Maintenance Workshops of an Industrial Company. Procedia Manufacturing, 38, 975–982. https://doi.org/10.1016/j.promfg.2020.01.181

[15] Mor, R. S., Bhardwaj, A., Singh, S., & Sachdeva, A. (2019). Productivity gains through standardization-of-work in a manufacturing company. Journal of Manufacturing Technology Management, 30(6), 899–919. https://doi.org/10.1108/JMTM-07-2017-0151

[16] Antoniolli, I., Guariente, P., Pereira, T., Ferreira, L. P., & Silva, F. J. G. (2017). Standardization and optimization of an automotive components production line. Procedia Manufacturing, 13, 1120–1127. https://doi.org/10.1016/j.promfg.2017.09.173

[17] Santos, D. M. C., Santos, B. K., & Santos, C. G. (2021). Implementation of a standard work routine using Lean Manufacturing tools: A case Study. Gestão & Produção, 28(1). https://doi.org/10.1590/0104-530x4823-20

[18] Reyes, J., Alvarez, K., Martínez, A., & Guamán, J. (2018). Total productive maintenance for the sewing process in footwear. Journal of Industrial Engineering and Management, 11(4), 814. https://doi.org/10.3926/jiem.2644

[19] Morales Méndez, J. D., & Rodriguez, R. S. (2017). Total productive maintenance (TPM) as a tool for improving productivity: a case study of application in the bottleneck of an auto-parts machining line. The International Journal of Advanced Manufacturing Technology, 92(1–4), 1013–1026. https://doi.org/10.1007/s00170-017-0052-4

[20] Amorim, G., Hatakeyama, K., & Rojas-Lema, X. (2019). Implantation of Total Productive Maintenance: A Case Study in the Manufacturing Industry (pp. 259–267). https://doi.org/10.1007/978-3-319-93488-4_29

[21] Bataineh, O., Al-Hawari, T., Alshraideh, H., & Dalalah, D. (2019). A sequential TPM-based scheme for improving production effectiveness presented with a case study. Journal of Quality in Maintenance Engineering, 25(1), 144–161. https://doi.org/10.1108/JQME-07-2017-0045

[22] Ribeiro, I. M., Godina, R., Pimentel, C., Silva, F. J. G., & Matias, J. C. O. (2019). Implementing TPM supported by 5S to improve the availability of an automotive production line. Procedia Manufacturing, 38, 1574–1581. https://doi.org/10.1016/j.promfg.2020.01.128

[23] Coppo-Romero, P., Soto-Loncharich, D., Quiroz-Flores, J. C., Flores-Pérez, A., & Collao-Díaz, M. (2022). Application of a Maintenance Management Model based on LEAN TPM to Increase OEE in Canning SMEs. Proceedings of WCSE 2022 Spring Event: 2022 9th International Conference on Industrial Engineering and Applications. https://doi.org/10.18178/wcse.2022.04.037

[24] Pinto, G., Silva, F. J. G., Baptista, A., Fernandes, N. O., Casais, R., & Carvalho, C. (2020). TPM implementation and maintenance strategic plan – a case study. Procedia Manufacturing, 51, 1423–1430. https://doi.org/10.1016/j.promfg.2020.10.198

[25] Quiroz-Flores, J. C., & Vega-Alvites, M. L. (2022). REVIEW LEAN MANUFACTURING MODEL OF PRODUCTION MANAGEMENT UNDER THE PREVENTIVE MAINTENANCE APPROACH TO IMPROVE EFFICIENCY IN PLASTICS INDUSTRY SMES: A CASE STUDY. South African Journal of Industrial Engineering, 33(2), 143–156. https://doi.org/10.7166/33-2-2711

[26] Saravanan, V., Nallusamy, S., & George, A. (2018). Efficiency Enhancement in a Medium Scale Gearbox Manufacturing Company through Different Lean Tools - A Case Study. International Journal of Engineering Research in Africa, 34, 128–138. https://doi.org/10.4028/www.scientific.net/JERA.34.128

[27] Ahmad, N., Hossen, J., & Ali, S. M. (2018). Improvement of overall equipment efficiency of ring frame through total productive maintenance: a textile case. The International Journal of Advanced Manufacturing Technology, 94(1–4), 239–256. https://doi.org/10.1007/s00170-017-0783-2

Biography

Diego Niño De Guzmán (*2001) is a student of the last cycle of industrial engineering at the University of Lima, with experience as an intern in the financial sector, where he gained knowledge about process automation, database management, data analysis and continuous improvement.

Dahana Obregon (*2000) Industrial Engineering graduate from the University of Lima, with experience in laboratories carrying out experimental research projects, as well as applying lean tools for the operation of equipment and the distribution of space in various laboratory projects.

Alberto Flores-Perez has a PhD in Education from Universidad de San Martin de Porres and a master's degree in supply chain management from Universidad ESAN. He holds a degree in Food Industry Engineering from Universidad Nacional Agraria La Molina. Specialist in the implementation of Continuous Improvement Projects, PDCA, HACCP, GMP in the agro-industrial sector, trainer of national governmental institutions and the United Nations (UNDP). He is a member of IEEE, SCEA Ohio, IOEM and CIP (College of Engineers of Peru).

CPSL
CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
CPSL 2023-2

5th Conference on Production Systems and Logistics

Investigation Of Laser-Based Drying Of Electrodes For Lithium-Ion-Battery Production Using Vertical-Cavity Surface-Emitting Lasers (VCSEL)

Daniel Neb[1], Sebastian Wolf[1], Benedict Ingendoh[1], Simon Klein[2], Benjamin Dorn[1], Heiner Heimes[1], Achim Kampker[1]

[1]Chair of Production Engineering of E-Mobility Components PEM, RWTH Aachen University, Aachen, Germany
[2]Faculty of Mechanical Engineering, RWTH Aachen University, Aachen, Germany

Abstract

Demand for lithium-ion batteries is expected to increase significantly within the upcoming decade. This trend is already evident today. Accordingly, an increasing number of new production lines as well as extensions of existing production lines can be observed. To reduce global CO_2 emissions and maintain competitiveness, the development of new, more efficient production technologies is essential. At the same time, innovative production methods can make a decisive contribution to significantly improve the quality and performance of lithium-ion batteries.
Currently, the convection drying technology marks the state of the art in drying the wet-coated electrode foils. Accounting for approximately one quarter of the total energy consumption in battery production, this technology represents one of the most cost-intensive process steps along the value chain. A promising approach to increase quality and efficiency of electrode drying is the use of vertical-cavity surface-emitting lasers (VCSEL). In addition to the improved controllability compared to conventional drying processes, these also offer the advantage of a direct energy contribution that is tailored to the material. Furthermore, the exceptionally high-power density enables a reduction in machine footprint while simultaneously increasing production throughput.
In this study, the general experimental setup for vertical drying of electrodes using VCSEL technology is described. Furthermore, the main results are presented and discussed in order to derive subsequent conclusions for further improvements in quality and energy efficiency in the drying process of electrodes for lithium-ion batteries.

Keywords

Lithium-Ion Batteries; Battery Production; Electrode Manufacturing; Laser Drying; VCSEL

1. Introduction

Since the beginning of the early 1990s, lithium-ion batteries have experienced a continuous increase in importance and have become an indispensable part of our everyday lives [1]. Their field of application predominantly ranges from the consumer sector up to the electromobility segment [2]. Due to the worldwide introduction of new regulations to increase sustainable mobility, the automotive sector is undergoing far-reaching transformations, with particular focus in the rapid development of the vehicle electrification [3, 4]. Accordingly, in 2022, the EU member states and the European Parliament reached an agreement that only climate-neutral vehicles shall be permitted by 2035 [5]. The current profound change in the automotive industry illustrates the increasing importance of electrochemical storage systems [6]. As a result of this trend,

DOI: https://doi.org/10.15488/15239
ISSN: 2701-6277
publish-Ing.

global demand is expected to increase between 2 and 4 TWh by 2030 [7].
However, the further development of the underlying production processes of lithium-ion batteries still faces many hurdles and is a key challenge for the industry [6]. One of the currently greatest challenges represents the reduction of the energy required in the production process. Together with the solvent recovery, the coating and drying of the anode as well as cathode foils present one of the most cost-intensive production steps within the value chain of lithium-ion batteries [8, 9, 10]. According to DEGEN et al., about 27% of the total energy consumption is attributed to this process step [10]. Furthermore, LIU et al. quantifies the share of energy required for drying in the total consumption at 46.84% [11]. Currently, the convection drying method shown in Figure 1, presents the most commonly used method for drying the electrodes. Disadvantages of this drying method lie in the high energy and installation space requirements.

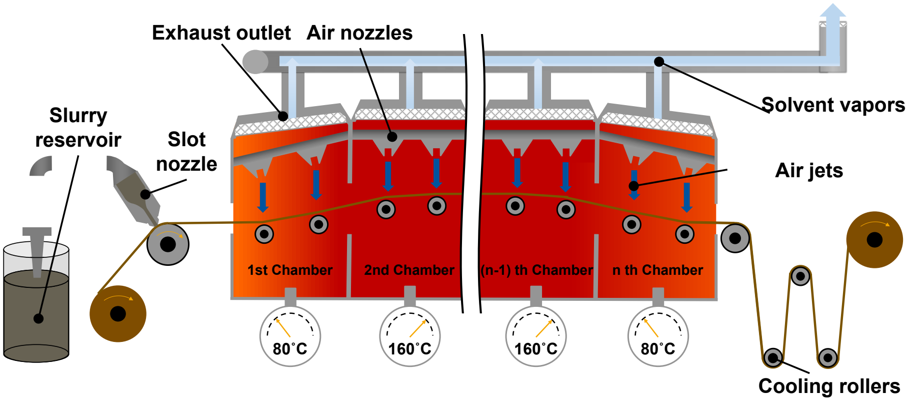


Figure 1: Coupled coating and convection drying machine of electrodes for lithium-ion battery cells

Typical production speeds of the convection drying method are in the range of 25 to 80 m/min with total furnace lengths of up to 100 meters due to the high dwell time required [8, 12]. Due to the substantial dryer length, these plants are often subject to very high investment costs [12]. Compared to alternative drying methods, the convection drying method is also characterized by relatively low energy efficiency and thus also represents a burden on the environment [13]. A further disadvantage of this drying technology lies in its poor controllability as well the limited responsiveness for changing production parameters.

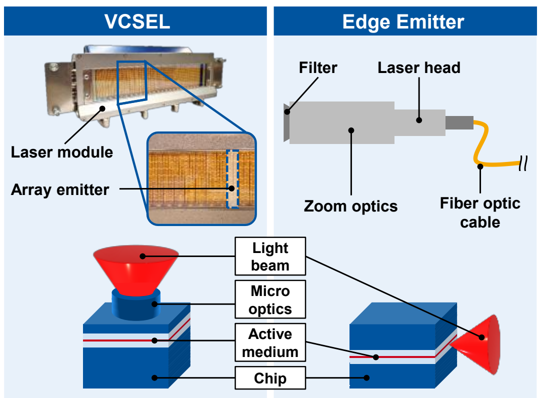


Figure 2: Comparison of VCSELs and edge emitters

A solution to this problem could be the use of lasers for drying the electrodes. This technology is characterized by high dynamic in the adjustment and control of the energy distribution on the wet coated electrode foils [14]. Furthermore, the use of laser-based drying technologies enables a reduction in energy consumption of over 50%, while at the same time increasing product quality and greatly reducing the system footprint [12, 15, 16, 17]. Figure 2 shows the two most common emitter types currently used for drying electrodes. VCSEL (vertical-cavity surface-emitting laser) are characterized by emitting their radiation perpendicular to the chip surface [18]. In contrast, the edge emitters of the diode lasers emit their radiation laterally to the chip plane [19]. The application of diode lasers for electrode drying has been extensively discussed by WOLF et al. [17, 20]. The following investigation focuses only on the use of VCSELs as an alternative technology for drying electrodes of lithium-ion batteries. According to GRONENBORN et al., VCSELs are largely scalable in power, have outstanding reliability, and offer a robust and economical solution, which makes an investigation of their application potential particularly interesting [21].

2. Experimental Setup

Figure 3 shows the schematic structure of the combined coating and VCSEL drying system used during the investigation. In order to reduce the risk of contamination during the manufacturing process, the machine is subdivided into individual chambers ("mini environments"). To further reduce the risk of product reactions with the surrounding process environment, each of the chambers can be operated partially or completely inerted. The test results shown in this experimental study were generated entirely under the exclusion of an inert gas atmosphere.

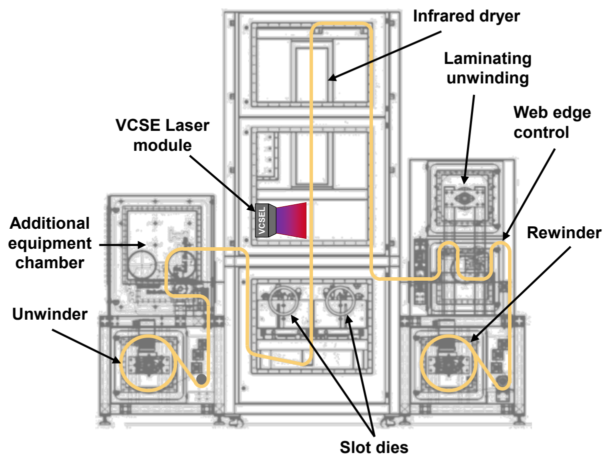


Figure 3: Schematic setup of the vertical coating line

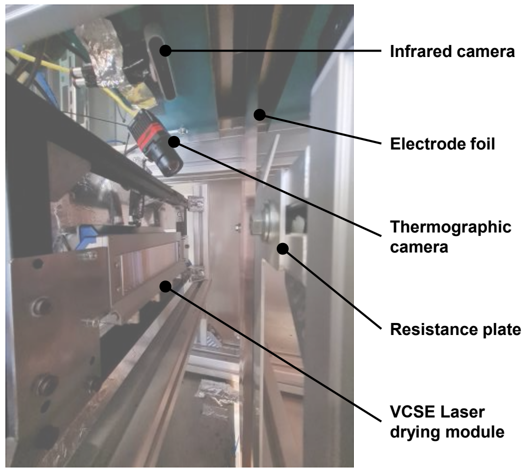


Figure 4: Setup of the VCSEL drying module inside the machine

The process starts by unwinding the foil and passing it through a chamber for additional equipment. The purpose of this second chamber is, for instance, the cleaning and activation of the film. However, no additional equipment was put into operation within the later described experiments. In the next chamber, the carrier foil is guided vertically between two opposing slot nozzles. This allows the simultaneous coating of the carrier foil on both sides without contact. Within this test series, the electrode slurries were coated centrally onto a 250 mm wide and 10 µm thick copper collector foil with a coating width of 125 mm.

Table 1 shows the composition of the three different anode slurries used during the evaluation. The utilization of different mixtures is due to the fact that the main component graphite was tested of two different material suppliers. In addition to the graphite powder, carboxy-methyl celluloses (CMC) as well as conductive carbon black are also added as further solid components to the slurry formulations.

Table 1: Composition of tested anode mixtures

Mixture no.	1	2	3
Components of the mixture	Mass percentage [wt_{solid} %]		
Graphite	42.3	38.1	55.4
SBR	3.4	3.4	4.4
CMC	0.9	0.9	1.2
Conductive carbon black	0.4	0.4	0.6
Solvent	53	57.2	38.4

For the production of the slurries, the solid and liquid components of the mixtures were homogenized by an intensive mixer. In this process, the solid components are first dry-mixed followed by the continuous addition of the solvent. The liquid components include deionized water as well as a 40 wt.% styrene butadiene rubber solution (SBR).

The coating chamber is followed by the vertical drying chamber wherein the VCSEL module is integrated. The general setup of the VCSEL drying module inside the machine is shown in Figure 4. Besides the laser drying module, the setup consists of two infrared cameras, one thermal imaging camera, an additional solvent suction system, as well as a resistance plate which cools and guides the collector foil during the laser drying process. Since only one VCSEL module was provided during the test series, only the production of single-sided coated electrodes is investigated within this study.

In addition to Figure 4, Figure 5 shows the structure of the sole VCSEL drying system. Apart from the required laser protection devices, the system also consists of the driver unit, an external cooling unit with two independent cooling circuits as well as additional connections for the energy, gas and data supply. According to PRUIJMBOOM et al. the module is specifically designed for the integration into technical equipment or machines for industrial thermal and photonic processing applications, such as drying [22]. Furthermore, the system is able to emit its energy in the form of infrared radiation at a wavelength of 980 nm.

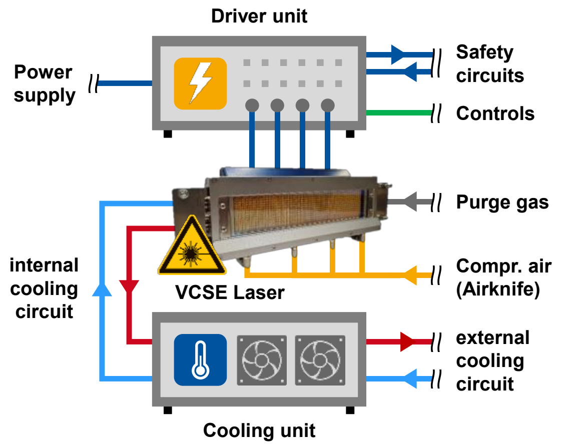


Figure 5: Structure of the sole VCSEL drying system

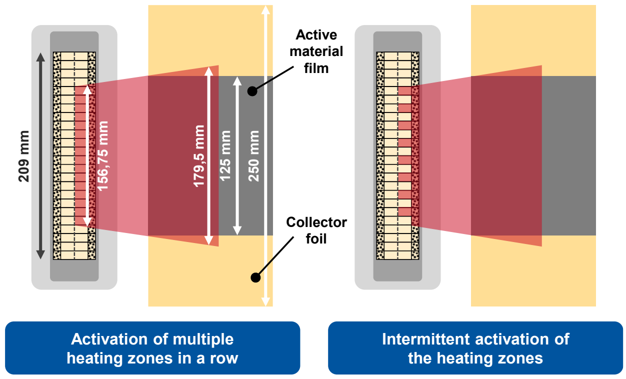


Figure 6: Independent activation of the heating zones

In total, the VCSEL module consists of 48 heating zones, which are divided into 24 VCSEL array emitters, each containing two heating zones. A heating zone consists of 28 VCSEL array chips connected in series, which measure 1.8 x 2.0 mm and contain 2205 individual VCSEL diodes [22]. This results in a rectangular emitter area of 209 x 40 mm from which the radiation is emitted. Each individual heating zone has a maximum output power of 200 W, so that a total power of up to 9.6 kW can be emitted. The area and power figures result in a maximum power density of 115 W/cm².

Figure 6 shows the experimental setup with activation of several heating zones in a row as well as intermittently activated heating zones. The output power level of the individual heating zones can be adjusted incrementally from 0 to 100%, whereby a homogeneous temperature profile can only be generated upwards the 3% level. Within the conducted experiments, the laser was operated at power levels between 5.25 and 11.5%. Following the drying process, the coated electrode foil is evenly wound up using a web edge control system.

Table 2 gives an overview of the parameter sets evaluated in this experimental study. The parameter sets were determined in the course of preliminary tests, which are not further described. The aim of the parameter study is to identify the various measurable influences on electrode quality. These influences can be divided into material related and equipment related influences, the latter being the main focus of this study. In addition to the influences of the web speed, the influences of changes in the laser power as well as the number of activated heating zones are described in the next chapter.

Table 2: Analysed parameter sets

Parameter set no.	1	2	3	4	5	6	7	8	9	10
Mixture no. (acc. to table 1)	1	1	2	2	1	2	3	3	3	3
Web speed [m/min]	0.8	0.8	0.8	1.6	0.8	1.0	0.8	0.8	0.8	0.8
Pump capacity [%]	20	20	20	20	20	30	30	40	30	30
Laser power [%]	5.25	5.75	11.5	11.5	6.25	11.5	5.75	5.75	5.6	5.6
No. of activated heating zones [-]	36	36	18	36	36	36	36	36	36	36
Emitted power [W]	378	414	414	828	450	828	414	414	403	403
Power input per area [W/cm²]	4.1	4.49	4.49	8.98	4.88	8.98	4.49	4.49	4.37	4.37
Energy input per area [J/cm²]	15.79	17.3	17.3	17.3	18.8	27.68	17.3	17.3	16.85	16.85
Dry film thickness [µm]	53.93	46.87	42.47	40.87	51.6	71.27	105.5	140.3	108.0	123.4
Residual moisture [%]	10.41	9.89	10.33	11.42	11.01	6.46	4.16	1.87	2.52	3.36
Maximum tension stress [MPa]	0.15	0.34	0.35	0.36	0.22	0.10	0.43	0.35	0.59	0.64

3. Evaluation

The coated and laser dried anodes are analyzed regarding different quality characteristics. In the course of the analysis the residual moisture, adhesion force, surface quality and dry film thickness were measured. In the following, the results of the process related analysis of the anode quality are presented and the presumed cause-effect relationships are explained.

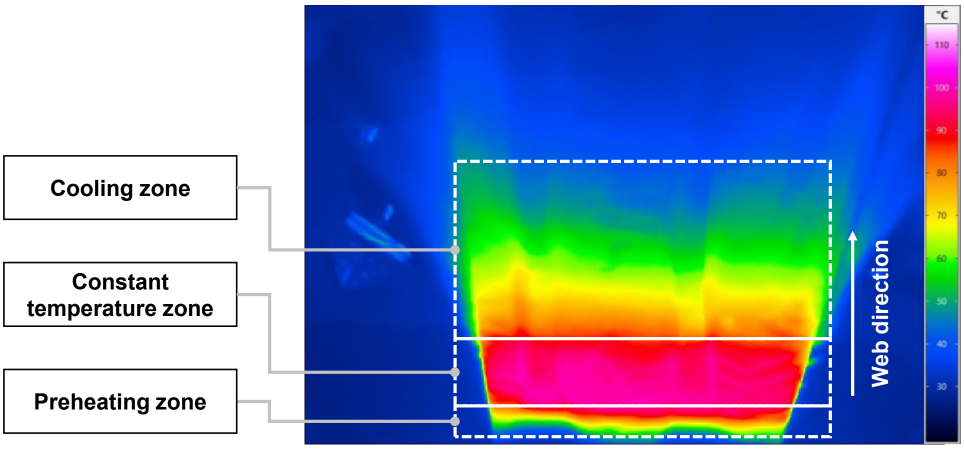


Figure 7: Thermographic analysis of the VCSE laser drying process

The thermographic analysis in Figure 7 shows that the VCSE laser drying process can be divided into 3 zones. The first zone represents the preheating zone. Due to the typically very low diffusion range of VCSEL arrays, this zone appears to be very short when using this technology without the addition of diffusor optics. The preheating zone is followed by the constant temperature zone. In this area, where most of the solvents are removed, the laser intensity must be specifically adapted to the evaporation of the solvent contained in the slurry. The third zone represents the cooling zone. In addition to convection air flows, cooling in this zone can be enhanced by contact with the resistance plate shown in Figure 4.

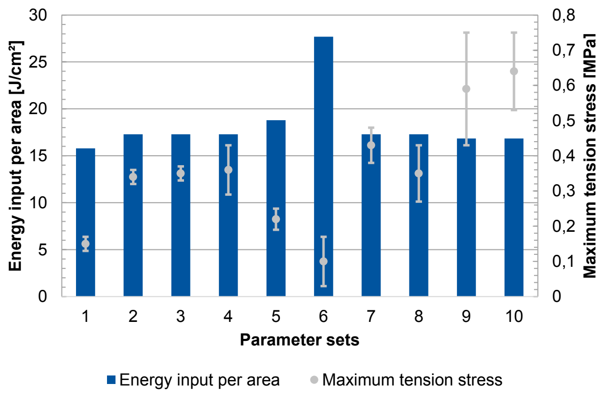


Figure 8: Energy input and tension stress

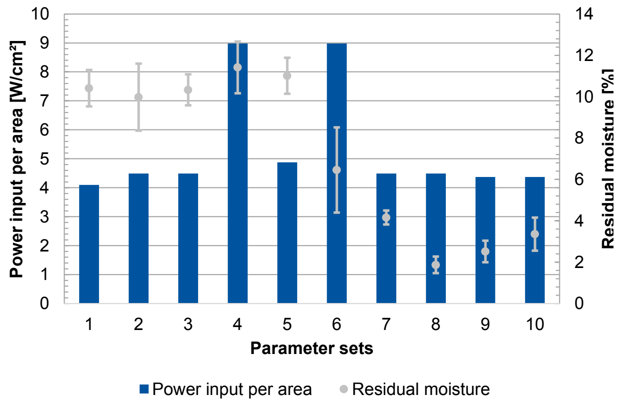


Figure 9: Power input and residual moisture

While Figure 8 shows the energy input per area over the maximum tensile stress, Figure 9 shows the power input per area over the measured residual moisture content. The analyzed experiments refer to the parameter sets described in Table 2 as well as the slurry mixtures shown in Table 1. With respect to the energy input per area, the parameters sets 3 and 4 show identical values of 17.3 J/cm². However, if the values of Figure 9 are taken into account, it can be seen that the power input per area has doubled from parameter set 3 to 4. The reason for this is that the web speed was increased from parameter set 3 to 4 from 0.8 to 1.6 m/min. To compensate for the increased web speed, the number of activated heating zones was increased from 18 to 36. Hereby the heating zones of parameter set 3 were switched off intermittently, as shown in the right sided example in Figure 6. The activation of the heating zones of all other parameter sets, including parameter set 4, were carried out according to the left sided example in Figure 6.

Within the test series, parameter set 6 experienced the highest energy input per area with 27.68 J/cm². To achieve this energy input, 36 heating zones were activated with a laser output power of 11.5%. At the same time, it is noticeable that parameter set 6 has the lowest adhesion values in the test series. Reasons for the poor adhesion values are most likely due to the effect of »binder migration« within the wet film layer. In this case, the rapid evaporation of the solvent leads to an accumulation of the binder material near the surface area [23]. According to JAISER et al. the inhomogeneous distribution of the binders also minimizes the adhesion forces between the copper foil and the active material [24].

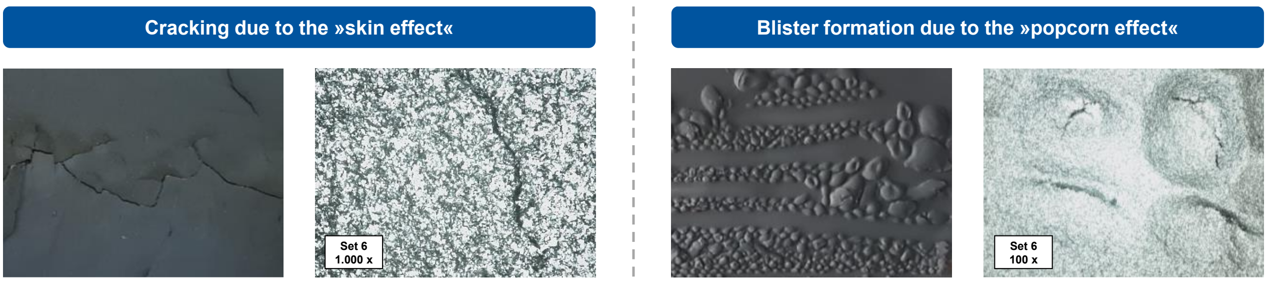


Figure 10: Microscopic images of defects in the dried coating of parameter set 6

Furthermore, the low adhesion values can be explained by an approximation or even exceeding of the decomposition temperature of the CMC and SBR components. The thermal stress within parameter set 6 leads also to the formation of cracks and blisters, which are shown in Figure 10. This represents a further explanation for the low adhesion results of the 6th parameter set. The formation of cracks on the electrode surface can be partially attributed to the »skin effect«. Within this effect, an excessively high power input per area in combination with a high drying rate causes the solvent to evaporate too quickly from the boundary layers. As a result, the outer layer of the active material is dried and forms a consolidated skin that reduces the penetrability of solvents. After the formation of this consolidation layer, solvent is still present in the deeper levels of the coating layer. This residual solvent is further heated by the absorbed laser radiation, which causes an expansion whereby the solvent can only slowly escape due to the limited permeability of the consolidation layer. Moreover, the rise of solvent by means of capillary forces is also reduced by this effect. This results in a pressure increase below the consolidation layer, so that the consolidation layer bulges outwards and blisters as well as cracks are formed. Through these cracks, the solvent is able to evaporate from the active material layer. According to KUMBERG et al. the application of higher layer thicknesses also results in a higher probability of cracking [25]. A further increase in the power input can also result in a »popcorn effect«. This is manifested in an explosion-like expansion of the contained solvent as a result of a far too high power input. The principles of the skin effect and the popcorn effect are roughly illustrated in Figure 11.

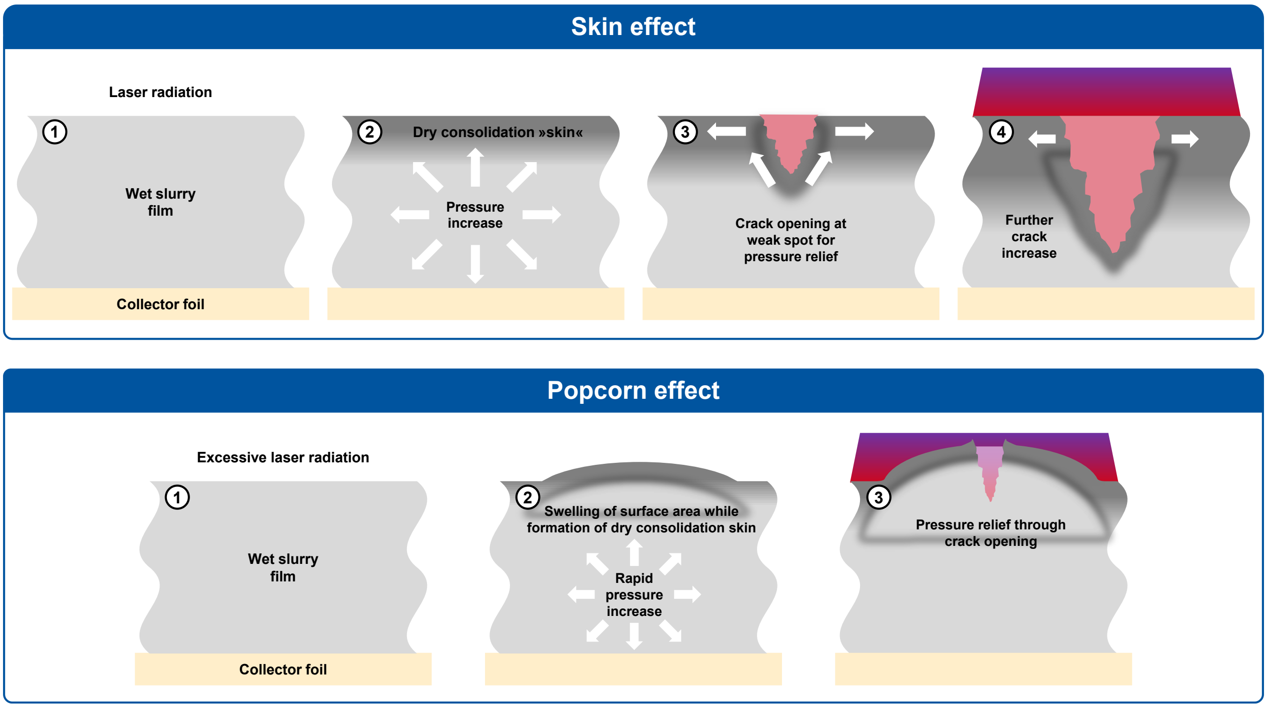


Figure 11: Illustration of the »skin effect« and »popcorn effect«

Figure 8 also shows that the parameter sets 9 and 10 have the highest average tensile values of 0.59 and 0.64 MPa. At the same time, both parameters have set humidity values of less than 3.5%. It is important to note that the parameter sets 9 and 10 with 108.0 and 123.4 µm show higher dry film thicknesses with lower solvent content of 38.4 wt.% compared to some of the other parameter sets. Despite the experimental pilot setup, these values are not far from electrodes produced in some series production. This highlights the applicability of the laser drying method for the production of electrodes and can be seen as a proof of concept for the use of the VCSEL technology.

4. Conclusion

Vertical-cavity surface-emitting laser (VCSEL) represent an innovative technology for energy-efficient and throughput increased electrode drying. Other research studies have shown that drying times could be reduced by up to 80% as well as energy consumption could be decreased by more than 50% using similar laser drying technologies [15, 20].

In this experimental study, the drying of several slurry formulations for anodes under different parameter settings was investigated using the VCSE laser technology. For this purpose, the experimental setup as well as the general structure of VCSE laser drying modules was described. Due to their high power density combined with high compactness, new types of machine setups can also be realized. The VCSEL technology, for example, enables the vertical coating and drying of electrodes, which was also investigated in this study.

In pilot operation at web speeds of up to 1.6 m/min, it was shown that residual moisture and adhesion values close to those of mass-produced electrodes could be generated. Thereby, the obtained research results can be considered as a proof of concept for the applicability of VCSE lasers for drying electrodes.

Due to the tremendously large number of different influencing variables, including numerous process and material parameters, the appropriate implementation of the VCSEL technology represents a complex challenge. The main target for the successful integration of the laser drying process is to achieve uniform drying, while avoiding phenomena such as »binder migration«, »skin effect« or even the »popcorn effect« in the event of excessively high energy input. The further increase of the web speeds as well as the investigation of the VCSEL application in hybrid drying processes to utilize synergies between different drying technologies represent further objectives for future research.

Further advantages of the VCSEL technology lie in its high control dynamics. For example, this is shown by the possibility of location-selected energy input, its precisely controlled energy transmission or its fast switch-on and switch-off times. The integration of sensor technology as well as the development of intelligent control and machine learning algorithms represent further open research topics with regard to VCSE laser drying. Lastly, it is also important to investigate the coating material more closely with the aim of developing laser-optimized material systems. In summary, VCSE laser drying represents a promising technology for energy efficient and quality-optimized lithium-ion battery production. Additionally, this technology bears great potential to significantly reduce greenhouse gas emissions during the manufacturing of battery cells.

Acknowledgements

This work is part of the Project LaserScale. The project has received funding from the German Federal Ministry of Education and Research (BMBF) under the funding code 03XP0316A. The authors are responsible for the content of this publication.

References

[1] Korthauer, R. (Ed.), 2019. Lithium-ion batteries: Basics and applications.

[2] Susarla, N., Ahmed, S., Dees, D., 2018. Modeling and analysis of solvent removal during Li-ion battery electrode drying. Journal of Power Sources 378, 660–670.

[3] Schulze, O. (Ed.), 2022. Elektromobilität - ein Ratgeber für Entscheider, Errichter, Betreiber und Nutzer: Facetten zu Ladeinfrastruktur, Subventionsregeln, Kosten und Handling. Springer, Wiesbaden, Heidelberg, 307 pp.

[4] Betz, J., Buchert, M., Dolega, P., Bulach, W., 2021. Resource consumption of the passenger vehicle sector in Germany until 2035–the impact of different drive systems: Study on behalf of the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety.

[5] Clausen, J., Grimm, A., Pfaff, M., 2022. Die erfolgreiche Transformation der Automobilbranche.

[6] Kampker, A., Vallée, D., Schnettler, A., 2018. Elektromobilität. Springer Berlin Heidelberg, Berlin, Heidelberg, 416 pp.

[7] Neef, C. (Ed.) 2022. Development perspectives for lithium-ion battery cell formats, Fraunhofer ISI.

[8] Heimes, 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.

[9] Küpper, D., Kuhlmann, K., Wolf, S., Pieper, C., Xu, G., Ahmad, J., 2018. The Future of Battery Production for Electric Vehicles. BCG Global.

[10] 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.

[11] Liu, Y., Zhang, R., Wang, J., Wang, Y., 2021. Current and future lithium-ion battery manufacturing. iScience 24 (4), 102332.

[12] von Horstig, M., Schoo, A., Loellhoeffel, T., Mayer, J.K., Kwade, A., 2022. A Perspective on Innovative Drying Methods for Energy-Efficient Solvent-Based Production of Lithium-Ion Battery Electrodes. Energy Tech, 2200689.

[13] Bryntesen, S., Strømman, A., Tolstorebrov, I., Shearing, P., Lamb, J., Stokke Burheim, O., 2021. Opportunities for the State-of-the-Art Production of LIB Electrodes - A Review. Energies 14 (5), 1406.

[14] Moench, H., Deppe, C., Dumoulin, R., Gronenborn, S., Gu, X., Heusler, G., Miller, M., Pekarski, P., Pruijmboom, A., 2012. Modular VCSEL solution for uniform line illumination in the kW range, in: High-Power Diode Laser Technology and Applications X. SPIE LASE, San Francisco, California, USA. Saturday 21 January 2012. SPIE, 82410B.

[15] 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.

[16] Pfleging, W., 2018. A review of laser electrode processing for development and manufacturing of lithium-ion batteries. Nanophotonics 7 (3), 549–573.

[17] Wolf, S., Neb, D., Hölting, F., Özkan, B., Clever, H., Dorn, B., Heimes, H., Kampker, A. 2023. Laser Drying Of Graphite Anodes For The Production Of Lithium-Ion Batteries - A Process- And Material-Side Analysis For Sustainable Battery Production.

[18] Neb, D., Stanislav, K., Clever, H., Dorn, B., Kampker, K. 2022. Current advances on laser drying of electrodes for lithium-ion battery cells.

[19] Propawe, R. (Ed.), 2005. Lasertechnik für die Fertigung: Grundlagen, Perspektiven und Beispiele für den innovativen Ingenieur. Springer Berlin Heidelberg, Berlin, Heidelberg, 526 pp.

[20] Wolf, S., Garbade, L., Göken, V., Tien, R., Börner, M., Neb, D., Heimes, H., 2023. Process and Material Analysis of Laser- and Convection-Dried Silicon - Graphite Anodes for Lithium-Ion Batteries. WEVJ 14 (4), 87.

[21] Gronenborn, S., Miller, M., Heusler, G., Mönch, H., 2012. Optical components and optical systems for VCSEL diode laser systems. Advanced Optical Technologies 1 (5).

[22] Pruijmboom, A., Apetz, R., Conrads, R., Deppe, C., Derra, G., Gronenborn, S., Gu, X., Kolb, J.S., Miller, M., Moench, H., Ogiewa, F., Pekarski, P., Pollmann-Retsch, J., Weichmann, U., 2015. VCSEL arrays expanding the range of high-power laser systems and applications, in: International Congress on Applications of Lasers & Electro-Optics. ICALEO 2015: 34th International Congress on Laser Materials Processing, Laser Microprocessing and Nanomanufacturing, Atlanta, Georgia, USA. October 18–22, 2015. Laser Institute of America, pp. 1–8.

[23] Font, F., Protas, B., Richardson, G., Foster, J.M., 2018. Binder migration during drying of lithium-ion battery electrodes: Modelling and comparison to experiment. Journal of Power Sources 393, 177–185.

[24] Jaiser, S., Müller, M., Baunach, M., Bauer, W., Scharfer, P., Schabel, W., 2016. Investigation of film solidification and binder migration during drying of Li-Ion battery anodes. Journal of Power Sources 318, 210–219.

[25] Kumberg, J., Müller, M., Diehm, R., Spiegel, S., Wachsmann, C., Bauer, W., Scharfer, P., Schabel, W., 2019. Drying of Lithium-Ion Battery Anodes for Use in High-Energy Cells: Influence of Electrode Thickness on Drying Time, Adhesion, and Crack Formation. Energy Technol. 7 (11), 1900722.

Biography

Daniel Neb (*1992) is the group lead of the department "Battery Production Management" (BPM) at PEM of RWTH Aachen University, where he also studied Mechanical Engineering with a specialization in Automotive Engineering.

Sebastian Wolf (*1997) is research associate in the group "Battery Production Management" (BPM) at the Chair of Production Engineering of E-Mobility Components (PEM) at RWTH Aachen University, where he also studied Mechanical Engineering and Business Administration.

Benedict Ingendoh (*1998) is research associate in the group "Battery Production Technology" (BPT) at the Chair of Production Engineering of E-Mobility Components (PEM) at RWTH Aachen University, where he also studied Mechanical Engineering and Business Administration.

Simon Klein (*1999) is student assistant at PEM of RWTH Aachen University, where he also studies Mechanical Engineering with a specialization in Automotive Engineering.

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 PEM's executive chief engineer from 2019 to 2023. In March 2023, he was appointed associate professor with a focus on "Production Engineering for Lithum-Ion Batteries". Together with Professor Achim Kampker, he is responsible for the strategic and operational management of the PEM Chair.

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.

CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
CPSL 2023-2

5th Conference on Production Systems and Logistics

Building A Knowledge Graph From Deviation Documentation For Problem-Solving On The Shop Floor

Yuxi Wang [1], Beatriz Bretones Cassoli[1] , Joachim Metternich[1]

[1]Institute of Production Management, Technology and Machine Tools, Darmstadt, Germany

Abstract

The description of deviations on the shop floor includes information about the deviation itself, possible causes and countermeasures. This information about current and already processed deviations and problems is a valuable source for future activities in the context of problem-solving and deviation management. However, extracting information from unstructured textual data is challenging. Furthermore, the relationships among the heterogeneous data are hard to represent. This paper proposes a framework to extract the knowledge contained in the deviation documentation and store it in a knowledge graph as triples. The proposed knowledge graph can then be used for the decision support system in production and will support more application scenarios in shop floor management in the future.

Keywords

Shop Floor Management; Deviation Management; Knowledge Graph; Decision Support System.

1. Introduction

The documentation of deviations serves as a valuable source of knowledge on the shop floor, encompassing various aspects such as problem-solving, production planning, and continuous improvement process [1]. It connects numerous entities involved in the production process, including people, processes, organizations, machines, and products. This documentation is especially useful for managers and workers on the shop floor as it aids in identifying significant deviations, exploring measures of similar deviations, and finding useful information [2]. However, processing the deviation documentation faces several challenges. One of the primary challenges is dealing with heterogeneous data, which comprises structured and unstructured information [1]. Especially the textual data, which contains crucial entities of deviations, is difficult to standardize due to the specificities of the production environment [3]. Moreover, the textual data often contains errors, making it challenging to accurately process and extract valuable insights from it [4]. Therefore, extracting representations of the relationships between deviations, measures, causes, and other relevant information from such documents containing unstructured data is challenging. Without this relational structure, the person accessing the information would have to search the records item by item using keywords, which would make it difficult to reuse the data. Over time, this knowledge of experience loses its value [5].

As a tool for organizing and integrating different knowledge and information, the knowledge graph (KG) has been a focus of research in the computer field since it was introduced by Google in 2012. It is capable of knowledge tracing and reasoning, providing significant assistance in decision support across various domains [6]. In the industrial sector, with the continuous advancement of digitization processes, industrial data has exhibited heterogeneous characteristics. As more and more application scenarios can be supported by data, the application of KG in the industrial sector is also gradually increasing. A KG offers a structured

DOI: https://doi.org/10.15488/15244
ISSN: 2701-6277

and interconnected representation of information, enabling better decision-making, knowledge reuse, and the development of advanced recommender systems to drive continuous improvement and efficiency in the production process [7]. It can support SFM from providing the possible measures, clustering the recurring deviations, visualising the problem-cause-solution loop and more application scenarios. Therefore, the goal of this paper is to design a framework for building a KG from deviation documentation for problem-solving on the shop floor. Based on this, the major research contributions of this work can be summarized as follows:

- A stepwise process is proposed and designed for constructing a KG from shop floor deviation documentation.
- Named entity recognition (NER) and rule-based methods are used to extract entities and relations from the unstructured data in the deviation documentation.
- Information from structured and unstructured data is fused into one KG for further problem-solving on the shop floor.

The remainder of this paper is structured as follows. Section 2 introduces the background and related work of this study. Section 3 presents the framework to build a KG including each step. Section 4 shows the detailed steps of KG construction with data from deviation documentation on the shop floor. Finally, Section 5 concludes this study and suggests directions for future research.

2. Related Work

2.1 Shop floor management

Shop floor management (SFM) is widely implemented in manufacturing to control and improve production processes continuously [8]. The basic elements of SFM included identifying and handling deviations, systematic problem-solving process for the deviation with unknown root causes, information and knowledge exchange in the regular shop floor meetings, and continuous improvement process [9]. For deviations that occur in production, if the cause of the deviation is unknown, the root cause should be analyzed through a problem-solving process so that it can be solved sustainably in a long-term perspective and does not reoccur [10]. Furthermore, while the problem-solving process can bring new standards to the processes on the shop floor, these criteria form the basis for new deviation measurement [11]. Deviation management and problem-solving process are two knowledge-intensive processes in SFM that require much experience to aid decision support [12]. Over the last years, many articles have emphasized the importance of data analysis for deviation management and problem-solving processes, and there has been some research on how to extract useful information from shop-floor management data for decision support [13,14]. However, fewer articles have mentioned how to correlate the different knowledge involved in this domain specific process with each other to provide a good database for knowledge retrieval and knowledge inference.

2.2 Knowledge graph

A KG is a data representation modality in which entities (depicted as nodes in the graph) are connected to other entities through edges. Edges describe the relationships which connect and relate these entities to each other [15]. A KG adds a layer of metadata to the data (also called semantic context), defining rules for its structure and interpretation [6]. They can, therefore, represent complex relationships in a domain in both machine friendly and human-readable forms to support reasoning and knowledge discovery [6].

Modelling data as a KG is particularly useful when the relationships within the data help to understand and solve the problem at hand [16]. KG can thus be used in a variety of applications, such as to generate reports from the data, provide a service to an end user in a retrieval system (e.g., in question answering and recommender systems), and also as part of machine learning pipelines [17]. The main task of KG construction is to reduce the granularity of data and avoid data redundancy while aggregating a large amount of knowledge, so that rapid response and inference of knowledge can be realized. KG construction methods are mainly categorized into top-down, bottom-up and hybrid methods [18,19]. Among them, generalized KG are mainly constructed using a bottom-up approach, i.e., entities and relationships are extracted from the data, and then ontologies are constructed. Domain KG, on the other hand, are more complex and also use a top-down or hybrid approach to narrow down the data by defining entities in advance. [19] The construction of a KG will generally be divided into the following processes: data acquisition, information extraction, knowledge fusion, quality control and graph construction [18,19,20].

2.3 Ontology

Ontology is a formal, explicit specification of a shared conceptualization, allowing a non-ambiguous semantic explanation of domain knowledge, enabling a better representation of the knowledge [21]. Ontologies define important structures for KG. Literature shows different ontologies related to deviation management and problem-solving. Ebrahimioour et al. propose an upper ontology where three concepts related to the failure modes and effects analysis information (i.e., deviation, cause and consequence) are modelled as an event and activities [22]. A deviation is modelled as an event, the beginning of a consequence. A consequence is an activity. A cause is an activity that causes a deviation. Dittmann et al. propose an ontology that is specialized into the entities such as component, function, failure mode, control method, risk priority number, and containment action [23]. They also propose a set of relationships among the entities. After reviewing the mentioned ontologies, the work from Ebrahimioour et al. were taken as reference. Section 4.2 explains the selected concepts that were adopted and the new concepts that are proposed, which are part of the contribution of this work.

3. Framework to build a KG from deviation documentation

Figure 1 presents the process of building a KG from the deviation documentation from the shop floor. The framework's design is based on the top-down KG construction process, as top-down KG construction is more suitable for domain knowledge [20]. This framework comprises five main tasks: data acquisition, ontology construction, knowledge extraction, knowledge fusion and KG construction.

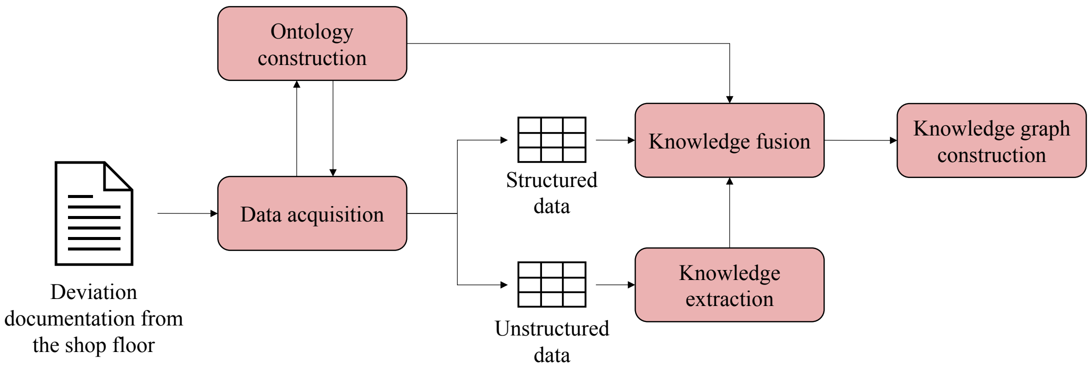


Figure 1 The process to build the knowledge graph

Data acquisition describes the data collection required for KG, which may involve structured or unstructured data. Structured data refers to data with strict structure [24], such as the deviation type, product type or date. Unstructured data include the deviation description, figures or videos containing detailed information about the deviation. As the KG for deviation management is domain-specific, the data sources should be identified and analyzed during the data acquisition.

Ontology construction is used to build a semantic explanation of the domain knowledge, which provides good instruction for knowledge extraction and a structure for the KG construction [7]. In this paper's proposed framework, the KG construction process can be started by either data acquisition or ontology construction, and there may be reciprocity in both processes. Since both deviation management and problem-solving process are essential components of SFM, their theoretical elements should be able to help accomplish ontology construction directly. There is also much research in the literature on how to build ontologies for the problem-solving process. However, in practice, a large amount of data related to deviation and problem-solving is knowledge-intensive, making ontology construction much more difficult [25]. Whether this data already exists in the system, in what system it is stored, and whether it is stored in a structured or unstructured form, the answers to these questions can vary greatly depending on the actual situation. It is, therefore, necessary to continuously adapt the ontology as it is being constructed to the actual situation and end use of the KG.

Knowledge extraction in the construction process of a KG mainly targets semi-structured and unstructured data. Its purpose is to discover valuable information within unstructured data and extract it. Knowledge extraction typically involves three tasks: entity extraction, relation extraction, and attribute extraction [20]. Since this process often deals with textual data, named entity recognition is a primary natural language processing method used for knowledge extraction [26].

Knowledge fusion mainly focuses on the integration of different data. In addition to the structured and unstructured data mentioned earlier, this data can also include third-party data from external sources. Another key task of knowledge fusion is to eliminate ambiguity in knowledge, such as merging entities and relationships that represent the same content.

KG construction involves integrating all the data based on a predefined ontology structure into a graph-based database, and it can be visualized in a graphical format.

4. Building a KG from deviation documentation

In order to better illustrate how the framework mentioned in Chapter 3 can be utilized to build a KG, we validate the KG construction process by using deviation documents from the shop floor of an industrial company in Germany as a database.

4.1 Data acquisition

In data acquisition, we perform both data cleaning and data understanding. The primary purpose of data cleaning is to remove meaningless or unclear content in the data. On this basis, the data can be better understood, which enables better ontology construction in the next step. In this process, it is also necessary to distinguish between structured and unstructured data and to analyse what additional information and knowledge unstructured data can bring to structured data.

4.2 Ontology construction

Based on the data acquisition and analysis in Section 4.1, we construct an ontology structure, as shown in Figure 2. This ontology structure is centred on the occurrence of deviations. It contains four types of core content related to them, three of which can be obtained directly from the structured data, which are the information related to the classification of deviations, the information on the location where the deviation occurred, and the information on the product where the deviation was found. This covers seven different entities and four different relationships. The last piece of content is the information related to the deviation event, which includes the symptoms at the time, the causes of the deviation, and the contra measures of the deviation after it has occurred. The employees record these data in the form of unstructured text in the deviation documents and need to be extracted into the KG through knowledge extraction. This part includes three entities and four relationships. In addition, the deviation documentation contains other information related to the deviation, such as the costs incurred by the deviation. Since this information is associated with a single deviation, it is stored as attribute in the deviation node. The details will be discussed in Section 4.4.

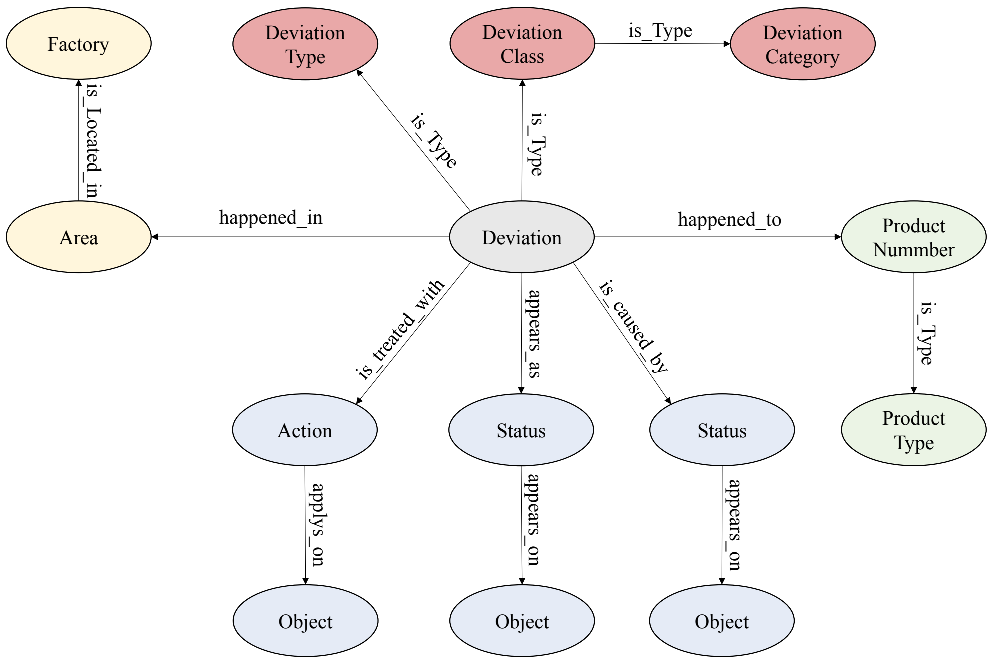


Figure 2 KG structure of the deviation documentation

4.3 Knowledge extraction

As mentioned in Section 3, the structured data already has a specific data model that can directly convert to entity, relation and attribute in the KG. Therefore, knowledge extraction focuses on the unstructured data in the deviation documentation, i.e., the descriptions of symptoms, causes, and measures. Based on the analysis of the writing characteristics, three types of node entities are set up, namely *Object*, *Status* and *Action*, where *Status* and *Object* can describe symptoms and causes. The measure needs to be described through *Action* and *Object*. Four relationship entities are set as *is_treated_with*, *appears_as*, *is_caused_by* and *appears_on*. The process and result of extracting node entities and relationship entities are shown in Sections 4.1.1 and 4.1.2.

4.3.1 Entity extraction

The task of entity extraction is to recognize all the deviation related objects, status and action in the unstructured data, so that the information can be stored in a structural way. As mentioned in Section 3, NER is used as a tool to complete the task. In the dataset given the total number of text data records involving deviation symptoms, causes, and measures is 5518. There are 2501 deviation symptoms, 1497 causes, and 1520 measures. The entities are labelled using the open-source annotator "NER Annotator for SpaCy" and stored in json file using BILOU structure as shown in Figure 3 [11].

English	Plug	glued
German	["Stecker verklebt\r",{"entities":[[0,7,"OBJECT"],[8,16,"STATUS"]]}]	

Figure 3 Annotation result in BILOU structure

In this paper, a NER model was created using the spaCy v3.6 named entity recognition system. The model architecture consists of a two-layer pipeline: a context embedding layer and a transformation-based chunking model (cite). The first layer uses a pre-trained language model to encode tokens into continuous vectors based on context. The second model predicts text structure by mapping it to a set of state transitions. It uses the output of the previous step (contextual word embeddings) to incrementally construct states from the input sequence and assigns entity labels to them using a multilayer neural network. We trained and compared two spacy-based entity recognition pipelines using German-BERT [27] and XLM-RoBERTa [28] as contextual embedding layers. The ratio of training set, test set, and validation set is 3:1:1. We use precision, recall, and F1-Score as evaluation metrics. The calculation formula is as follows:

$$Precision = \frac{\sum_{k=1}^{n} \text{The number of correctly predicted labels in sentence}_k}{\sum_{k=1}^{n} \text{The number of predicted labels in sentence}_k}$$

$$Recall = \frac{\sum_{k=1}^{n} \text{The number of correctly predicted labels in sentence}_k}{\sum_{k=1}^{n} \text{The number of labels that should be included in sentence}_k}$$

$$F_1 - Score = \frac{2 \cdot \text{Precision} \cdot \text{Recall}}{Precision + Recall}$$

The training results of each model on the test set are shown in Table 1. Overall, XLM-RoBERTa + spaCy has the better prediction performance.

Table 1. Performances of different models on entity extraction related to symptoms

	German-BERT + spaCy			**XLM-RoBERTa + spaCy**		
	Precision	Recall	F1-Score	Precision	Recall	F1-Score
Symptoms	87.76%	83.50%	85.57%	**88.66%**	**86%**	**87.31%**
Causes	79.17%	69.72%	74.15%	**87.76%**	**83.50%**	**85.57%**
Measures	83.51%	76.42%	79.80%	**88.21%**	**84.73%**	**86.43%**

4.3.2 Relation extraction

Rule-based relation extraction methods are suitable for text-poor linguistic environments [29]. However, unlike many other relation extraction tasks, the text in deviation documents are mostly short texts and the syntax of sentences is often incomplete, with no words between entities that can be used to construct regular relations, making it unsuitable for mining relations using a relational triple extraction. By analysing the linguistic patterns in the data, this paper summarizes three typical relationships. For symptoms, causes and measures the patterns are similar:

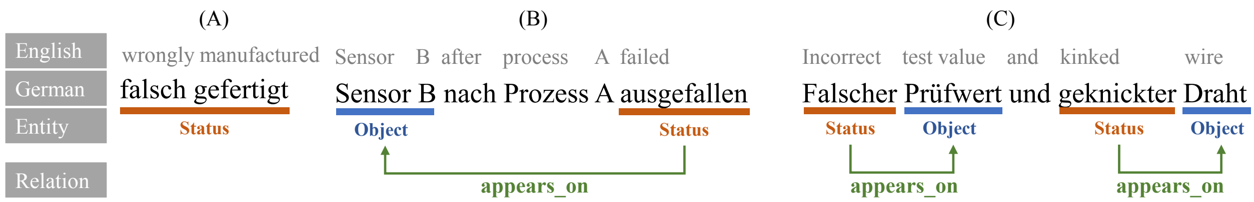


Figure 4 Patterns recognition for rule-based relation extraction (with symptoms as examples)

(A) *Status*/*Action(s)* without *Object*: in these cases, the deviation can directly link to the *Status* or *Action(s)* with the relationship *is_treated_with*/*appears_as*/*is_caused_by*.

(B) One *Status*/*Action* with more *Objects*: in these cases, the relationship *appear*_on between *Status* and *Object* is one-to-many.

(C) More *Status*/*Action(s)* with more *Objects*: there are many different possibilities for this scenario. In order to simplify the process of relation extraction, this paper analyzes the situation that comes out of most texts and decides to assign relations on a one-to-one basis according to position. Here, the relations between *Objects* and *Status* that are in the same order are one-to-one.

4.4 Knowledge fusion

In the knowledge fusion process, the main task is to connect structured and unstructured data. Here, we first process the structured data and establish relationships between them. Tables 2-5demonstrate how the structured data is specifically stored in entity nodes related to deviation, location and product.

Table 2 Entities about deviation

Type	Label	Property	Example	Number of Entities
Node entity	Deviation	Name	1713	4052
		Number of Scrap	1	
		Unit cost	317,88 €	
		Total cost	317,88 €	
		Date	26.03.2020	
	Deviation Type	Name	Masseschluss (Ground fault)	44
		Code	443	
	Deviation Class	Name	Arbeitsbeschädigt (Work-damaged)	34
	Deviation Category	Name	Produktion (Production)	10
Relation entity	is_Type (from Deviation to Deviation Type)	Name	is_Type	4035
	is_Type (from Deviation to Deviation Class)	Name	is_Type	4031
	is_Type (from Deviation Class to Deviation Catogory)	Name	is_Type	36

Table 3 Entities about location

Type	Label	Property	Example	Number of Entities
Node entity	Area	Name	Übertrager (Transformer)	13
	Factory	Name	1002	5
Relation entity	is_Located_in (from Area to Factory)	Name	is_Located_in	26

Table 4 Entities about product

Type	Label	Property	Example	Number of Entities
Node entity	Product No.	Name	847152694	1176
	Product Type	Name	TRIEBWERK 122 (ENGINE 122)	572
		Serial Number	4-85471-885	
Relation entity	is_Type (from Product No. to Product Type)	Name	is_Type	1024

Table 5 Entities between deviation, location and product

Type	Label	Property	Example	Number of Entities
Relation entity	happened_in (from Deviation to Area)	Name	happened_in	4038
	happened_to (from Deviation to Product No.)	Name	happened_to	1259

4.5 KG construction

Using the py2neo toolkit, data is stored in the Neo4j graph database, and the visualization results in the following graph as shown in Figure 5. After importing the deviation-related, location-related and product-related data from the deviation documentation into KG, 9277 nodes and 22297 relations were created.

Figure 5 The KG from deviation documentation in neo4j (deviation at the middle)

Figure 5 shows an ontology-similar KG with one deviation in the center. With the KG, the deviation related information can be stored in with a graph-based database. In addition to store the information in KG in a structured way, the KG from deviation documentation can achieve more convenient query and statistic functions. For example, if workers on the shop floor have the deviation relevant to "Electronic" and "defect", they can use the KG to find possible measures in the past. The query statement can be "MATCH p=(ac:Action)<-[]-()-[]->(s:Status{statusId:"defekt"})-[]->(o:Object{objectId:"Elektronik"}) RETURN p". As shown in Figure 6, the *Action* "exchanged" pointing on the *Object* "Electronic" is found.

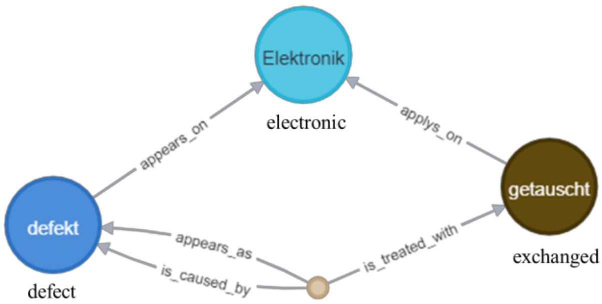


Figure 6 The KG from deviation documentation in neo4j (searching for measures)

Furthermore, the KG can help cluster and analyze the deviations for one product type. With the query "MATCH p=()<-[]-()<-[r:appears_as]-()-[]->()-[]->(pt:ProductType{producttypeId:"ROTOR 13558"}) RETURN p", the KG can find out all the *Status* and their related *Object* with the relation *appears_as* in between as connection. As shown in Figure 7, all the deviations that have happened to a product type are automatically clustered.

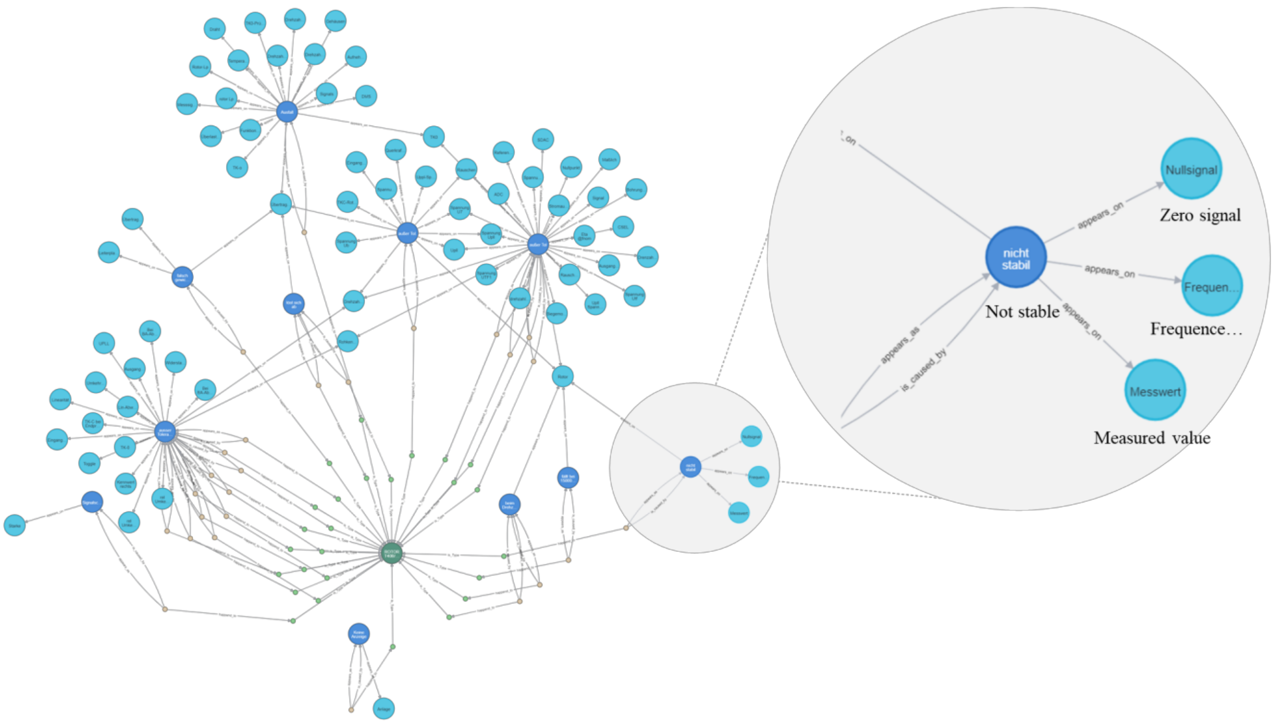


Figure 7 The KG from deviation documentation in neo4j (categorizing the deviations for a product type)

The KG of deviation management can serve as a data foundation for many new application scenarios in the future. Firstly, it enables visualization of the knowledge involved in the deviation management. With the queries, the information and data for certain usage can be found out based on the keywords. It is no longer necessary to browse through complex deviation archives; instead, the past deviations can be categorized by extracting the graph, which leads to a better understanding. The connections between different pieces of information also enable knowledge retrieval. By simply issuing straightforward command statements, the possible causes and solutions to deviations can be searched, which leads to the reduction of response time. Moreover, the KG can be utilized with artificial intelligence algorithms for predictions, such as forecasting the potential impact of newly occurring deviations, providing decision support for more activities in the SFM.

5. Conclusion and Outlook

This paper describes how to build a KG in SFM from the information in deviation documents. To this end, in this article framework is designed for building a top-down KG based on the data characteristics and target application scenarios in SFM. In the process of knowledge extraction, this paper uses the NER approach to extract the entities out of the unstructured textual data with spacy-based entity recognition pipelines using German-BERT and XLM-RoBERTa as contextual embedding layers. The results showed that compared to German-BERT, the XLM-RoBERTa as embedding layers had a better performance. For extracting the relations, this paper designed a rule-based method subject to the language specifications. After completing the knowledge fusion for structured data and unstructured data, this paper presented the KG in Neo4j and illustrated the futural usages of the KG for the problem-solving process on the shop floor.

Due to the specificity of shop floor deviation management and problem-solving data, some improvement space has been identified in this paper during the study of KG construction techniques, which can be continued through future research. For example, the process of detecting deviations, handling deviations and solving deviations contains not only the state of the product and the production line (time point), but also the attempts made by the workers to understand the deviations and to fix them (events with time periods). If these events and states can also be represented in the KG as entities and connected with relations, it can greatly help the decision support process for future problem solving. Furthermore, the large language models such as the Large Language Model Meta AI (LLaMA) and the Generative Pre-trained Transformer (GPT) can also be tested for the NLP tasks in KG construction processes. It should be evaluated whether the large language models can have a better performance on the domain specific data such as the data from shop floor.

The use of KG in shop floor-related activities is not yet widespread, but many possibilities exist. One example is evaluating the deviations through the complete information of the deviations in the KG, determining which deviations need to be handled with systematic problem-solving, and determining their prioritization. A knowledge backtracking of KG can also be designed to provide solutions for newly recognized deviations in production. Graph-based algorithms can be used to predict the possible impact of newly occurring deviations to trigger the proactive measures to prevent the deviations. These future application scenarios for KG are well worth continuing to investigate.

Acknowledgement

This research is funded by the European Institute of Innovation & Technology (EIT) Manufacturing.

References

[1] Wang, Y., Longard, L., Hertle, C., Metternich, J., 2023. Beyond Pareto Analysis: A Decision Support Model for the Prioritization of Deviations with Natural Language Processing. Hannover: publish-Ing, 11 pp.

[2] Müller, M., Alexandi, E., Metternich, J., 2021. Digital Shop Floor Management Enhanced by Natural Language Processing. Procedia CIRP 96, 21–26.

[3] Müller, M., Frick, N., Lee, J.-U., Metternich, J., Gurevych, I., 2020. Chats als Datengrundlage für KI-Anwendungen in der Produktion. Zeitschrift für Wirtschaftlichen Fabrikbetrieb : ZWF 115 (7-8), 520–523.

[4] Müller, M., Metternich, J., 2021. Production Specific Language Characteristics to Improve NLP Applications on the Shop Floor. Procedia CIRP 104, 1890–1895.

[5] Müller, M., Terziev, G., Metternich, J., Landmann, N., 2020. Knowledge Management on the Shop Floor Through Recommender Engines. Procedia Manufacturing 52, 344–349.

[6] Barrasa, J., Hodler, A., Webber, J., 2021. Knowledge Graphs. O'Reilly Media, Incorporated.

[7] He, L., Jiang, P., 2019. Manufacturing Knowledge Graph: A Connectivism to Answer Production Problems Query With Knowledge Reuse. IEEE Access 7, 101231–101244.

[8] Pötters, P., Schindler, P., Leyendecker, B., 2018. Status quo Shopfloor Management. Zeitschrift für wirtschaftlichen Fabrikbetrieb 113 (7-8), 522–525.

[9] Suzaki, K., 1993. The new shop floor management: Empowering people for continuous improvement. The Free Press, New York, 462 pp.

[10] Peters, R., 2009. Shopfloor Management: Führen am Ort der Wertschöpfung. LOG_X, Stuttgart, 141 pp.

[11] 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.

[12] 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.

[13] Longard, L., Schiborr, L., Metternich, J., 2022. Potentials and obstacles of the use of data mining in problem-solving processes. Procedia CIRP 107, 252–257.

[14] Lin, H.K., Harding, J.A., 2007. A manufacturing system engineering ontology model on the semantic web for inter-enterprise collaboration. Computers in Industry 58 (5), 428–437.

[15] Robinson, I., Webber, J., Eifrem, E., 2015. Graph databases: new opportunities for connected data. " O'Reilly Media, Inc.".

[16] Gosnell, D., Broecheler, M., 2020. The Practitioner's Guide to Graph Data: Applying Graph Thinking and Graph Technologies to Solve Complex Problems. " O'Reilly Media, Inc.".

[17] Bretones Cassoli, B., Jourdan, N., Metternich, J., 2022. Knowledge Graphs for Data And Knowledge Management in Cyber-Physical Production Systems, in: Proceedings of the Conference on Production Systems and Logistics: CPSL 2022. Hannover: publish-Ing, pp. 445–454.

[18] Danling Yuan, Keping Zhou and Chun Yang. Architecture and Application of Traffic Safety Management Knowledge Graph Based on Neo4j.

[19] Chicaiza, J., Valdiviezo-Diaz, P., 2021. A Comprehensive Survey of Knowledge Graph-Based Recommender Systems: Technologies, Development, and Contributions. Information 12 (6), 232.

[20] Tamašauskaitė, G., Groth, P., 2023. Defining a Knowledge Graph Development Process Through a Systematic Review. ACM Trans. Softw. Eng. Methodol. 32 (1), 1–40.

[21] Giovannini, A., Aubry, A., Panetto, H., Dassisti, M., El Haouzi, H., 2012. Ontology-based system for supporting manufacturing sustainability. Annual Reviews in Control 36 (2), 309–317.

[22] Ebrahimipour, V., Rezaie, K., Shokravi, S., 2010. An ontology approach to support FMEA studies. Expert Systems with Applications 37 (1), 671–677.

[23] Dittmann, Rademacher, Zelewski. Performing FMEA Using Ontologies.

[24] Tianxing Wu, Guilin Qi, Cheng Li and Meng Wang. A Survey of Techniques for Constructing Chinese Knowledge Graphs and Their Applications.

[25] Ansari, F., Khobreh, M., Seidenberg, U., Sihn, W., 2018. A problem-solving ontology for human-centered cyber physical production systems. CIRP Journal of Manufacturing Science and Technology 22, 91–106.

[26] Deng, J., Wang, T., Wang, Z., Zhou, J., Cheng, L., 2022. Research on Event Logic Knowledge Graph Construction Method of Robot Transmission System Fault Diagnosis. IEEE Access 10, 17656–17673.

[27] Branden Chan, Stefan Schweter, Timo Möller. German's Next Language Model.

[28] Conneau, A., Khandelwal, K., Goyal, N., Chaudhary, V., Wenzek, G., Guzmán, F., Grave, E., Ott, M., Zettlemoyer, L., Stoyanov, V., 2019. Unsupervised Cross-lingual Representation Learning at Scale, 12 pp. http://arxiv.org/pdf/1911.02116v2.

[29] Nasar, Z., Jaffry, S.W., Malik, M.K., 2022. Named Entity Recognition and Relation Extraction. ACM Comput. Surv. 54 (1), 1–39.

Biography

Yuxi Wang, M. Sc. (*1995) is a research associate and PhD candidate at the Institute for 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.

Beatriz Bretones Cassoli, M. Sc. (*1995) is a research associate and PhD candidate at the Institute for Production Management, Technology and Machine Tools (PTW) at the Technical University of Darmstadt since 2019. Her research investigates the use of graph-structured data and graph neural networks for predictive quality applications.

Prof. Dr.-Ing. Joachim Metternich (*1968) is head of the Production Management division at the Institute for 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 2023 and he is scientific partner of the Conference on Production Systems and Logistics (CPSL).

CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
CPSL 2023-2

5th Conference on Production Systems and Logistics

Material Flow Simulation in Lithium-Ion Battery Cell Manufacturing as a Planning Tool for Cost and Energy Optimization

Maximilian Lechner[1], Paul Mothwurf[1], Lasse Nohe[2], Rüdiger Daub[1]
[1]*Institute for Machine Tools and Industrial Management, Technical University of Munich, 85748 Garching, Germany*
[2]*Northvolt AB, Alströmergatan 20, Stockholm, Sweden*

Abstract

Lithium-ion batteries are seen as a key technology for powering electric vehicles and energy storage. Still, their high cost and energy-intensive manufacturing process remain a significant barrier to wider adoption. Due to the high moisture sensitivity of certain processed materials, the operation of dry rooms is required, constituting a critical contributor to cost and energy consumption in lithium-ion battery production. As the operating costs for these dry rooms strongly depend on the volume and adjusted humidity of the air, it is vital to choose an appropriate operation strategy already in the planning and designing phase of the factories. In this regard, simulation tools can effectively support the planning process by providing predictive information on the production system. The simulation model presented in this paper offers an approach to optimize the material and energy consumption associated with the production of lithium-ion batteries while also considering current material-related production challenges regarding moisture. By calculating a time-resolved material flow, the model enables to identify individual process times and storage durations depending on the chosen production layout. This allows for a material-specific dimensioning of the buffers and supports the dry room design. Hence, the data generated by the model can serve as a basis for planning more cost- and energy-efficient production environments.

Keywords

lithium-ion battery; battery production; material flow simulation; gigafactory; dry room; moisture sensitivity; production planning

1. Introduction

As the global drive towards mitigating climate change intensifies, the need for sustainable energy solutions has become more critical than ever. Lithium-ion batteries have emerged as a pivotal technology, powering a wide range of applications such as electric vehicles, grid energy storage, and portable electronic devices [1]. However, the increasing demand for these batteries requires cost-efficient production methods to ensure their widespread adoption and affordability [2]. In this context, the establishment of gigafactories – large-scale production facilities for battery cells – has gained significant importance. These factories play a central role in meeting the soaring market demand, reducing production costs through economies of scale, and promoting the transition to clean energy alternatives [3,4]. A conventional lithium-ion battery cell, comprising a cathode, an anode, a separator, and a liquid electrolyte within a protective housing, is produced in multiple successive process steps (cf. Figure 3) [2]. In this regard, a major challenge is the requirement for moisture control within the production environment, as the production involves processing moisture-sensitive materials like nickel (Ni)-rich cathode active materials or electrolyte materials [2]. Excessive humidity can entail safety hazards during production and harm the battery quality, leading to losses in capacity, lifetime, and overall performance [5,6]. To mitigate these risks, controlled atmospheres in the form of dry rooms are commonly employed to maintain optimal humidity levels during various production stages [7,8]. With regard to the energy consumption in lithium-ion battery production, it can be stated that dry rooms account for about 30 to 50 % of the overall energy consumption [1,9,10]. When looking at the energy consumption of an exemplary dry room, it becomes apparent that it strongly depends on the adjusted humidity level and the number of persons in the room [11]. These relations are depicted in Figure 1 and underline the dry rooms' significant impact on operational costs. Therefore, the design and implementation of such dry rooms must be carefully planned to ensure energy- and cost-efficiency while also considering material-based requirements. To address these challenges, a comprehensive and systematic approach for designing the production layout and dry room facilities is essential. In this endeavor, material flow simulation models like digital factory twins emerge as valuable tools, enabling the calculation of throughput-specific data like lead and storage times for various production layout alternatives. The model presented in the following allows for considering both material- and production-related requirements and serves as a basis for an optimization approach for dry room design and operation in gigafactories.

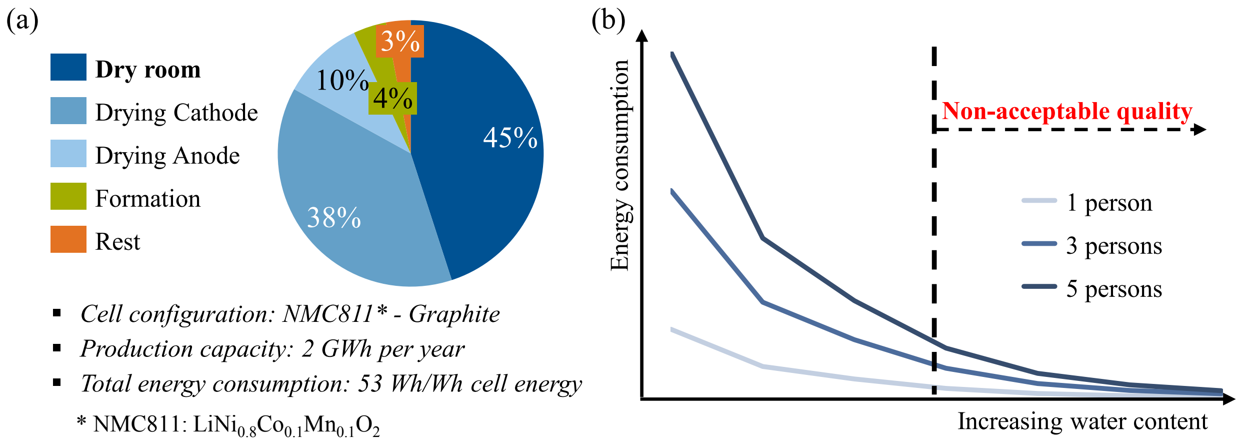


Figure 1: (a) Distribution of energy consumption between process steps in lithium-ion battery production according to [10] and (b) qualitative relation of energy consumption in dependence of humidity level and number of persons in the room for an exemplary dry room [11]

2. Background & Approach

With regard to the current material trends for lithium-ion batteries, Ni-rich cathode active materials play a major role. By increasing the Ni share in the cathode active material, higher energy contents can be achieved. Besides that, social aspects can be addressed when substituting the critical and expensive raw material cobalt, which is currently widely used [12]. The progression in state-of-the-art cathodes went from Ni shares of around 30 % to over 80 % today, with further increasing Ni contents [13,14]. However, the increased Ni shares impose higher requirements on the production atmosphere as Ni-rich active materials are susceptible to moisture (H_2O) and carbon dioxide (CO_2). When in contact with the ambient atmosphere, the particle surface can form impurities by reacting with H_2O and CO_2, leading to lithium-ion consumption. Consequently, losses in capacity, rate capability, and lifetime occur, which are influenced by the moisture content and exposure time [8,15–17]. For that reason, high-quality Ni-rich cathodes require production under low humidity levels, which can be realized in dry rooms with controlled environments [12]. Figure 1 (b) indicates that for a cost- and energy-efficient production, the humidity level of the dry room should be kept as low as possible. However, due to uncertainty regarding the required dryness levels, drying units tend to be oversized to ensure that the cell quality is not negatively affected, resulting in significantly increased energy consumption and operational costs during cell production [18]. Consequently, this work aims to establish an approach that supports practitioners to identify an efficient individual moisture management strategy, which is detailed in the following.

In this regard, Figure 2 shows an overview of the methodological approach and highlights the role of the digital factory twin.

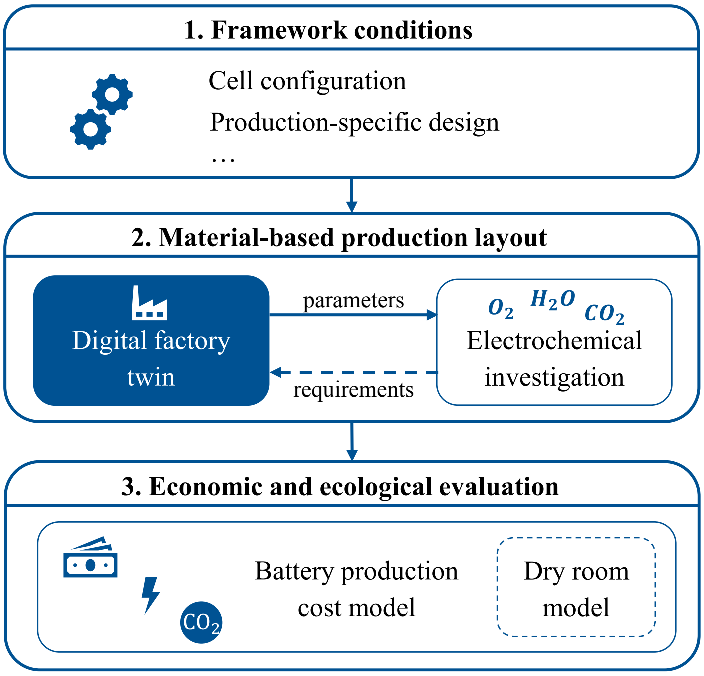


Figure 2: Overview of the methodological approach for optimizing dry room design and operation and the integration of the digital twin

The concept consists of three stages and starts by setting the framework conditions. Here, the cell configuration, including cell format and chemistry, must be determined to select an appropriate process chain. This step also requires the specification of factory-related variables like production capacity, operation days, machine availabilities, and buffer sizes. In the next stage, a suitable production layout can be identified based on material- and process-specific requirements using the digital factory twin. Based on the framework conditions, the latter enables the calculation of individual storage and lead times, which is essential for considering material-specific requirements. Knowing the exposure times of the intermediate products along the production process chain, targeted material-based experiments can then be conducted to evaluate the sensitivity toward a specific environment. In that way, the impacts on the material can be identified so that the production layout can be adjusted accordingly using the digital factory twin. By changing critical parameters like buffer sizes, number of machines, and dry room design, the model enables to quickly adapt to an appropriate production layout in terms of moisture management. To evaluate the adjusted production layout from both an energy consumption and cost perspective, a combined calculation model can be used. This model, which is part of the last stage, comprises a battery cell production cost model and a dry room model that is able to represent the framework conditions of the dry room design and operation.

3. Material Flow Simulation Model

3.1 Digital Factory Twin

Digital twin technology has emerged as a significant enabler for the production sector, offering substantial benefits [19]. In this context, a digital twin refers to a virtual depiction of a physical production system, though no single definition exists here [20]. In lithium-ion battery production, rapid development and uncertainty during factory planning can increase costs. Employing a digital twin in early design stages enables accurate production estimation and concurrent development between product design and factory planning, addressing these challenges. For the herein-presented digital factory twin, discrete event simulation (DES) is chosen as a suitable tool to model the complex battery cell production system. In this regard, the platform Tecnomatix Plant Simulation (PlantSim), established by the company Siemens, is selected since it supports flexible large-scale simulations, enabling users to quickly simulate complex scenarios [21].

A central aspect of factory planning involves determining the optimal size of material buffers situated between the individual process steps. These buffers impact the factory design and space requirements, substantially influencing operational expenditures (OPEX). This is primarily because most processes must be conducted within environmentally controlled dry rooms with heightened energy consumption demands, as stated above. At the same time, the buffer sizes also have an impact on the exposure times of the individual materials to the specific environment. This circumstance allows to adapt to material-specific requirements by adjusting the production system. So, the purpose of the digital factory twin is to facilitate the evaluation of material buffers between individual processes to enable appropriate dimensioning as well as an accurate prediction of the space requirements.

3.2 Modularization & Simulation Logic

The production of lithium-ion battery cells comprises a high number of sequential and interdependent process steps, leading to increased complexity [22]. Hence, for expedient modeling, it is crucial to capture the characteristics of the process steps in terms of their interaction with the buffer. This requires a thorough depiction of the processes and their material throughput, whereby the general calculation principle is based on previous publications [23,24]. Table 1 shows the considered processes for the calculation classified as modules, including the general and throughput-specific input parameters. The *splicing* and *slitting factor* accounts for optional foil separation that might be implemented in continuous process steps. Regarding the modules, it needs to be mentioned that the cell assembly consists of several individual process steps. However, as the focus is on electrode production, cell assembly is modeled as a single process without any internal buffers. Additionally, to expedite simulation time, the cell assembly is modeled batch-wise, described by the parameter *batch size*. Besides the direct material-throughput parameters, also general machine parameters are considered that indirectly influence the throughput. Here, the yield defines the variable scrap rate, whereas the performance indicates the machine's processing speed relative to the maximum possible speed. This factor can be used to synchronize anode and cathode processes for balanced buffer stocks and is particularly used for the coating process. The availability considers machine downtimes due to defects or maintenance work and specifies the available processing time of the machine. In this regard, the mean time to repair the machine and the auxiliary process time, which indicates set-up times, is also considered to enable more realistic modeling. Therefore, by additional consideration of blocked and idle machine times during production in combination with the machine-based parameters defining the overall equipment effectiveness, the individual process efficiencies can be determined. The process efficiency indicates the utilization and output yield of all machines in the respective process step.

For a rapid and efficient parametrization, the digital factory twin incorporates functions that automatically update all module parameters, including equipment and buffer settings, based on input tables. These input tables enable a centralized adjustment and examination of different production layouts and designs. By that, it is possible to adapt to material and production effects seamlessly. The required data tables comprise product-related information like the electrode design and dimensions, process-related data like process and machine parameters, and production-related settings like the buffer and machine counts. The latter are used in a line balancing function, which autonomously places and connects the machines based on the input table. Line balancing aims to efficiently operate the machines while reducing the product's lead time. For an efficient component routing between the modules, individual process plans for cathode, anode, and jelly roll (cell body consisting of anode, cathode, and separator) handling need to be defined. This allows to consider the unique properties of the components and enables their appropriate handling by independent material flow. For smooth inter-module movement, the modules provide feedback on production availability and buffer space for component transfer. This feedback is crucial in ensuring efficient component flow through the production process. In the simulation, a function is implemented that controls the transport of the components after successful processing, whereby the process plan specifies the target module but not the specific station. To ensure even distribution and minimize bottlenecks, individual stations request components as soon as they have the capacity, guaranteeing movement to unoccupied stations.

Table 1: Modules and required input parameters of the PlantSim model

Module	Input parameters	
	Throughput-specific parameter	**General parameter**
Slurry mixing (Cathode/Anode)	Mixing time / $\mathrm{l_{Batch}/min}$	Yield / % Performance / % Availability / % Auxiliary process time / s Mean time to repair (MTTR) / min Minimum/Maximum of MTTR / min
Coating (Cathode/Anode)	Coating speed / $\mathrm{m/min}$ Slurry usage / $\mathrm{kg/m}$ Splicing/Slitting factor / $-$	
Slitting (Cathode/Anode)	Slitting speed / $\mathrm{m/min}$ Splicing/Slitting factor / $-$	
Calendering (Cathode/Anode)	Calendering speed / $\mathrm{m/min}$ Splicing/Slitting factor / $-$	
Post-drying (Cathode/Anode)	Drying time / h Number of coils per chamber / $-$	
Cell building – Winding/Stacking	Cells per minute / $\mathrm{parts/min}$ Anode/Cathode/Separator foil length / m Number of anode/cathode sheets / $-$	
Cell assembly	Assembly speed / $\mathrm{parts/min}$ Batch size / $-$	

4. Case Study – Impact of buffer sizes

A short case study is presented in the following to demonstrate the possible applications of the digital twin model. For that, two scenarios are compared, which should show the applicability of the model for evaluating storage durations of specific cathode materials. The simulation duration was set to 17 days, with the initial three days designated as a tuning phase to fill the buffers and machines and to ensure a smooth process start [25]. Data capture and recording started after the completion of this tuning phase, considering the required ramp-up times of the machines to stabilize. Hence, the results represent a production run of 14 days.

4.1 Scenario

For the modeling of the material flow, first, the battery cell has to be defined. A state-of-the-art lithium-ion battery cell, currently deployed in the automotive industry, with $LiNi_{0.8}Co_{0.1}Mn_{0.1}O_2$ (NMC811) cathode and graphite anode, is chosen for the case study. The areal cathode capacity is set to 5 mAh cm^{-2}, considering specific capacities of 200 mAh g^{-1} for the cathode active material and 360 mAh g^{-1} for the anode graphite material [12,13,26]. As cell format, a tabless cylindrical cell type “4680” is assumed so that a winding process is considered. The cell housing dimensions are chosen so that an overall energy content of about 84 Wh is reached, aligning with current benchmark studies [27].

The assumed process chain, depicted in Figure 3, considers coating and drying as one integrated process step. For the cathode, the slitting is conducted before the calendering due to the risk of wrinkles, which affects the tabless cell design quality [28]. The modeling ends with the cell assembly as the last module since the focus here is on electrode production and its intermediate products. Overall, the factory is designed with a production capacity of 16 GWh per year, based on the maximal output of the considered coating process and assuming an operation over 24 hours per day and 365 days per year for a simplified plan machine occupancy of 100 %. The related machine, process, and production parameters are summarized in Table 2 in the Appendix. The individual material buffers are located between the process steps so that, in total, five buffers are integrated for the electrode production, comprising slurry, coated coils, slitted coils, calendered coils, and post-dried coils. To showcase the effect of different buffer sizes on the storage durations, two scenarios are compared. For that, the buffer sizes are dimensioned based on the individual inventory coverage (IC) and the potential material throughput of the coating process (TC). Hence, the buffer sizes (BS) correspond to the same cell amount and are calculated as follows [29]:

$$BS = IC \cdot TC \tag{1}$$

As inventory coverage, 8 hours (representing one shift) and 24 hours (representing one working day) are chosen. This means that when the buffers are entirely filled, production could continue at least for this amount of time in case of, e.g., material shortages or delivery delays. This ensures the desired cell output since the production capacity and required cycle time are based on the material output of the coating and drying process due to the high investment costs and area footprint associated with this process step [3].

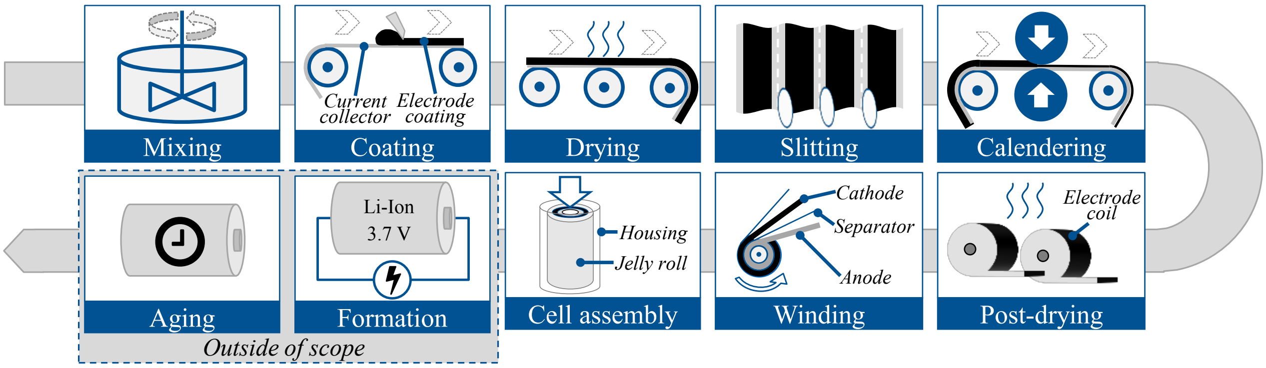


Figure 3: Process chain and individual process steps used as a basis for the simulation model

4.2 Results & Discussion

Figure 4 shows the average storage times of the products in the specific buffers along the cathode manufacturing process chain for the two scenarios.

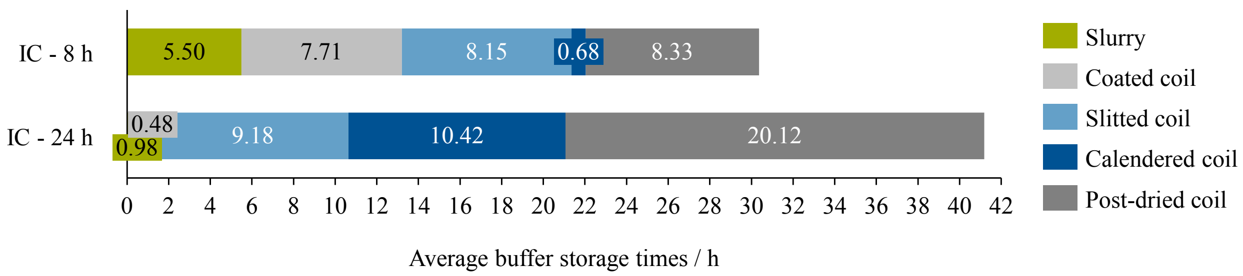


Figure 4: Average buffer storage times of the individual cathode components along the electrode process chain for the two simulation scenarios with 8 hours and 24 hours of inventory coverage (IC)

Noticeably, the variation of buffer sizes leads to a shift in the storage durations with different effects on the individual buffers. Whereas for the IC of 8 hours, rather long slurry and coated coil storage times can be detected, these durations are considerably shorter for the IC variant of 24 hours. Also, significant differences between the two scenarios can be seen for the calendered and post-dried coil storage times. These occurring imbalances can be explained by the output-based dimensioning of the buffers, leading to material quantities that correspond to the coating throughput and, hence, differ from other process steps. This consequently causes blocked machines and full buffers at certain points of the process chain. Therefore, an individual dimensioning of specific buffers in combination with machine-based adaptions would enable a more efficient buffering and material flow. This would also allow the adaptation toward material-specific aspects, considering moisture sensitivities and storage durations. These numbers demonstrate that changing the buffer size can significantly impact the production system, necessitating the adaption of production parameters along the entire process chain. Hence, it is evident that finding an appropriate production layout is a complex interaction between many parameters, suggesting to proceed iteratively.

The results also indicate that larger buffer sizes can positively influence the process efficiencies shown in Figure 5 for the two scenarios. These numbers suggest that increased buffer capacity can contribute to improved operational efficiency, as it allows for smoother material flow and reduces the likelihood of equipment downtime due to material shortages or blocked conditions. The rather low numbers for the slitting process can be attributed to the high scrap rate and relatively low availability factor assumed for this process step. For efficient production and material flow, it should be ensured that the machines are available for processing while not standing idle for longer periods. Here, available capacity in the subsequent buffer is essential to avoid blocked machines in the upstream process step. A potential approach for controlling the material flow and buffer functionality could be to adjust the coating performance, as the line balancing is carried out based on the coating process. Alternatively, adding extra machines at bottleneck positions could help to optimize the material flow efficiency. However, additional equipment entails increased investment costs and requires additional production space, also impacting OPEX.

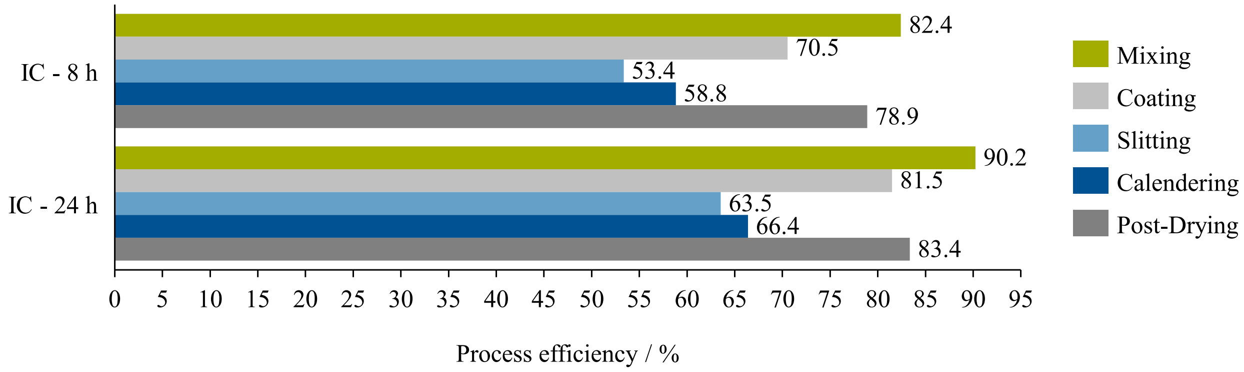


Figure 5: Process efficiencies of the cathode production line for the two simulation scenarios with 8 hours and 24 hours of inventory coverage (IC)

Furthermore, it should be noted that the model is generally very susceptible to changes in input parameters, particularly concerning the number and availability of the machines. Altering the number of parallel machines can significantly impact the calculated buffer storage times and subsequent material flow. More machines can reduce the material storage times but increase the risk of machine downtimes in case of buffer shortages. Therefore, when using the model, it is crucial to carefully assess and validate any modifications made to the machine and production layout, as they can have substantial consequences on the overall material flow and efficiency of the production system. Hence, the model is particularly effective when examining specific scenarios in real production systems, thereby supporting the decision-making process.

5. Conclusion & Outlook

The trend towards Ni-rich cathode active materials in lithium-ion battery production imposes high requirements for the production atmospheres regarding H_2O and CO_2. Therefore, cost- and energy-intensive dry rooms are used to ensure the production of high-quality battery cells. As the energy consumption of these dry rooms significantly depends on the size and desired dryness level, it is vital to identify an appropriate moisture management strategy throughout production. This work presents a methodological approach to this challenge by introducing a digital twin of a large-scale lithium-ion battery cell production to evaluate the production layout regarding material- and area-specific requirements. This model serves as a basis for electrochemical investigations of the material as it enables the prediction of exposure times for the materials and intermediate products based on a defined production layout. Hence, the model supports the planning and designing process of the factory by quickly evaluating the effects of critical production-related parameters.

As a next step, the impact of buffer sizes and the overall production layout on the required dry room space can be examined in detail, allowing to determine the effects on operational costs. Thus, it is possible to optimize the dry room area by appropriately designing the production parameters. For further development of the digital factory twin, considering the transport conditions between processes and buffers would be an interesting aspect, as this impacts the exposure time and atmosphere of the material. Concerning the overall approach, it is essential to find appropriate experimental set-ups and measurement methods for evaluating the required production atmospheres for specific cathode active materials. In this respect, it is necessary to further identify and understand the atmosphere's effects on the cell quality, as some studies indicate that under certain conditions, ambient atmosphere could be sufficient for producing high-quality Ni-rich cathodes [8,30]. Furthermore, for a detailed examination of the production layout from an energy consumption and cost perspective, a dry room model should be implemented in a battery cell production cost model. This would allow for considering the whole factory, enabling to point out the impact of the dry room operation on the total energy demand and production cost.

Acknowledgments

The authors sincerely thank the German Federal Ministry of Education and Research for funding the research project "InMiTro" (FKZ: 03XP0345A) as part of the research competence cluster "InZePro". Their gratitude also goes to Marc Wegmann for the valuable discussions and the joint supervision of the student project.

Appendix

Table 2: Assumed machine, process, and production parameters for the simulation (A: Anode; C: Cathode), including the related reference (expert values and assumptions without reference)

Module	# Machines	Process speed	Coil dimension / m x cm (length x width)	Splicing factor / -	Slitting factor / -	Performance / %	Yield / % [31]	Availability / %	MTTR / s	Fixed scrap rate / m	Auxiliary process time / s
C Slurry Mixing	7	5:00 h/batch	-	1	1	100	98,5	90	7200	-	6000
C Coating	2	1,3 m/s [24]	18000 x 96	3	1	100	96,5	85	7200	300	60
C Slitting	3	1 m/s [32]	5900 x 96	3	6	100	92 [24]	75	1200	-	60
C Calendering	10	1,6 m/s [24]	1898 x 16	1	2	100	99,45	70	1200	-	60
C Vacuum Drying	4	12000 m^2/shift [24]	1746 x 8	1	1	100	99,9	95	1200	-	600
A Slurry Mixing	7	5:00 h/batch	-	1	1	100	98,5	90	7200	-	6000
A Coating	2	1,3 m/s [24]	12300 x 96	3	2	100	96,5	85	7200	300	60
A Calendering	4	1,6 m/s [24]	3933 x 48	1	1	100	99,45	70	1200	-	60
A Slitting	6	1 m/s [32]	3796 x 48	2	6	100	92 [24]	75	1200	-	60
A Vacuum Drying	3	20000 m^2/shift [24]	1887 x 8	1	1	100	99,9	95	1200	-	600
Winding	20	1,1 m/s [33]	3.3 x 8	-	-	100	95	85	180	20 [23]	1 [33]
Cell Assembly	13	36 cells/min [24]	-	-	-	100	98	85	180	-	

References

[1] Liu, Y., Zhang, R., Wang, J., Wang, Y., 2021. Current and future lithium-ion battery manufacturing. iScience 24.

[2] 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, 290–300.

[3] 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.

[4] Duffner, F., Krätzig, O., Leker, J., 2020. Battery plant location considering the balance between knowledge and cost: A comparative study of the EU-28 countries. Journal of cleaner production 264, 121428.

[5] Kosfeld, M., Westphal, B., Kwade, A., 2023. Moisture behavior of lithium-ion battery components along the production process. Journal of Energy Storage 57, 106174.

[6] Singer, C., Töpper, H.-C., Günter, F.J., Reinhart, G., 2021. Plant Technology for the Industrial Coating Process for Sulfide-Based All-Solid-State Batteries. Procedia CIRP 104, 56–61.

[7] Ahmed, S., Nelson, P.A., Dees, D.W., 2016. Study of a dry room in a battery manufacturing plant using a process model. Journal of Power Sources 326, 490–497.

[8] Mayer, J.K., Huttner, F., Heck, C.A., Steckermeier, D., Horstig, M.-W. von, Kwade, A., 2022. Investigation of Moisture Content, Structural and Electrochemical Properties of Nickel-Rich NCM Based Cathodes Processed at Ambient Atmosphere. J. Electrochem. Soc. 169 (6), 60512.

[9] Yuan, C., Deng, Y., Li, T., Yang, F., 2017. Manufacturing energy analysis of lithium ion battery pack for electric vehicles. CIRP Annals (1), 53–56.

[10] Jinasena, A., Burheim, O.S., Strømman, A.H., 2021. A Flexible Model for Benchmarking the Energy Usage of Automotive Lithium-Ion Battery Cell Manufacturing. Batteries 7 (1), 1–21.

[11] Munters Corporation, 2023. Munters dry room calculator. https://battery-dry-rooms-calculator.munters.com/#/. Accessed 11 June 2023.

[12] Heck, C.A., Horstig, M.-W. von, Huttner, F., Mayer, J.K., Haselrieder, W., Kwade, A., 2020. Review—Knowledge-Based Process Design for High Quality Production of NCM811 Cathodes. J. Electrochem. Soc. 167 (16), 1–12.

[13] Günter, F.J., Wassiliadis, N., 2022. State of the Art of Lithium-Ion Pouch Cells in Automotive Applications: Cell Teardown and Characterization. Journal of The Electrochemical Society 169, 1–21.

[14] Li, W., Erickson, E.M., Manthiram, A., 2020. High-nickel layered oxide cathodes for lithium-based automotive batteries. Nature Energy 5 (1), 26–34.

[15] Busà, C., Belekoukia, M., Loveridge, M.J., 2021. The effects of ambient storage conditions on the structural and electrochemical properties of NMC-811 cathodes for Li-ion batteries. Electrochimica Acta 366, 1–10.

[16] Faenza, N.V., Bruce, L., Lebens-Higgins, Z.W., Plitz, I., Pereira, N., Piper, L.F.J., Amatucci, G.G., 2017. Growth of Ambient Induced Surface Impurity Species on Layered Positive Electrode Materials and Impact on Electrochemical Performance. Journal of The Electrochemical Society 164 (14), A3727-A3741.

[17] Jung, R., Morasch, R., Karayaylali, P., Phillips, K., Maglia, F., Stinner, C., Shao-Horn, Y., Gasteiger, H.A., 2018. Effect of Ambient Storage on the Degradation of Ni-Rich Positive Electrode Materials (NMC811) for Li-Ion Batteries. Journal of The Electrochemical Society 165 (2), A132-A141.

[18] Vogt, M., Dér, A., Khalid, U., Cerdas, F., Herrmann, C., 2022. Model-based planning of technical building services and process chains for battery cell production. Journal of cleaner production, 1–18.

[19] Rosen, R., Wichert, G. von, Lo, G., Bettenhausen, K.D., 2015. About The Importance of Autonomy and Digital Twins for the Future of Manufacturing. IFAC-PapersOnLine 48 (3), 567–572.

[20] 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.

[21] Siemens. Tecnomatix digital manufacturing software | Siemens software. Siemens.

[22] 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.

[23] Schünemann, J.-H., 2015. Modell zur Bewertung der Herstellkosten von Lithiumionenbatteriezellen (engl.: Cost Model to Validate Production Cost of Lithium-Ion Batteries). Phd thesis, Braunschweig, 204 pp.

[24] Knehr, K.W., Kubal, J.J., Nelson, P.A., Ahmed, S., 2022. Battery Performance and Cost Modeling for Electric-Drive Vehicles. Argonne National Laboratory, 146 pp.

[25] Mayer, G., Pöge, C., Spieckermann, S., Wenzel, S. (Eds.), 2020. Ablaufsimulation in der Automobilindustrie. Springer Vieweg, Berlin, Heidelberg, 400 pp.

[26] Andre, D., Kim, S.-J., Lamp, P., Lux, S.F., Maglia, F., Paschos, O., Stiaszny, B., 2015. Future generations of cathode materials: an automotive industry perspective. Journal of Materials Chemistry A (3), 6709–6732.

[27] Tesla 4680 Cell - Battery Design, 2022. https://www.batterydesign.net/tesla-4680-cell/. Accessed 4 July 2023.

[28] Günther, T., Schreiner, D., Metkar, A., Meyer, C., Kwade, A., Reinhart, G., 2020. Classification of Calendering-Induced Electrode Defects and Their Influence on Subsequent Processes of Lithium-Ion Battery Production. Energy Technol. 8 (2), 1900026.

[29] Schneider, M. (Ed.), 2008. Logistikplanung in der Automobilindustrie. Gabler, Wiesbaden.

[30] Heck, C.A., Huttner, F., Mayer, J.K., Fromm, O., Börner, M., Heckmann, T., Scharfer, P., Schabel, W., Winter, M., Kwade, A., 2023. Production of Nickel-Rich Cathodes for Lithium-Ion Batteries from Lab to Pilot Scale under Investigation of the Process Atmosphere. Energy Tech, 2200945.

[31] 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), 1–7.

[32] Nelson, P.A., Ahmed, S., Gallagher, K.G., Dees, D.W., 2019. Modeling the Performance and Cost of Lithium-Ion Batteries for Electric-Drive Vehicles, 3.th ed., 130 pp.

[33] Wuxi Lead Intelligent Equipment Co. Ltd., 2022. Cylindrical JR Winding Machine. Wuxi Lead Intelligent Equipment Co. Ltd. https://www.leadchina.cn/en/product-list3/247. Accessed 23 November 2022.

Biography

Maximilian Lechner graduated in mechanical engineering at the Technical University of Munich, focusing on manufacturing engineering and the production of lithium-ion cells. Currently, he works as a research associate at the Institute for Machine Tools and Industrial Management (*iwb*) at the Technical University of Munich.

Paul Mothwurf studies mechanical engineering and management at the Technical University of Munich. Currently, he is writing his master's thesis on the challenges of the production of Nickel-rich lithium-ion battery cells.

Lasse Nohe graduated in mechanical engineering and management at the Technical University of Munich. In his master's thesis, he focused on developing an agile digital twin within the early factory design phase for the production of lithium-ion battery cells. Currently, he works as a cell cost analyst at the lithium-ion battery cell manufacturer *Northvolt*.

Rüdiger Daub has been head of the Chair of Production Technology and Energy Storage Systems at *iwb* at the Technical University of Munich and the Fraunhofer Institute for Foundry, Composites, and Processing Technology IGCV since 2021. Previously, Prof. Dr.-Ing. Rüdiger Daub has held several positions at the *BMW Group*, most recently as head of technology development and prototype construction for lithium-ion cells.

5th Conference on Production Systems and Logistics

Comparative Analysis of Lithium Metal Anode Production Methods: Evaluating Liquid-Based Manufacturing Technology for Mass Production

Gerrit Bockey[1], Jan Felix Plumeyer[1], Sarah Wennemar[1] Benjamin Dorn[1], Heiner Hans Heimes[1], Achim Kampker[1]

[1]Production Engineering of E-Mobility Components (PEM), RWTH Aachen University, Aachen, Germany

Abstract

Lithium metal anodes (LMA) have gained significant attention for their potential to revolutionize rechargeable battery technology, offering high theoretical capacity and low electrode potential. Their implementation in various applications, such as electric vehicles and portable electronics, holds the promise of significantly improving energy density and battery performance. Additionally, the successful integration of lithium metal anodes remains a crucial and yet-to-be-resolved challenge in the development of All-Solid-State Batteries (ASSBs), which aim to provide safer and more efficient energy storage systems. Overcoming the production challenges associated with lithium metal anodes is essential for realizing their full potential. This paper presents a comprehensive technology analysis and evaluation of production methods for lithium metal anodes. The analysis explores various techniques and their potential for mass production. Furthermore, this analysis evaluates the viability of each approach by considering factors such as the potential for performance improvement, cost savings, quality enhancement, and the technology readiness level. The paper outlines future directions for the development of these techniques while focusing on the liquid-based processing approach, aiming to address quality issues and enhance its scalability for large-scale production. In conclusion, this technology analysis and evaluation underscores the potential of liquid-based manufacturing technology for the mass production of high-quality lithium metal anodes and highlights the need to overcome production challenges. An approach is presented that offers a way to work through the challenge of LMA production, paving the way to next-generation battery cells.

Keywords

Lithium Metal; Anode Production; Mass Production; Lithium Metal Anode; Solid-State Battery; Next-Generation Battery

1. Introduction

Lithium metal anodes have attracted considerable attention due to their potential to revolutionize rechargeable battery technology. With their high theoretical capacity and low electrode potential, LMAs promise to significantly improve energy density and battery performance. In particular, the development of solid-state batteries, which are expected to provide safer and more efficient energy storage, depends heavily on the effective incorporation of lithium metal anodes. A focus issue in the use of lithium metal is dendrite growth, which must be controlled for the safe application of battery technology. In this context, the use of a solid electrolyte is considered particularly promising. The production of lithium metal anodes is associated with considerable challenges that need to be overcome to unlock their full potential for mass production. [1,2]

DOI: https://doi.org/10.15488/15282
ISSN: 2701-6277

2. Overview of production methods

Despite the potential benefits offered by lithium metal anodes, there are several challenges associated with their manufacturing and usage. For example, minor contaminants can increase lithium metal reactivity and trigger undesirable side reactions. Therefore, the processing of lithium metal anodes must occur in a dry atmosphere to prevent oxidation upon contact with air. Safety measures, including preventive fire protection, are recommended to mitigate handling risks with lithium. [3] Furthermore, lithium metal is highly adhesive, which poses challenges for roll-to-roll processes and handling tools. Special measures and supporting layers may be necessary to facilitate the processing of lithium metal anodes. [3] Additionally, uniform lithium metal deposition is crucial for future lithium metal batteries, with a required thickness range of 2–30 µm for lithium anodes [4]. Non-uniform deposition impacts battery performance, making precise control and optimization of manufacturing processes essential in lithium metal electrode fabrication. [4] In addition to manufacturing challenges, addressing utilization and performance challenges during the usage phase is imperative. These challenges include dendrite formation, volume changes, and an unstable solid-electrolyte interphase (SEI) [5–9]. However, in this paper, the focus lies on the manufacturing process.

It is imperative to overcome these challenges to enable their mass production, improve performance, reduce costs, and enhance the overall quality of lithium metal anodes. Four production technologies are currently the focus of science to tackle these challenges.

2.1 Vapor-Based Techniques

Physical vapor deposition (PVD) techniques involve the deposition of thin films and coatings by transporting material from a condensed matter source through the gas phase onto a target surface. Unlike conventional ceramic processing methods that require high-temperature heat treatment or densification, PVD techniques offer robust and efficient alternatives [10]. The vapor deposition process has the potential to purify the lithium metal in addition to making thin lithium metal films [11]. To ensure process integrity and minimize potential sources of contamination, ultrahigh vacuum (UHV) conditions are established and maintained before and during the deposition process. PVD techniques provide a reliable and controlled approach for thin-film deposition, allowing for the fabrication of coatings with desirable properties in various applications. [1] Based on individual scientific studies, deposition rates of 1-1.5 µm/s or correspondingly high dynamic deposition rates of 20-30 µm-m/min are achievable for lithium. [12] PVD encompasses various methods, including electron beam evaporation, pulsed laser deposition, sputter deposition, and thermal evaporation. These techniques offer distinct advantages and are characterized by their specific operating principles and process parameters. [1,13]

Electron beam evaporation

Electron beam evaporation involves heating (T=2,000°C) a source material using an electron beam, which causes the material to vaporize and form a flux of atoms or molecules. [14] This vaporized material then condenses onto the substrate, forming a thin film. Electron beam evaporation offers precise control over high deposition rates and allows for the deposition of a wide range of materials. [1,14]

Pulsed Laser Deposition

Pulsed laser deposition utilizes a high-energy laser to ablate material from a target. The ablated material is then deposited onto the substrate to form a thin film. This technique offers excellent stoichiometric control, as well as the ability to deposit complex materials, such as oxides and nitrides, with high film quality. The process requires a deposition time of 1-4 h at pressures around $2x10^{-5}$ Pa. [1]

Sputter Deposition

Sputter deposition involves bombarding a target material with energetic ions, causing atoms or molecules to be ejected from the target surface. These ejected particles then deposit onto the substrate, forming a thin film. Sputter deposition allows for precise control of film composition, thickness, and morphology, making it suitable for a wide range of materials and applications. The process promises high deposition rates and a temperature range between 100-500°C as well as pressures of 10^{-7} – 10^{-2} mbar. [1]

Thermal Evaporation

Thermal evaporation relies on heating a source material to its vaporization temperature, allowing the atoms or molecules to escape and deposit onto the substrate. This technique is often used for materials with low melting points and offers simplicity and cost-effectiveness for thin film production. The application process takes place in a high vacuum. Thermal effects on the substrate can be excluded due to temperatures around room temperature. [1]

2.2 Liquid-based processing

The liquid-based technique is a promising method for preparing lithium metal anodes for lithium metal batteries (LMBs). By utilizing the low melting point (180.5°C) of lithium, it can be easily transformed into a liquid state under anaerobic conditions and deposited onto a substrate or surface using methods like dip coating, spray coating, or doctor blading. However, the major technological challenge of this approach is the low wettability of melted lithium on various substrates due to its high surface energy. Regulating the wettability between liquid lithium and scaffold materials is crucial in this process. [1] The focus of this process is therefore specifically on the selection of the substrate, rather than the application process. Influencing parameters are accordingly the quality of the substrate, web speed, the temperature of the lithium, and, for instance in dip coating, the coating angle. [4]

2.3 Electrodeposition

Electrodeposition, also known as electroplating, is a widely used technique for depositing metallic coatings onto a substrate via an electrochemical process. It involves the application of an electric current to drive the deposition of metal ions from a solution onto an electrode surface. [1] During electrodeposition, the substrate to be coated is immersed in an electrolyte solution containing metal ions of the desired coating material. An electric potential is then applied between the substrate (acting as the cathode) and a separate electrode (acting as the anode) in the electrolyte. This potential difference drives the reduction of metal ions at the cathode surface, leading to the formation and growth of a metallic layer. [1] Electrodeposition offers several advantages for coating production. It allows for precise control over coating thickness, uniformity, and adhesion strength. The process can be tailored to deposit a wide range of metals and alloys, providing versatility for various applications. Electrodeposition also enables the deposition of complex shapes and intricate geometries, making it suitable for coating objects with intricate surfaces. [15] To optimize electrodeposition, various parameters need to be carefully controlled, including the composition and concentration of the electrolyte, deposition current density, temperature, and deposition time. These parameters impact the coating quality, morphology, and physical properties. [16] Electrodeposition finds applications in diverse fields, including corrosion protection, decorative coatings, electronics, the automotive industry, and energy storage. By utilizing electrodeposition techniques, researchers and manufacturers can achieve tailored and controlled metallic coatings with desired properties, enhancing the functionality, durability, and aesthetics of various materials and components. [17,18,15]

2.4 Extrusion

The most common lithium foils are produced by hydraulic extrusion of lithium ingots[19,20]. The lithium metal ingots are fed into the extruder, where they are compressed and forced through a slot-shaped exit cross-section. This extrusion step imparts the desired shape and dimensions to the lithium metal, transforming it into a continuous foil. After extrusion, the lithium foil undergoes mechanical rolling at controlled pressure and temperature to ensure homogeneity, surface roughness, and final film thickness. This refines surface texture and thickness uniformity, enhancing quality and performance.

The high-intensity process for lithium metal rolling is distinct from conventional techniques due to the nonporous nature of metallic lithium and the targeted thickness of 10-20 µm. Polymeric supporting layers help mitigate lithium's adhesive properties, allowing the production of thin, damage-free films. Commercially, this method is employed to produce limited quantities of 30-75 µm thick lithium metal strips [21,22]. A post-production passivation coating safeguards the lithium foil, enabling processing in a dry room without the need for an inert gas atmosphere. It effectively prevents lithium reactivity, facilitating handling and integration into battery systems. [19]. Since pure lithium reacts with chromium(III) oxide, an oxide derived from the alloying element chromium in stainless steel, it is difficult to remove thin lithium from the rolls. [20] For smooth processing, use compatible rollers in extrusion and mechanical rolling. Plastic rollers, like polyacetal, are commonly used due to their compatibility with the adhesive nature of metallic lithium. [19] Due to the forming process and the resulting recrystallization, slip lines are created which would act as defects in electrochemical stripping/ plating. Depending on the technology and the manufacturer, lubricants are used that have to be removed later in the process. [23,20] Figure 1 shows schematically all previously described technologies.

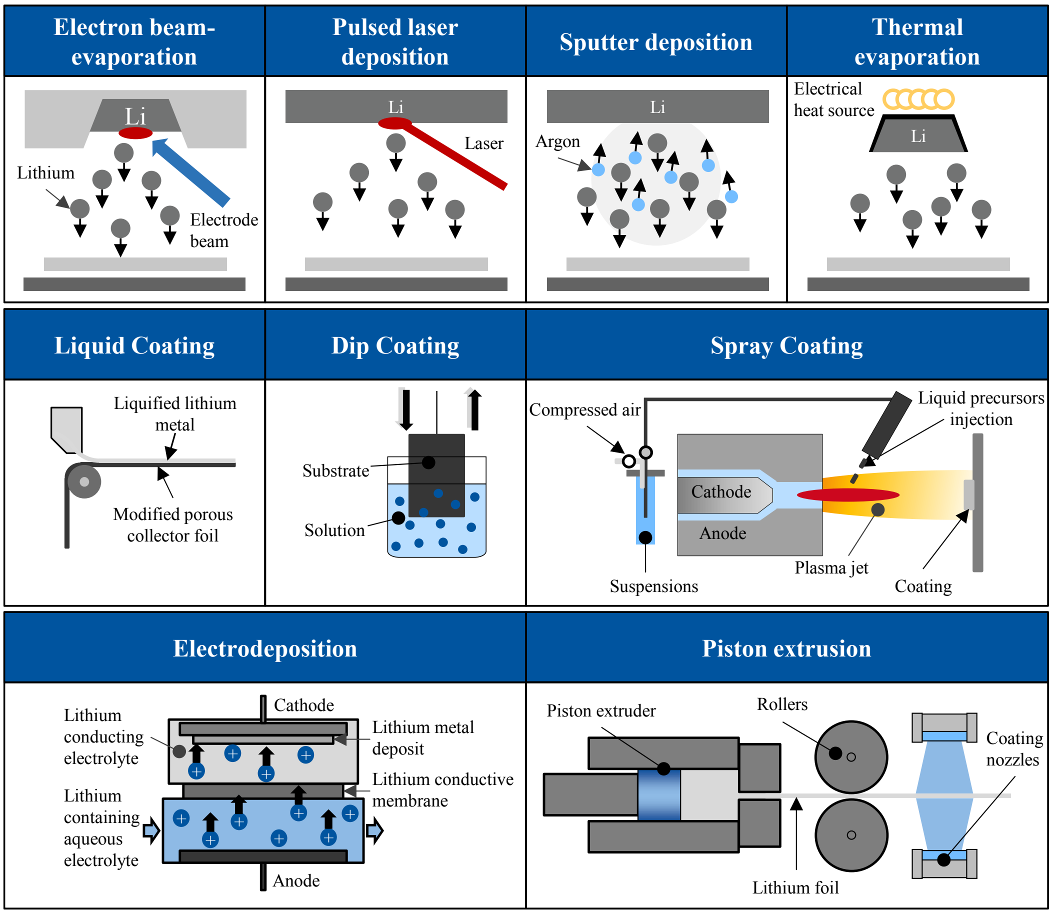


Figure 1: Schematic illustration of described coating processes

3. Methodology

Specific evaluation criteria have been established to evaluate selected production processes for the mass production of lithium metal anodes. In the style of the evaluation method of DEGEN & KRÄTZIG, evaluation parameters are selected based on which the selected processes are evaluated [24]. Due to the significant difference in the development stages and the limited research in this field of production technology, no conclusive validation can be made:

Technological maturity:

- *Technology readiness level:* The current stage of development and readiness for practical implementation of the production method [25].

Technology parameter:

- *Performance improvement potential:* The ability of the method to enhance the performance characteristics of lithium metal anodes, such as capacity, cycling stability, and rate capability.
- *Cost-effectiveness*: The economic feasibility of the production method, considering factors such as equipment costs, material costs, and process efficiency.
- *Quality enhancement:* The impact of the method on the quality and consistency of the produced lithium metal anodes, including factors such as uniformity, porosity, and surface morphology.

The benchmarking results employ a systematic evaluation approach, including the Technology Readiness Level (TRL) assessment on a scale of 1 to 9 [26,25]. This allows for a standardized assessment of the technological maturity of each method. This standardizes the assessment of technological maturity for each method. Additionally, performance improvement potential, cost-effectiveness, and quality enhancement are assessed using separate scales, carefully chosen for a comprehensive comparison. For instance, performance potential can be rated as lower than reference (-; 1 point), same as reference (0; 2 points), or higher than reference (+; 3 points). Cost-effectiveness considers equipment, material costs, and process efficiency, while quality enhancement evaluates factors like uniformity, porosity, and surface morphology. Using these evaluation scales enables a thorough and standardized comparison, clarifying the methods' relative strengths and weaknesses in technological readiness, performance improvement, cost-effectiveness, and quality enhancement.

The evaluation aims to identify potential production processes that could provide an alternative to the extrusion process in the future. In the following sections, the critical components and sub-processes are analyzed to provide recommendations for scalable production and increasing the TRL. To achieve further development of the manufacturing process, the current status and influencing parameters of the respective process must be identified. These are examined in more detail and defined based on parallels with existing production to define a methodological framework for equipment-side process and product optimization. [27]

4. Results and discussion

The evaluation of the technology is presented in Tables 1-4 and is in each case qualitatively compared to the benchmark process of mechanical rolling following the extrusion process.

Table 1: Rating of production methods for lithium metal in terms of their TRL

Technology	TRL	Explanation
Extrusion	9	Technology is widely implemented and utilized on a large scale in various industries. [1]
Vapor-Based techniques	7	Development phase for scalable component production for lithium anodes. [12,28]
Electrode-position	4	Successful experiments conducted in research laboratories [29,30,15]
Liquid-based processing	5	Development phase for scalable component production for lithium anodes. [4]

Table 2: Rating of production methods for lithium metal in terms of their process performance potential

Technology	Rating	Explanation
Extrusion	*Ref.*	The piston extrusion method is widely used for mass-producing lithium anodes in current polymer solid-state batteries. It offers high efficiency, scalability, and significant benefits for fabrication. [31,32]

Vapor-Based techniques	+	Vapor-based PVD methods, such as sputtering and evaporation, hold potential for lithium metal foil production. They deposit purer and more reactive lithium compared to rolling and electrodeposition. These established processes allow broad coating, including roll-to-roll applications, on diverse substrates like alloys. [1,20]
Electrode-position	-	Lithium electrodeposition has mixed process performance. It has strengths in its established use across industries and the ability to structure deposited films. However, its commercial availability is limited, and it is less commonly applied compared to other metals. [1,30,15]
Liquid-based processing	+	Lithium melt deposition shows promising process performance, creating thin lithium metal anodes with high utilization and precise coating control. Scalable roll-to-roll processing allows efficient high-volume production with variable dimensions. [1,4]

Table 3: Rating of production methods for lithium metal in terms of their economic efficiency

Technology	Rating	Explanation
Extrusion	*Ref.*	Piston extrusion for lithium metal foil is economically efficient, offering potential cost reduction benefits. Its ability to create thin, continuous foils with high material utilization and scalability contributes to its favorability. Further multistep calendaring leads to a total cost of about 250$/kg. [31,33,34]
Vapor-Based techniques	-	Vapor-based techniques for lithium metal foil production may face economic challenges due to higher costs related to equipment, vacuum sealing, and processing thin foils. The vapor also deposits on the walls of the vacuum chamber, resulting in a waste of material. [1,31,12,4,20]
Electrode-position	*0*	Electrodeposition for lithium metal foil production holds promise for lower costs due to lower process temperatures and raw material expenses. However, roll-to-roll processes may result in slower production rates and significant electrolyte recycling costs, impacting overall profitability. [1,31]
Liquid-based processing	+	Liquid-based processing for lithium metal foil production shows promising economic efficiency. High-quality and thickness-controlled layers on the copper current collector, achieved through ultrathin lithium metal films, lead to overall thickness reduction and higher energy densities on the cell level. Less subsequent operations after extrusion lead to cost savings. [1,33,4]

Table 4: Rating of production methods for lithium metal in terms of their quality potential

Technology	Rating	Explanation
Extrusion	*Ref.*	Piston extrusion can produce thin, continuous foils with attributes like homogeneity, uniformity, and precise thickness control. However, the process may also exhibit strong texture behavior due to shear stress. [11,34]
Vapor-Based techniques	+	Vapor-based processes such as thermal evaporation in PVD enable precise, defect-free coatings for efficient lithium metal foil production at lower temperatures. They can remove impurities from the lithium, although controlling the deposition rate remains a challenge. [11,4,34]
Electrode-position	+	Electrodeposition techniques promise high-quality lithium metal foil with pure and homogeneous layers, allowing precise control over morphology and thickness. Despite challenges in achieving uniform morphologies and high

		coulombic efficiencies, conformal coatings improve battery performance and adhesion. [1,35,15]
Liquid-based processing	*0*	Liquid-based processing offers promising quality potential for producing thin lithium metal foil. The low melting point of lithium allows an easy transition to the liquid state, enabling standard wet coating methods. However, previous attempts at melt deposition led to unsuitable film thicknesses and weak adhesion. Hence, the development of efficient and scalable coating methods in the desired thickness range is essential. [1,4]

Figure 2 shows the cumulative evaluation of manufacturing processes based on their TRL. The analysis demonstrates the potential of the liquid application of lithium, offering opportunities for process optimization and further development to raise the TRL evaluation. To raise the TRL from level 5 to at least level 6 and optimize manufacturing technology, a conceptual design of a scalable approach is essential [36]. Achieving these results without changing the process necessitates a close examination of the sub-processes used.

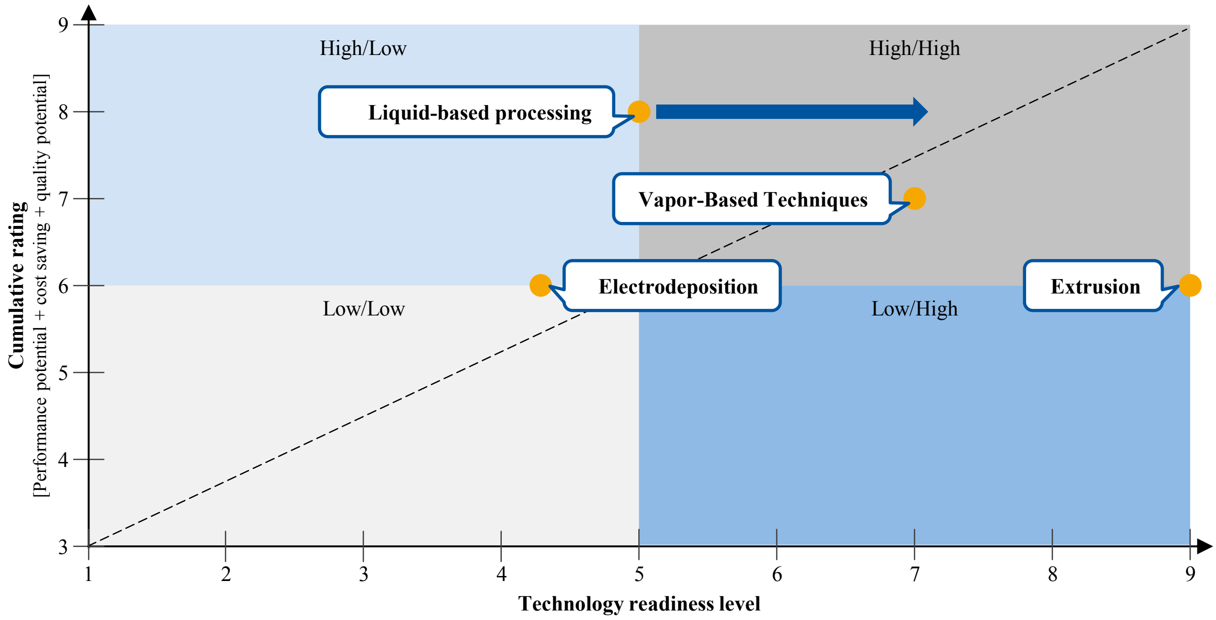


Figure 2: Attractiveness of lithium metal production methods in terms of TRL and overall cumulative rating.

The evaluation carried out shows that the application of liquid lithium has potential in the context of lithium metal anode production. SCHÖNHERR'S approach shows that there is a general feasibility, but there are still some challenges in industrializing this approach. For this purpose, it is necessary to take a closer look at the process with the individual technologies used and to identify limit values that must be considered during industrialization.

The current development status of liquid lithium deposition can be divided into individual sub-processes. In an upstream process, the surface is modified to produce a lithiophilic surface. Subsequently, liquid lithium is applied in a glovebox filled with argon. Within this inert mini-environment, the lithium metal anode is wound up and the substrate is implicitly tempered by dipping it into the heated lithium coating. The overall process can thus be divided into four sub-functions in which the control of the atmosphere is not initially considered due to the inconsistency over the entire process.

Surface treatment

The lithiophilic layer is produced in SCHÖNHERR'S process using a muffle furnace. For the production of copper(I) oxide (Cu_2O), temperatures of at least 200°C are necessary, as a result of which a chemical reaction with oxygen occurs. [37] When molten lithium interacts with the Cu_2O layer, it is consumed, resulting in

Li_2O and Cu species that are no longer present as a compact film and are bound in the boundary region. The reaction is as follows: $Cu_2O + 2\ Li \leftrightarrow 2\ Cu + Li_2O$ [38,4]. The Cu_2O layer's formation depends on temperature and duration. Excessive energy input at elevated temperatures can lead to porosity and the formation of copper(II) oxide (CuO), observable from 320°C [38]. Delamination can occur at a layer thickness of 1500 nm, and CuO is less ideal for the interlayer formation. [39]. This suggests the reaction: $CuO + 2\ Li \leftrightarrow Cu + Li_2O$ [40].

To determine parameters for liquid application production, assume web speeds of 80 m/min based on the conventional and commercially used rolling process. [41–43,34] For an inline production of Cu_2O substrate and to increase TRL, a layer with a thickness of several hundred nanometers, not exceeding 1500 nm, must be produced as quickly as possible. A temperature of approx. 320°C should not be exceeded in order to maintain the quality or to achieve no loss of quality compared to the current process. The substrate's quality is directly influencing the coating process. [44,4]

Coating process

The liquid application coating process uses dip coating with lithium bath, bath heater, and drive as functional carriers in a glovebox filled with argon, primarily to avoid reactions with atmospheric humidity. Under normal conditions, lithium reacts slowly with air. It can be assumed that a dry air atmosphere has less effect on the lithium metal anode in an accelerated manufacturing process. [36] The process's physical conditions depend on web speed and temperature-dependent rheological properties of lithium. [27,45,36,44] At the melting point of about 180.5°C, lithium has a viscosity of η =0.645 mPas, a density of ρ = 516 kg/m³ and a surface tension of σ = 0.396 N/m². [46] The coating thickness (h) as a function of web speed (U) is determined by the following equation [47]:

$$h = 0.944 * \frac{\mu U^{\frac{1}{6}}}{\sigma} * \frac{\mu U^{\frac{1}{2}}}{\rho g}$$

The coating's inclination was not considered due to uneven thickness distribution in case of coating on both sides. The equation represents web speed, and with a targeted thickness of around 20 µm, the maximum web speed is U = 4.3 m/min. At a production speed of 80 m/min, this results in a coating thickness of 140 µm. Dip-coating is not suitable for scaled consideration; therefore, alternative coating technologies like slot dies must be taken into account. Slot dies have easily scalable process parameters, with slurry viscosity ranging from 1 mPas to multiple kPas and surface tension from less than 25 mPas to more than 500 mPas, both matching liquid lithium requirements. [48] According to KRAYTSBERG et al. a coating with a slot die is considered stable if the ratio of the distance of the slot die (h) in relation to the wet film thickness (t) meets the following requirement:

$$\frac{h}{t} \leq 1.49 * \frac{\mu U^{-\frac{2}{3}}}{\sigma}$$

At a web speed of 80 m/min and lithium at the melting point, the wet film thickness requires a minimum spacing of about h = 1.7 mm. [48,49] In summary, increasing quality can be achieved through controlled substrate treatment and varying the application system, leading to a relatively simple potential increase in TRL. [50]

5. Outlook and conclusion

This paper discusses current manufacturing processes and approaches for lithium metal anode production and evaluates and classifies them on the TRL scale. A cumulative rating, was determined, considering process performance, economics and quality potential, with the liquid-based processing application receiving the highest rating but having a relatively low TRL. To optimize equipment, a product structure analysis is conducted. Relevant process parameters are presented as framework conditions for product development and process improvement. An alternative coating technology is proposed after a critical analysis of the coating process. Detailed system design and development based on liquid lithium application offer a promising alternative and can enhance quality through controlled parameters. This paper serves as a basis for further development and accelerated progress in lithium metal anode production, which is crucial for future generations of battery cells.

References

[1] Acebedo, B., Morant‐Miñana, M.C., Gonzalo, E., Ruiz de Larramendi, I., Villaverde, A., Rikarte, J., Fallarino, L., 2023. Current Status and Future Perspective on Lithium Metal Anode Production Methods. Advanced Energy Materials 13 (13).

[2] Wu, B., Wang, S., Evans IV, W.J., Deng, D.Z., Yang, J., Xiao, J., 2016. Interfacial behaviours between lithium ion conductors and electrode materials in various battery systems. J. Mater. Chem. A 4 (40), 15266–15280.

[3] Meyer, H.C., 1957. Some Practical Aspects of Handling Lithium Metal, in: , Handling and Uses of the Alkali Metals, vol. 19. ACS, Washington, pp. 9–15.

[4] Schönherr, K., Schumm, B., Hippauf, F., Lissy, R., Althues, H., Leyens, C., Kaskel, S., 2022. Liquid lithium metal processing into ultrathin metal anodes for solid state batteries. Chemical Engineering Journal Advances 9, 100218.

[5] Fang, C., Li, J., Zhang, M., Zhang, Y., Yang, F., Lee, J.Z., Lee, M.-H., Alvarado, J., Schroeder, M.A., Yang, Y., Lu, B., Williams, N., Ceja, M., Yang, L., Cai, M., Gu, J., Xu, K., Wang, X., Meng, Y.S., 2019. Quantifying inactive lithium in lithium metal batteries. Nature 572 (7770), 511–515.

[6] Jin, C., Liu, T., Sheng, O., Li, M., Liu, T., Yuan, Y., Nai, J., Ju, Z., Zhang, W., Liu, Y., Wang, Y., Lin, Z., Lu, J., Tao, X., 2021. Rejuvenating dead lithium supply in lithium metal anodes by iodine redox. Nat Energy 6 (4), 378–387.

[7] Liu, Y., Li, Y., Sun, J., Du, Z., Hu, X., Bi, J., Liu, C., Ai, W., Yan, Q., 2023. Present and future of functionalized Cu current collectors for stabilizing lithium metal anodes. Nano Research Energy 2, e9120048.

[8] Shen, X., Zhang, R., Shi, P., Chen, X., Zhang, Q., 2021. How Does External Pressure Shape Li Dendrites in Li Metal Batteries? Advanced Energy Materials 11 (10), 2003416.

[9] Yuan, H., Ding, X., Liu, T., Nai, J., Wang, Y., Liu, Y., Liu, C., Tao, X., 2022. A review of concepts and contributions in lithium metal anode development. Materials Today 53, 173–196.

[10] Rahaman, M.N., 2017. Ceramic processing and sintering, Second edition ed. CRC Press, Boca Raton, 875 pp.

[11] Ho, A.S., Westover, A.S., Browning, K., Maslyn, J.A., Parkinson, D.Y., Sahore, R., Dudney, N., Balsara, N.P., 2022. Comparing the Purity of Rolled versus Evaporated Lithium Metal Films Using X-ray Microtomography. ACS Energy Lett. 7 (3), 1120–1124.

[12] Saager, S., Decker, L., Kopte, T., Scheffel, B., Zimmermann, B., 2023. High-Performance Anodes Made of Metallic Lithium Layers and Lithiated Silicon Layers Prepared by Vacuum Technologies. Batteries 9 (2), 75.

[13] Vanleeuw, D., Sapundjiev, D., Sibbens, G., Oberstedt, S., Salvador Castiñeira, P., 2014. Physical vapour deposition of metallic lithium. J Radioanal Nucl Chem 299 (2), 1113–1120.

[14] Vasile, B.S., Birca, A.C., Surdu, V.A., Neacsu, I.A., Nicoară, A.I., 2020. Ceramic Composite Materials Obtained by Electron-Beam Physical Vapor Deposition Used as Thermal Barriers in the Aerospace Industry. Nanomaterials (Basel, Switzerland) 10 (2).

[15] Pu, J., Shen, Z., Zhong, C., Zhou, Q., Liu, J., Zhu, J., Zhang, H., 2020. Electrodeposition Technologies for Li-Based Batteries: New Frontiers of Energy Storage. Advanced materials (Deerfield Beach, Fla.) 32 (27), e1903808.

[16] Xiong, S., Nyholm, L., Matic, A., Zhang, C., 2022. Lithium electrodeposition for energy storage: filling the gap between theory and experiment. Materials Today Energy 28, 101060.

[17] Dunn, B., Kamath, H., Tarascon, J.-M., 2011. Electrical energy storage for the grid: a battery of choices. Science (New York, N.Y.) 334 (6058), 928–935.

[18] Pu, J., Li, J., Shen, Z., Zhong, C., Liu, J., Ma, H., Zhu, J., Zhang, H., Braun, P.V., 2018. Interlayer Lithium Plating in Au Nanoparticles Pillared Reduced Graphene Oxide for Lithium Metal Anodes. Adv. Funct. Mater. 28 (41), 1804133.

[19] Heimes, H.H., Kampker, A., Wennemar, S., Scheibe, A., Plumeyer, J.F., 2023. Production of an All-Solid-State Battery Cell. PEM RWTH Aachen; VDMA, Frankfurt am Main, 24 pp.

[20] Wu, W., Luo, W., Huang, Y., 2023. Less is more: a perspective on thinning lithium metal towards high-energy-density rechargeable lithium batteries. Chemical Society reviews 52 (8), 2553–2572.

[21] Hovsepian, B.U., 1971. ROLLING OF LITHIUM. US19710174227 B21B1/40;B21B3/00;H01M4/12;B21B45/00;B21B3/00;B23P17/04.

[22] Schmuch, R., Wagner, R., Hörpel, G., Placke, T., Winter, M., 2018. Performance and cost of materials for lithium-based rechargeable automotive batteries. Nat Energy 3 (4), 267–278.

[23] Li, T., Shi, P., Zhang, R., Liu, H., Cheng, X.-B., Zhang, Q., 2019. Dendrite-free sandwiched ultrathin lithium metal anode with even lithium plating and stripping behavior. Nano Res. 12 (9), 2224–2229.

[24] Degen, F., Kratzig, O., 2022. Future in Battery Production: An Extensive Benchmarking of Novel Production Technologies as Guidance for Decision Making in Engineering. IEEE Trans. Eng. Manage., 1–19.

[25] Mankins, J.C., 1995. Technology Readiness Levels. NASA. https://www.researchgate.net/publication/247705707_Technology_Readiness_Level_-_A_White_Paper/citations. Accessed 25 July 2023.

[26] Greenwood, M., Wrogemann, J.M., Schmuch, R., Jang, H., Winter, M., Leker, J., 2022. The Battery Component Readiness Level (BC-RL) framework: A technology-specific development framework. Journal of Power Sources Advances 14, 100089.

[27] Feldhusen, J., Grote, K.-H. (Eds.), 2013. Pahl/Beitz Konstruktionslehre: Methoden und Anwendung erfolgreicher Produktentwicklung, 8., vollständig überarbeitete Auflage ed. Springer Vieweg, Berlin, Heidelberg, 883577 pp.

[28] Strauß, F., Hüger, E., Heitjans, P., Trouillet, V., Bruns, M., Schmidt, H., 2015. Li–Si thin films for battery applications produced by ion-beam co-sputtering. RSC Adv. 5 (10), 7192–7195.

[29] Choi, B.N., Seo, J.Y., Kim, B., Kim, Y.S., Chung, C.-H., 2020. Electro-deposition of the lithium metal anode on dendritic copper current collectors for lithium battery application. Applied Surface Science 506, 144884.

[30] Porthault, H., Decaux, C., 2016. Electrodeposition of lithium metal thin films and its application in all-solid-state microbatteries. Electrochimica Acta 194, 330–337.

[31] Delaporte, N., Perea, A., Léonard, M., Matton, J., Demers, H., Collin-Martin, S., Rozon, D., Clément, D., Guerfi, A., Kim, C., 2023. Method for Benchmarking Li Metal Anodes: A Mandatory Step toward Reliable Lithium Metal Batteries. Batteries 9 (7), 368.

[32] Gao, Y., Ding, J., 2023. Multifunctional structural composite fibers in energy storage by extrusion-based manufacturing. Journal of Materials Research 38 (10), 2615–2630.

[33] Schnell, J., Knörzer, H., Imbsweiler, A.J., Reinhart, G., 2020. Solid versus Liquid—A Bottom‐Up Calculation Model to Analyze the Manufacturing Cost of Future High‐Energy Batteries. Energy Technol. 8 (3), 1901237.

[34] Xiao, J., Shi, F., Glossmann, T., Burnett, C., Liu, Z., 2023. From laboratory innovations to materials manufacturing for lithium-based batteries. Nat Energy 8 (4), 329–339.

[35] Hu, F., Li, Z., Wang, S., Tenhaeff, W.E., 2020. Mirror-Like Electrodeposition of Lithium Metal under a Low-Resistance Artificial Solid Electrolyte Interphase Layer. ACS applied materials & interfaces 12 (35), 39674–39684.

[36] Lyublinski, I.E., Vertkov, A.V., Evtikhin, V.A., 2009. Application of lithium in systems of fusion reactors. 1. Physical and chemical properties of lithium. Plasma Devices and Operations 17 (1), 42–72.

[37] Kwon, H., Kim, J., Ko, K., Matthews, M.J., Suh, J., Kwon, H.-J., Yoo, J.-H., 2021. Laser-induced digital oxidation for copper-based flexible photodetectors. Applied Surface Science 540, 148333.

[38] Choudhary, S., Sarma, J.V.N., Pande, S., Ababou-Girard, S., Turban, P., Lepine, B., Gangopadhyay, S., 2018. Oxidation mechanism of thin Cu films: A gateway towards the formation of single oxide phase. AIP Advances 8 (5), 55114.

[39] Kaskel, S., Althues, H., Schumm, B., Dresel, N., Schönherr, K., 2018. Verfahren zum herstellen eines mit einem Alkalimetall beschichteten Substrats mittels einer Vermittlerschicht sowie ein beschichtetes Substrat: Utility Patent, 23 pp.

[40] Chen, K., Song, S., Xue, D., 2015. Faceted Cu 2 O structures with enhanced Li-ion battery anode performances. CrystEngComm 17 (10), 2110–2117.

[41] Bühler Redex GmbH, 2022. Precision Lithium Foil Rolling Mill. https://redex.sharefile.eu/share/view/s52f210724c3d4312ac2112901dd60a7b. Accessed 25 July 2023.

[42] Heimes, H., Kampker, A., Wennemar, S., Plocher, L., Bockey, G., Michaelis, S., Schütrumpf, J., 2023. Production Process of a Lithium-Ion Battery Cell. PEM RWTH Aachen; VDMA, Frankfurt am Main, 24 pp.

[43] Wolf, S., Garbade, L., Göken, V., Tien, R., Börner, M., Neb, D., Heimes, H.H., 2023. Process and Material Analysis of Laser- and Convection-Dried Silicon–Graphite Anodes for Lithium-Ion Batteries. WEVJ 14 (4), 87.

[44] Sankapal, B.R., Ennaoui, A., Gupta, R.B., Lokhande, C.D. (Eds.), 2023. Simple Chemical Methods for Thin Film Deposition: Synthesis and Applications, 1st ed. 2023 ed. Springer Nature Singapore; Imprint Springer, Singapore, 225 pp.

[45] Ito, Y., Minami K., Nagashima, A., 1989. Viscosity of liquid lithium by an oscillating-cup viscometer in the temperature range 464-923 K. International Journal of Thermophysics 10.

[46] Davison, H.W., 1968. Compilation of thermophysical properties of liquid lithium: Data correlation of thermophysical properties of saturated liquid lithium as function of temperature. https://ntrs.nasa.gov/api/citations/19680018893/downloads/19680018893.pdf. Accessed 25 July 2023.

[47] Scriven, L.E., 1988. Physics and Applications of DIP Coating and Spin Coating. MRS Online Proceedings Library 121 (1), 717–729.

[48] Ding, X., Liu, J., Harris, T.A.L., 2016. A review of the operating limits in slot die coating processes. AIChE J. 62 (7), 2508–2524.

[49] Kraytsberg, A., Ein-Eli, Y., 2016. Conveying Advanced Li-ion Battery Materials into Practice The Impact of Electrode Slurry Preparation Skills. Adv. Energy Mater. 6 (21), 1600655.

[50] Liu, H., Cheng, X., Chong, Y., Yuan, H., Huang, J.-Q., Zhang, Q., 2021. Advanced electrode processing of lithium ion batteries: A review of powder technology in battery fabrication. Particuology 57, 56–71.

Biography

Gerrit Bockey (*1995) is a 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 product development at RWTH Aachen University.

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.

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

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.

Prof. Dr.-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. From March 2019 to 2023, he was PEM's Executive Chief Engineer before being appointed Professor.

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.

5th Conference on Production Systems and Logistics

From Machinery to Insights: A Comprehensive Data Acquisition Approach for Battery Cell Production

Achim Kampker[1], Benjamin Dorn[1], Robert Ludwigs[1], Henning Clever[1], Felix Kirchmann[1]
[1] *Chair of Production Engineering of E-Mobility Components (PEM), RWTH Aachen University, Aachen, Germany*

Abstract

To ensure the widespread use of sustainably produced battery cells, further progress in research is needed. The transition to automated data acquisition is complicated by the technical complexity of industrial data acquisition. Existing software solutions also fall short in meeting usability, reproducibility, extensibility, and cost-effectiveness requirements for research-scale battery production lines. To address these gaps, this paper presents and evaluates a comprehensive data acquisition and collection solution for research-scale battery production lines. It offers a systematic overview of the industrial data acquisition process, focusing on gathering data from various existing machinery and utilizing the industry standard OPC UA protocol. Given the lack of existing solutions that meet the specified requirements, the paper introduces the "ProductionPilot" software as a solution. “ProductionPilot” is designed to provide an extensible platform with a user-friendly web interface. It enables users to select, structure, monitor, and export live production data delivered via OPC UA. The effectiveness of the proposed system is validated at the CELLFAB battery production research facility at eLab of RWTH Aachen university, demonstrating its capability for long-term data acquisition and the generation of digital shadows. By addressing the limitations of current data collection methods and providing a comprehensive solution, this research aims to facilitate the broader adoption of lithium-ion batteries in renewable energy applications.

Keywords

Battery Cell Production; Industry 4.0; Automated data acquisition; Digitalization; OPC UA

1. Introduction

Batteries play a crucial role in powering our technologically advanced and sustainable future, from electric vehicles to renewable energy storage. To meet the increasing global demand, optimizing battery production processes is essential. Data-driven research has proven pivotal in driving progress across industries, including batteries. By leveraging data analytics, researchers gain valuable insights into battery production, leading to enhanced processes and performance.

Central to data-driven battery research is the development of efficient data gathering and monitoring systems. These systems provide real-time data from machinery and processes, enabling researchers to optimize production lines and embrace automation. This paper presents a comprehensive guideline for digitalizing battery production lines, using the PEM of RWTH Aachen University research production line as a case study. By showcasing the importance of data-driven research and sophisticated data acquisition systems, we aim to enable battery manufacturers and researchers to successfully implement digital transformation of their machine and plant technology.

DOI: https://doi.org/10.15488/15313
ISSN: 2701-6277

2. Research Background

The following sections will delve into digitalization in production, the lithium-ion battery production process, and a comprehensive overview of related work in the field.

2.1 Digitalization in production

The term digitalization describes "the comprehensive networking of all areas of the economy and society as well as the ability to collect, analyse and convert relevant information into actions". [1] When referring to digitalization in production, the term usually refers to data collection by a physical system or process, often designed for a specific purpose. A definition of a digital shadow states that "a digital shadow is a set of temporal data traces and/or their aggregation and abstraction, collected in relation to a system for a specific purpose in relation to the original system." [2] The creation of a digital shadow in battery production research requires the acquisition of data from industrial machines. Industrial connectivity, which involves communication and data exchange between devices in industrial environments, plays a critical role in this process, such as programmable logic controllers, which are the main source of industrial data. It also entails communication protocols such as OPC UA, which is widely used to simplify data collection in industrial applications. [3,4]

Programmable logic controllers (PLCs) are widely used as proprietary technology in industrial machinery for software-based control. They connect to various sensors and actuators, enabling complex machine operations. To enable communication between PLCs, sensors, actuators, computer networks, and other peripherals, a diverse range of interfaces have been adopted within the industry by PLC manufacturers. Common protocols include Profibus, Profinet, Modbus, EtherCAT, and EtherNet/IP. Ensuring data collection from heterogeneous industrial devices can be difficult due to this variety of interfaces. However, the adoption of OPC UA as a common standard for industrial connectivity is gaining momentum, simplifying data acquisition in the industrial sector. [5]

The OPC UA protocol is an industry-standard platform-independent standard that facilitates data transfer between industrial devices and applications. It follows a client-server architecture and uses a binary protocol over TCP/IP for communication. OPC UA allows access to machine variables (tags) through server discovery, enabling reading, writing, and subscription-based monitoring. Subscribed clients receive updates when changes occur, with customizable sampling rates for data collection. OPC UA also offers encryption, event handling, and remote method calling. Despite its complexity, OPC UA is widely adopted and serves as a powerful tool for accessing and monitoring data in industrial applications. [5,6]

2.2 Lithium-ion battery production process

The process chain of lithium-ion battery cell production includes several essential steps. The main sections are electrode manufacturing, cell assembly and cell finishing (see Figure 1). The electrode manufacturing starts with the preparation of active materials, i.e., mixing and coating of cathode and anode materials onto metal foils. The active materials are then dried and calendered before the electrode webs are cut into coils. During cell assembly, the next step typically entails winding or stacking the anode and cathode together with the separator to form the cell's core compound. The separator is integrated between the electrodes to prevent electrical short-circuits. Tabs are then welded on, which form the subsequent poles of the battery before the cell is filled with electrolyte. The cell gets hermetically sealed to prevent leakage. In cell finishing soaking and formation processes are conducted to achieve the desired electrochemical cell performance. Lastly, the cell undergoes comprehensive testing and quality checks during aging and EOL testing, ensuring compliance with automotive standards for use in electric vehicles. [7]

In the lithium-ion battery production process, data collection plays a crucial role. Generating vast quantities of data enables to effectively monitor and control the production process to meet the product specifications.

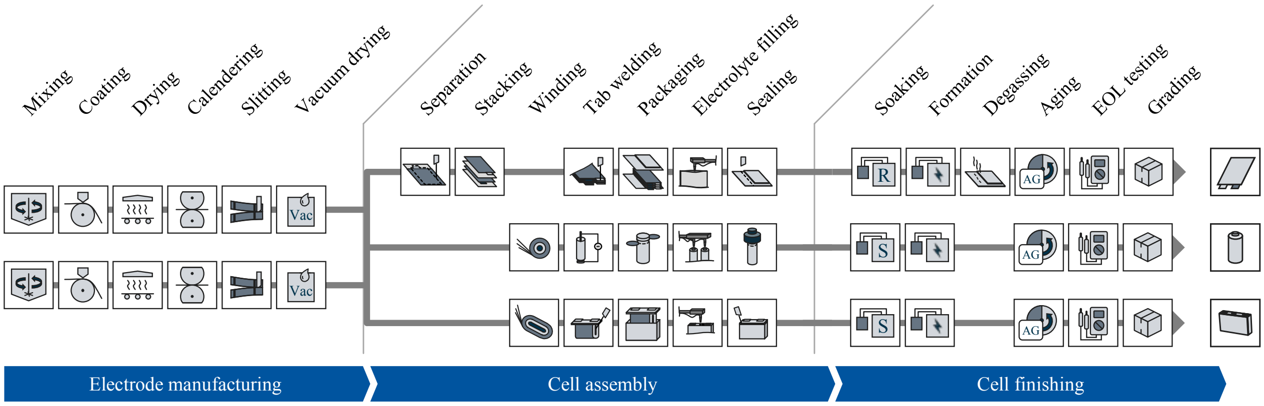


Figure 1: Generic process chain in battery cell production for pouch, prismatic and cylindrical cells [8]

The data is acquired from various sources, e.g., process equipment and programmable logic controllers (PLC), sensors and measuring devices, laboratory and operational records. The acquired data comes in different formats, including time series, databases, tabular data and discrete data files. [9] Discrete data input may contain for instance material property information, data sheets of components as well as equipment features and specifications. [10] In production, a large number of heterogeneous data types are commonly found in the form of structured, semi-structured and unstructured data, including measured values, product records, text, logs, audio, video. [11] The primary objective is to determine the relevant data for the relationship between the process, the intermediates, and the final product. In order to capture this data, a variety of different production machines and analytical devices from diverse suppliers must be accessed. [12]

As different equipment manufacturers are involved in various production steps, there is no uniform framework for seamless data exchange. [13] This hinders efficient data collection and analysis, impacting process optimization. Proprietary data interfaces used by specialized equipment suppliers lead to data silos and compatibility issues. Implementing standardized data interfaces will enable the battery industry to fully leverage data-driven manufacturing, ensuring a successful and sustainable battery production.

2.3 Related Work

Different approaches for the digitalization and data acquisition in battery cell production can be found in the literature. *Ayerbe et al.* generally explore the current status and near-term developments in digitalizing the battery cell manufacturing chain, combining modelling approaches, data acquisition, and communication protocols. [14] In this context, a practical implementation of most approaches has only been realized in research and pilot lines. *Turetskyy et al.* propose a data-driven approach to holistically capture and evaluate interactions between production steps and cell properties in battery cell production. This approach presents a concept for acquiring relevant data throughout the production line, including technical building services and cell diagnostics. The approach combines automated and manual data collection, integrating data from different sources, protocols, and formats for accessible, efficient data management, and visualization. [12] *Han et al.* addressed the challenge of integrating heterogeneous automation equipment in lithium-ion battery manufacturing by establishing a standardized information model. The model allows interconnection and interoperability of data at various network levels, enabling manufacturing informatization and intelligence. The approach maps the information model to OPC UA for data storage and interaction. [15] *Liu et al.* investigate the smart manufacturing of lithium-ion batteries using an event data model for data sharing and interoperability by implementing various sensor nodes and subsystems. Therefore, different components or services in battery cell production can be flexibly integrated and included. [16] *Wessel et al.* introduce a methodology for an ontology-based traceability system in battery cell production. This system integrates various data types and sources, enabling precise tracing throughout the manufacturing process and data organization that can be adapted for similar manufacturing setups in the future. [17] *Zhou et al.* highlight the benefits of a software system based on micro-service architecture for battery cell production by using a supplementary extension scheme to enhance the existing Manufacturing Execution System (MES) without modifying it. The microservice-based approach allows for scalable and agile development, catering to personalized requirements of manufacturing enterprises. [18]

While data acquisition for battery production (at research scale) has been broadly addressed, there is no comprehensive solution for data collection with an industrial data acquisition process integrating a vast variety of machinery and devices yet. Therefore, a solution shall be developed that meets these requirements and provides an extensible platform with a user-friendly web interface to select, structure, monitor and export live production data delivered via OPC UA.

3. Approach

This paper presents a standardized framework for the structured development of a data acquisition and provision system. That encompasses capturing the current state of industrial systems, defining the target state, developing a coherent system design, and implementing the customized solution (see Figure 2). This adapted approach for tailored digitalization concepts [19] aims to optimize industrial data collection, fostering improved performance, user-friendliness and overall system optimization in research-scale battery cell production.

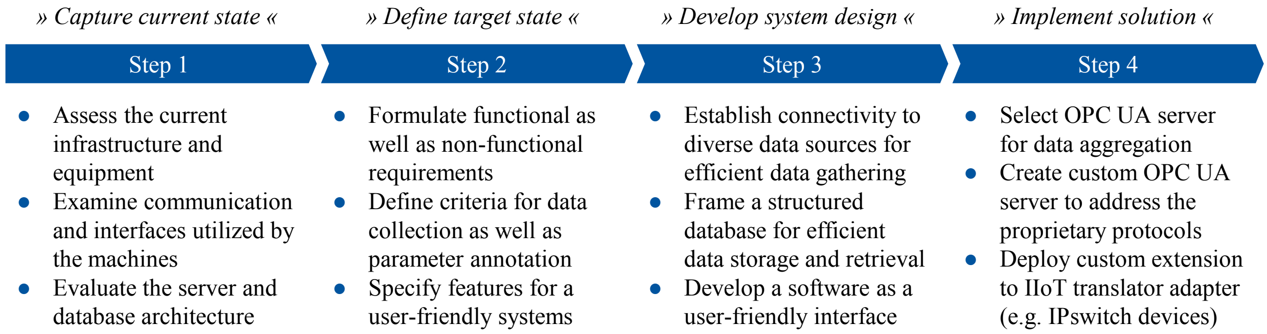


Figure 2: Approach for deriving an automated solution for data acquisition in research-scale battery production

The first step entails an in-depth evaluation of the existing infrastructure, equipment, and machinery. Through a systematic assessment of communication protocols and interfaces, insights into the setup of the current system are gained. The subsequent phase aims to formulate functional and non-functional requirements. These requirements serve as a blueprint for the planned data acquisition and provision system. For this purpose, criteria for data acquisition and parameter annotation are defined to ensure the reliability and integrity of the data. Further emphasis is placed on defining features that will improve usability and simplify the operation of the system. The next step centres on the setup of efficient mechanisms for data acquisition, storage and provision. For this purpose, a corresponding concept is developed based on the requirements from step 2. This includes a database, an OPC UA server, and a data management system. The latter represents the interface between the user and the database as well as the OPC UA server. The final step is the implementation of the concepts from step 3 in a concrete facility. This includes establishing a connection to various data sources to ensure a continuous flow of real-time information as well as selection of a suitable OPC UA server. To overcome proprietary limitations, the OPC UA server will be customized to act as a bridge between legacy systems and new devices. In addition, a custom extension of the “IIoTranslator” adapter is deployed to further improve data communication and translation between industrial components. A structured database is set up that can handle the expected volume of data and enable fast and reliable data retrieval. A user-friendly software interface is developed that facilitates intuitive interactions and system control.

4. Results

Chapter 4 delves into the current state, target state, system design, and implementation of the data collection system for lab-scale battery production research. It elaborates the infrastructure, machines, interfaces, and protocols of the CELLFAB research production line, outlines functional and non-functional requirements, and introduces the components that make up the system, including the OPC UA server, database, and the user-friendly data management system known as Production Pilot.

4.1 Actual state (Infrastructure, Machines, Interfaces, Protocols)

The CELLFAB is a research production line for the manufacturing of lithium-ion battery cells and belongs to the PEM of the RWTH Aachen University. The line is semi-automated and is used for research of production processes as well as new manufacturing technologies. A picture of the CELLFAB in which pouch cells are produced can be found in the Appendix in Figure 6. Especially in the field of laboratory lines for the production of lithium-ion battery cells, there are hardly any turnkey suppliers that cover the entire process chain from end to end. The PEM line, for example, consists of over 20 systems from more than 14 equipment suppliers. In addition, there is a variety of measurement technology and offline equipment from even more suppliers, such as a line scan camera from Isra Vision. The machines are usually connected via their PLC. The fact that the equipment is very heterogeneous is shown, among other things, by the fact that not every system has a PLC and even if it does, these are from different manufacturers or generations. For example, the Bürkle Coater has both a Siemens S7 and an S7-300. The camera integrated into the line (Isra Vision), for example, uses a measuring computer and no PLC at all. To enable the acquisition and analysis of production data, a corresponding IT infrastructure was set up at CELLFAB, which consists of a network including Ethernet cables, switches, gateways and a server on the hardware side. In addition, hardware adapters were used for the connection of equipment that does not have an Ethernet interface. An example of this is the Eirich mixer, which only has a Profibus connection. A Helmholz NETLink PRO was used to integrate this into the system. This adapter provides an Ethernet interface and thus enables communication via Internet protocol. The server represents the central unit of the system in which the data is aggregated and made available. For this purpose, all production equipment was connected to the server via Ethernet cable. On the equipment side, the CELLFAB battery production line incorporates diverse interfaces such as RS 232, Fanuc PLC, Siemens S7-300, Siemens S7-1200, and others. Some equipment, like the Coatema coating machine, has a fixed/static IP address predetermined by the manufacturer, while others can obtain an IP address through DHCP. Additionally, certain equipment supports the OPC UA protocol (e.g., Coatema or Saueressig calenders), while others utilize proprietary protocols (e.g., Binder climate chambers).

4.2 Target state (Requirements analysis)

In order to develop a user-friendly data collection system, specific requirements categorized into functional and non-functional types shown in Figure 3, are presented in this chapter. In terms of *Device & Tag Visualization*, the system should display a selection of connected devices and their available tags, including their online status, names, update counts, last known values, and timestamps. Filtering methods for tags should be provided, allowing users to create parameters from the displayed tags. For *Parameter Selection & Annotation*, the system should store a list of parameters referring to device tags, annotated with user-specified names, sampling intervals, units of measurement, and descriptions. Parameters should be grouped into machines, with the ability to add, modify, and delete machines and associated parameters. Regarding *Data Collection*, the system should query parameter values at their specified sampling intervals, collect and store the data points in a structured format, and associate each measurement with the corresponding parameter and timestamp. It should also display the status of data collection for each parameter and machine. In terms of *Data Management & Export*, the system should provide structured formats for exporting selected measurements that can be easily imported by programming languages and spreadsheet applications. It should also allow users to organize measurements into batches, defined by unique names and containing tuples of machines, start and end times. Additionally, an API may be provided to allow access to the data base.

Functional	R1: Device and Tag Visualization • Enable identification of relevant tags with convenient filtering function and live parameter values
Functional	R2: Parameter Selection and Annotation • Identify, filter and organize machine tags into descriptive and enable annotation capabilities
Functional	R3: Data Collection • Continuously record all parameters for later research into a systematic and standardized database
Functional	R4: Data Management and Export • Organize measurements into batches and export them in a standardized format (such as .csv or similar)
Non-func	R5: Usability • Offer a streamlined, device-independent user interface with a focus on relevant features and parameters
Non-func	R6: Flexibility and extensibility • Design as an extensible open-source application capable of integrating future machinery or devices

Figure 3: Overview of functional and non-functional requirements

In addition to functional requirements, non-functional requirements play a crucial role in the user experience, adaptability and reduction of training requirements. These non-functional requirements ensure that the application is user-friendly, adaptable to evolving research needs, and easily maintainable and extensible. For *usability*, the application should minimize training requirements and focus on relevant features. Interactions should be automated, and the user interface should update tag and parameter values in a timely manner. The application's user interface must be accessible over a computer network without requiring the installation of specific software on client devices. It should also minimize external dependencies and configuration requirements for quick setup. In terms of *flexibility and extensibility*, the application should be able to integrate future devices without modifying its source code. It should be simplified for improved maintainability and extensibility. The source code should be available and modifiable by user organizations, and the application should use mature, documented, and actively maintained libraries.

4.3 System design

The system to be developed, based on the requirements outlined in Chapter 4.2, consists of three essential components OPC UA Server, Database and Data Management System. The OPC UA Server functions as the data collector and aggregator. The database serves as the storage for the collected data. The data is grouped in the database according to defined parameters and machines. Data Management System is a newly developed software component. It undertakes several tasks to provide a user-friendly interface for managing the data, specifically targeted towards battery production researchers. A schematic illustration of the system can be seen in Figure 4. It serves as a user-friendly interface for managing the data within the system.

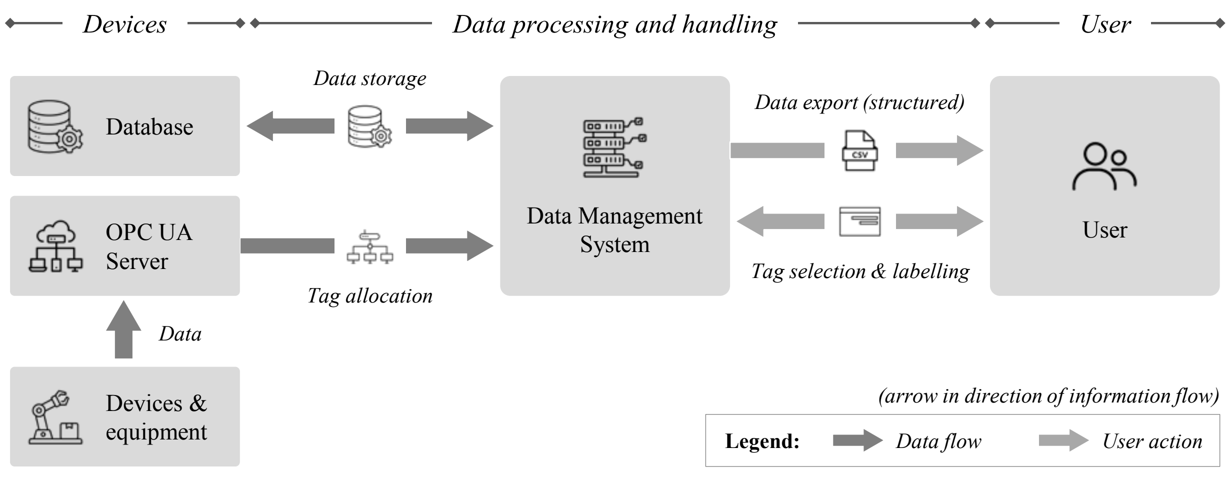


Figure 4: Overview of the structure and core functionality of the Data Management System and periphery

First, it provides an interface to manage the connected data sources via the OPC UA Server. Researchers can define and monitor these sources effectively. The data management system also enables the creation of new data points in the database and facilitates the seamless transfer of data from the OPC UA Server. Researchers can add new data points as required and ensure the continuous flow of information for analysis. Furthermore, the Data Management System offers a data provisioning feature, allowing researchers to select specific facilities, parameters, and time frames of interest. It then extracts the requested data and provides it in a convenient CSV file format. Lastly, data management system includes visualization capabilities, providing researchers with real-time insights into facility statuses and live machine data. This enhances their ability to monitor and analyse production processes effectively. Overall, the Production Pilot acts as a user-friendly, comprehensive interface for battery production researchers. It simplifies data management tasks, enables easy data selection and extraction, and enhances the efficiency of production research activities.

4.4 Implementation

Based on the requirements outlined in Chapter 4.2, a data collection, management, and provisioning system were designed. The structure and components of the system can be seen in Figure 5.

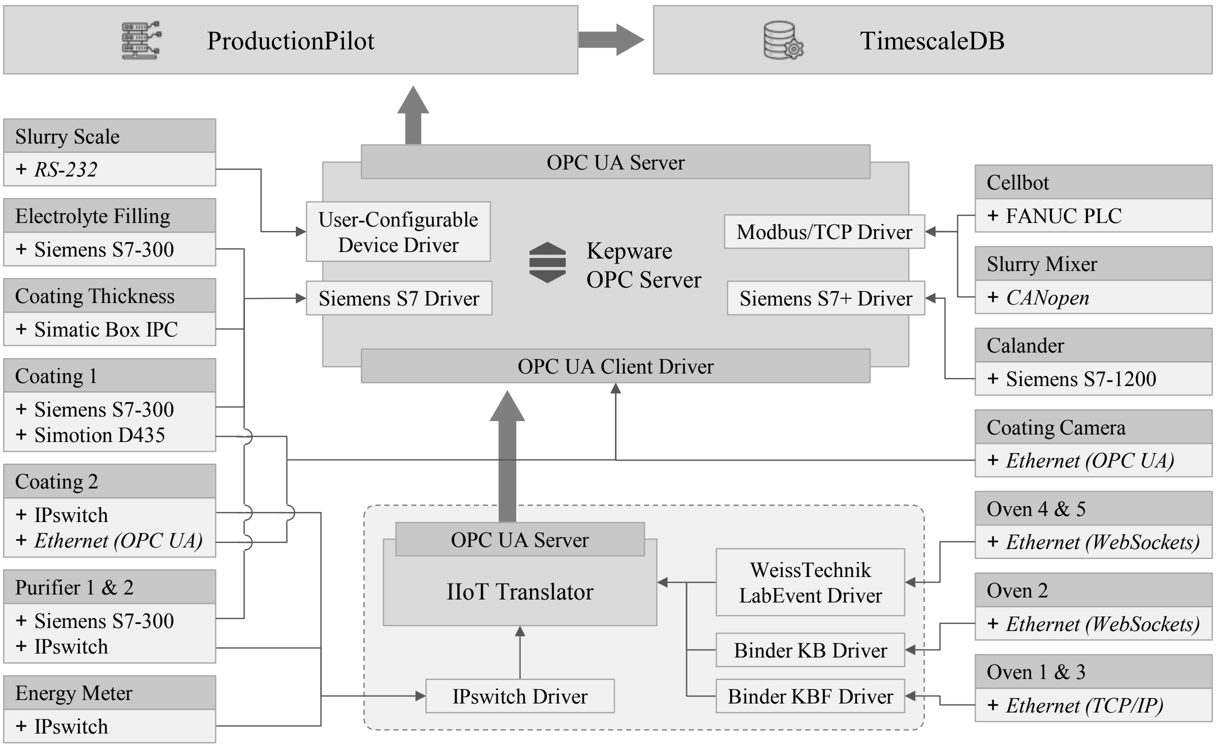


Figure 5: Data acquisition and collection architecture of the Data Management System

The machine integration, data acquisition, and aggregation were implemented using KepserverEX, a connectivity platform provided by PTC that is based on OPC technology. OPC UA was chosen as the communication protocol due to its ability to standardize data collection on the OPC UA standard. OPC UA is increasingly becoming an industry standard, enabling secure communication and has been a focal point in research projects such as DataBatt and Enlarge conducted at PEM. KepserverEX offers a wide range of drivers for machine communication, facilitating seamless data acquisition from various machines. For devices such as energy meters and climate chambers (Binder) that required specific communication interfaces, a custom-developed IIoTranslator was employed. To address the challenges associated with proprietary protocols, a custom adapter called IIoTranslator was developed. This adapter, depicted in Figure 5, functions as an OPC UA server and establishes connections with devices using their unique protocols. It then converts the data into OPC UA tags, ensuring compatibility with the OPC UA standard for a range of target devices. A suitable database was selected to store the acquired data. Factors such as data volume, data structure, and query performance were considered during the selection process. The chosen *database* provides efficient storage and retrieval capabilities for the collected data, ensuring data integrity and accessibility. As shown in Figure 5 a TimescaleDB database, was used. TimescaleDB is an extension built on PostgreSQL and is specifically designed for managing time-series data. The decision to select TimescaleDB for the application is based on the advantages it offers, particularly its foundation on PostgreSQL. This allows TimescaleDB to inherit the benefits of its parent relational database management system (RDBMS), including SQL support, scalability, and reliability. The support for standard SQL queries in TimescaleDB is expected to reduce training requirements, as SQL is widely used in the industry and developers are likely to already be familiar with this query language. Another advantage of using a widely adopted RDBMS database is the availability of support in the Java Persistence API (JPA) framework. A *data management system* was developed as the user interface for data collection and provisioning. This system serves as a centralized platform for users, specifically battery production researchers, to interact with the data acquisition system. It allows users to manage connected data sources, create new data points in the database, perform data pipelining from the OPC UA server to the database, and extract data based on user-defined criteria. Additionally, the data management system provides visualization of equipment status and real-time machine data, enhancing the user experience and facilitating efficient data exploration and analysis. The Production Pilot software acts as an OPC UA client in the system as shown in Figure 5. For data collection and aggregation, ProductionPilot has a way to select and semantically describe data points (tags). As the screenshot in Figure 7 in the appendix shows, the semantic description includes the assignment to a machine, naming, human readable explanation, and unit. In addition, the query rate for the respective tags can be determined. For direct access to the database, the program has a REST API. The REST API in ProductionPilot provides researchers with a standardized method to access stored information, ensuring compatibility and ease of integration with a future Python API. With its user-friendly design and integrated Swagger UI documentation, researchers can explore the API's functionality and perform direct testing from their web browser, facilitating efficient retrieval of data on machines, parameters, batches, and measurements. In general, ProductionPilot is web-based to allow access from different end devices with internet access. A central user administration is used to ensure that only authorized persons have access. The User Interface (UI) component of Production Pilot serves as the primary platform for users to interact with the application as can be seen in Figure 7 in the appendix. It displays the application's state and relies on various other services. The UI is designed to fulfil functional requirements such as displaying an overview of tags with their live values, implementing filtering methods for tags, allowing users to create parameters from tags, presenting a list of parameters grouped by machine for easy management, and showing a list of batches with options for creating, editing, and deleting them, along with an export functionality for downloading measurements in a user-friendly format.

5. Discussion and Conclusion

The research paper successfully demonstrates the digital connectivity of heterogeneous machine parks for research-scale battery production, showcasing the potential of advancing automation in data acquisition. By utilizing battery production as an example, the study emphasizes the importance of user-friendly systems for data acquisition, storage, and access to facilitate data-driven research. The proposed framework, exemplified by the PEM system at RWTH Aachen University, serves as a valuable blueprint for other facilities aiming to implement similar automation strategies. As future prospects, the authors suggest expanding the system to achieve end-to-end traceability for automated linking of process data with products and visualizing the data through dashboards to enhance decision-making capabilities. In addition, an extension of the system with ontologies that enable a semantic description and linking of the data is conceivable. This could simplify an automated analysis of the process data using AI. This advancement in data acquisition will undoubtedly drive improvements in battery production processes and contribute to the development of efficient and reliable energy storage solutions.

Acknowledgements

This paper is based on the research results of the projects “DataBatt” [03XP0323A]. The project is funded by the German Federal Ministry of Education and Research. The authors of this publication thank the ministry for the funding.

Appendix

Figure 6: CELLFAB Battery Cell Production Line at PEM of RWTH Aachen University

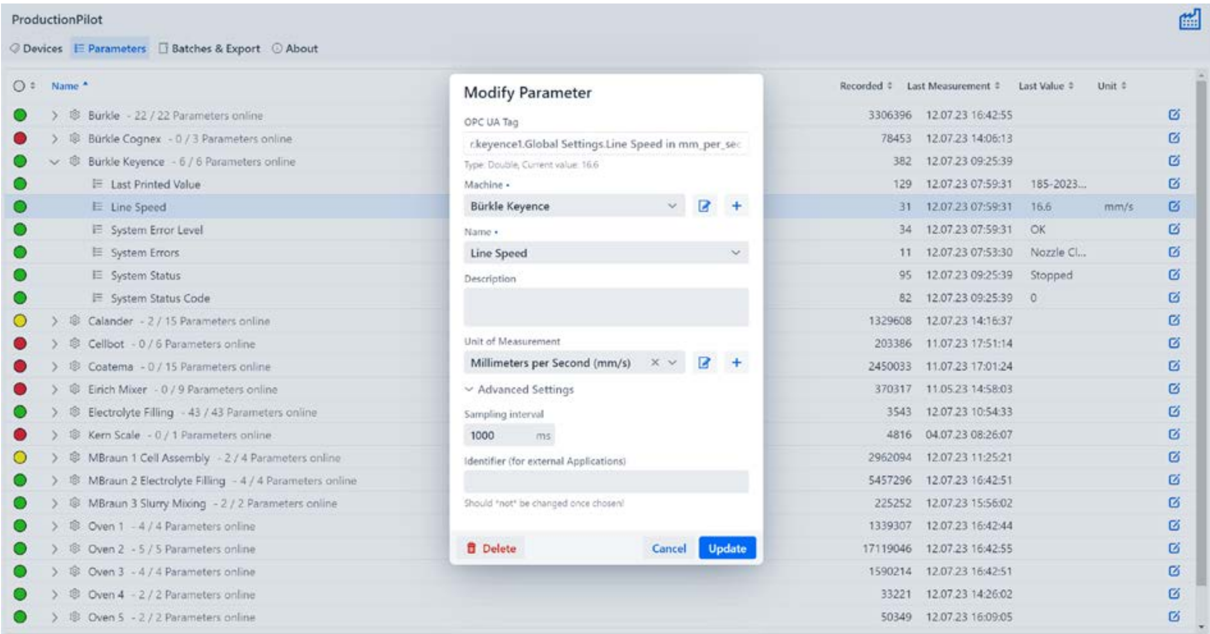


Figure 7: User interface of the Production Pilot data management system

References

[1] 2015. Industrie 4.0 und Digitale Wirtschaft: Impulse für Wachstum, Beschäftigung und Innovation. https://www.bmwk.de/Redaktion/DE/Publikationen/Industrie/industrie-4-0-und-digitale-wirtschaft.pdf%3F__blob%3DpublicationFile%26v%3D3.

[2] Braun, S., Dalibor, M., Jansen, N., Jarke, M., Koren, I., Quix, C., Rumpe, B., Wimmer, M., Wortmann, A., 2023. Engineering Digital Twins and Digital Shadows as Key Enablers for Industry 4.0, in: Vogel-Heuser, B., Wimmer, M. (Eds.), Digital Transformation. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 3–31.

[3] Becker, F., Bibow, P., Dalibor, M., Gannouni, A., Hahn, V., Hopmann, C., Jarke, M., Koren, I., Kröger, M., Lipp, J., Maibaum, J., Michael, J., Rumpe, B., Sapel, P., Schäfer, N., Schmitz, G.J., Schuh, G., Wortmann, A., 2021. A Conceptual Model for Digital Shadows in Industry and Its Application; International Conference on Conceptual Modeling. Springer, Cham, pp. 271–281.

[4] P. Drahoš, E. Kučera, O. Haffner, I. Klimo, 2018. Trends in industrial communication and OPC UA, in: 2018 Cybernetics & Informatics (K&I). 2018 Cybernetics & Informatics (K&I), pp. 1–5.

[5] Klaeger, T., Gottschall, S., Oehm, L., 2021. Data Science on Industrial Data—Today's Challenges in Brown Field Applications. Challenges 12 (1), 2.

[6] Mahnke, W., Leitner, S.-H., Damm, M., 2009. OPC Unified Architecture. Springer Berlin Heidelberg, Berlin, Heidelberg.

[7] Heimes, H.H., Kampker, A., Lienemann, C., Locke, M., Offermanns, C., Michaelis, S., Rahimzei, E., 2018. Produktionsprozess einer Lithium-Ionen-Batteriezelle /Autoren Dr.-Ing. Dipl.-Wirt.-Ing. Heiner Hans Heimes, Prof. Dr.-Ing. Achim Kampker, Christoph Lienemann, Marc Locke, Christian Offermanns [und weitere], 3. Auflage, [revidierte Ausgabe] ed. PEM der RWTH Aachen; VDMA, Aachen, Frankfurt am Main, 24 Seiten.

[8] Kampker, A., Heimes, H., Dorn, B., Clever, H., Scheibe, A., 2023. Potentials and Implementation Strategies For Flexible Battery Cell Production. Hannover : publish-Ing.

[9] Zanotto, F.M., Dominguez, D.Z., Ayerbe, E., Boyano, I., Burmeister, C., Duquesnoy, M., Eisentraeger, M., Montaño, J.F., Gallo-Bueno, A., Gold, L., Hall, F., Kaden, N., Muerkens, B., Otaegui, L., Reynier, Y., Stier, S., Thomitzek, M., Turetskyy, A., Vallin, N., Wessel, J., Xu, X., Abbasov, J., Franco, A.A., 2022. Data Specifications for Battery Manufacturing Digitalization: Current Status, Challenges, and Opportunities. Batteries & Supercaps 5 (9), e202200224.

[10] Kampker, A., Heimes, H.H., Dorn, B., Clever, H., Ludwigs, R., Li, R., Drescher, M., 2023. Concept for Digital Product Twins in Battery Cell Production. WEVJ 14 (4), 108.

[11] Dai, H.-N., Wang, H., Xu, G., Wan, J., Imran, M., 2020. Big data analytics for manufacturing internet of things: opportunities, challenges and enabling technologies. Enterprise Information Systems 14 (9-10), 1279–1303.

[12] Turetskyy, A., Thiede, S., Thomitzek, M., Drachenfels, N. von, Pape, T., Herrmann, C., 2020. Toward Data-Driven Applications in Lithium-Ion Battery Cell Manufacturing. Energy Technol. 8 (2), 1900136.

[13] Bockey, G., Kampker, A., Dorn, B., Offermanns, C., Wennemar, S., Clever, H., Sasse, K., Vienenkötter, J., Locke, M., Soldan, N., Kisseler, N., Cacciotti, P., 2022. BATTERY ATLAS 2022: SHAPING THE EUROPEAN LITHIUM-ION BATTERY INDUSTRY, 1. Auflage ed. PEM der RWTH Aachen University, Aachen, 20 pp.

[14] 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.

[15] Han, Y., Hu, Y., Wang, Y., Jia, G., Ge, C., Zhang, C., Huang, X., 2020. Research and Application of Information Model of a Lithium Ion Battery Intelligent Manufacturing Workshop Based on OPC UA. Batteries 6 (4), 52.

[16] Liu, M.-C., Chang, H.-C., Huang, C.-H., Hsu, F.-R., 2022. An implementation of industrial IoT: a case study in lithium-ion battery pack and assembly. Int J Adv Manuf Technol 123 (9-10), 3361–3375.

[17] Wessel, J., Turetskyy, A., Wojahn, O., Abraham, T., Herrmann, C., 2021. Ontology-based Traceability System for Interoperable Data Acquisition in Battery Cell Manufacturing. Procedia CIRP 104, 1215–1220.

[18] J. Zhou, L. Li, N. Zhou, 2019. Research and Application of Battery Production Data Management System Based on Microservice, in: 2019 IEEE 9th International Conference on Electronics Information and Emergency Communication (ICEIEC), pp. 1–5.

[19] Haghi, S., Summer, A., Bauerschmidt, P., Daub, R., 2022. Tailored Digitalization in Electrode Manufacturing: The Backbone of Smart Lithium-Ion Battery Cell Production. Energy Technol. 10 (10), 2200657.

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.*

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.*

Robert Ludwigs *(*1993) is research assistant at the Chair of Production Engineering of E-Mobility Components (PEM) at RWTH Aachen University and head of the technology field Electromobility and Data Science since 2022. He studied mechanical engineering with a specialization in production engineering 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 with a specialization in production engineering at RWTH Aachen University.*

Felix Kirchmann *(*1995) is a student research assistant at the Chair of Production Engineering of E-Mobility Components (PEM) at RWTH Aachen University digitizing the battery production process. He recently earned his master's degree in computer science at RWTH Aachen University.*

CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
CPSL 2023-2

5th Conference on Production Systems and Logistics

DesignChain: Process Automation From Recording Of Customer Requirements To Production Release

Lars Rödel[1], Gregor Müller[1], Jonas Krebs[1], Timo Denner[1] and Thomas Bauernhansl[1,2]

[1]*Fraunhofer Institute for Manufacturing Engineering and Automation IPA, Nobelstr. 12, 70569 Stuttgart, Germany*
[2]*Institue of Industrial Manufacturing and Management IFF, Allmandring 35, 70569 Stuttgart, Germany*

Abstract

Growing price pressure due to an increasing number of global suppliers, increasing individualization of products and ever-shorter development cycles are challenges facing the engineering industry. In this context, mass personalization represents the customized production of customer products with batch size one at the low unit costs of mass production.

The possibilities of digitalization and automation of technical order processing open up the opportunity for companies to significantly reduce their complexity costs and lead times and thus increase their competitiveness. Many companies already use a range of simulation tools and configuration solutions but only as stand-alones. Often, the expert knowledge of employees is hidden in "knowledge silos" and is rarely networked across processes.

The concept "DesignChain" will address these challenges by automating and digitalizing technical process planning from recording customer requirements to releasing a product to the shop floor. Configurators within DesignChain allow for mapping variant-rich products. This transformation of customer requirements into product properties makes it possible to generate even complex CAD models, such as models for large-scale equipment based on specific rules. An automated CAx chain will help to digitally transfer production-relevant documents to the shop floor for parts fabrication. This process, which can be fully automated, allows for the customized creation of variants based on current approval statuses.

Keywords

DesignChain; mass personalization; configurator; CAD; automation; CAx; process chain; CAM; technical process planning, digitalization

1. Introduction

The advent of modern technology and changing consumer preferences have led to an increased demand for personalized products. Customers now seek products that reflect their unique tastes, preferences, and requirements. Nowadays, companies have to keep the balance between offering products tailored to customer needs and manufacturing products quickly and cost-effectively. Achieving these goals poses a challenge to production as such and to the preparation of production – especially in technical process planning. Manual activities in indirect areas of the order processing chain lead to long lead times and high costs for customized products [1]. Employees across departments and functions spend a large proportion of their working day searching for the right information. This is mainly due to the insufficient coordination of cross-departmental processes. This paper explores what role a DesignChain can play in the technical order processing of customized products. It examines how the successful integration of DesignChain can enhance the efficiency of order processing and customization ultimately lead to improved customer satisfaction.

DOI: https://doi.org/10.15488/15261
ISSN: 2701-6277
publish-Ing.

1.1 Initial situation

The procedure for processing orders is heavily dependent on robust technical process planning, which includes designing individual variants, creating bills of material, as well as numerical control (NC) programs for machine tools. These are manual tasks that can hardly be tailored to batch size one. This means that, if the case arises, separate individual designs, parts lists and NC codes must be created for each variant. In the toolmaking industry, for instance, the continuing automation of production brings about that more employees are distributed to processes carried out in upstream production stages [2]. At the same time, 29% of design work is outsourced due to a lack of capacity [2]. This means that production preparation requires more and more time while the necessary specialized staff is missing or not available in sufficient numbers. This leads to the following problem statement:

How can the production preparation effort be reduced as the degree of customization continues to increase?

1.2 Possible solutions

Solutions are already available that use digitalization and automation tools for addressing the challenge of skilled workers shortage in production preparation:

1) (Product) configurators for translating customer requirements into technical specifications [3]; [4],

2) Automation of CAD programs for rule-based modification of designs [5], and

3) Computer-aided manufacturing (CAM) programs for simulating machining operations and the associated derivation of NC programs [6].

The process chain is typically not end-to-end and, thus, the IT landscape is very heterogeneous.

2. State of the art

2.1 Mass Personalization

The proliferation of e-commerce platforms and advancements in manufacturing technologies provides better access for customers to unique and customizable products. From clothing and accessories to home decor and electronics, personalized options are becoming increasingly prevalent across various industries. Customization allows customers to feel a sense of ownership and connection with their products. It enables businesses to create a unique selling proposition, differentiate themselves from competitors, and foster stronger customer loyalty. As a result, companies must adapt their operations to meet the demands of individualization effectively. This trend can be observed both in the end customer segment, and in the business-to-business (B2B) segment. Even complex industrial goods are increasingly required to adapt to the customer's individual circumstances.

Accordingly, mass personalization calls for a paradigm shift from "production to stock" to "production to order" [7]. This paradigm shift must be accomplished in the order processing chain, which will be discussed in the following paragraph.

2.2 Order processing

Order processing refers to the process of managing customer orders, from order lead to delivery of the product or service to the customer (lead to cash) [8]. Thus, order processing is a typical end-to-end process. It includes planning, monitoring, and controlling orders to ensure they are completed on time and within budget. Order processing also involves communication with customers, coordination of suppliers, and management of contracts and financial aspects. The typical handling of a customer order covers three process phases: Clarification and release, procurement and production, and shipment and completion [8]. In a commercial environment where personalization plays a major role, make-to-stock processing is rarely applicable. Products and/or semi-finished products cannot be kept in stock for specific individualization. These use cases often require to provide a certain amount of technical functions in the order processing.

The Y-CIM model according to Scheer illustrates how logistical and technical tasks in a production company interact [9]. The model seeks to represent functions in the order of sequence, indicating details down to the level of data and function model [9]. It thus provides a framework for the systems used and how they are connected. The left branch consists of the logistic tasks for production planning and control. The right branch points out the typical engineering process chain. The model assumes that the planning and implementation phase only begins after the design phase.

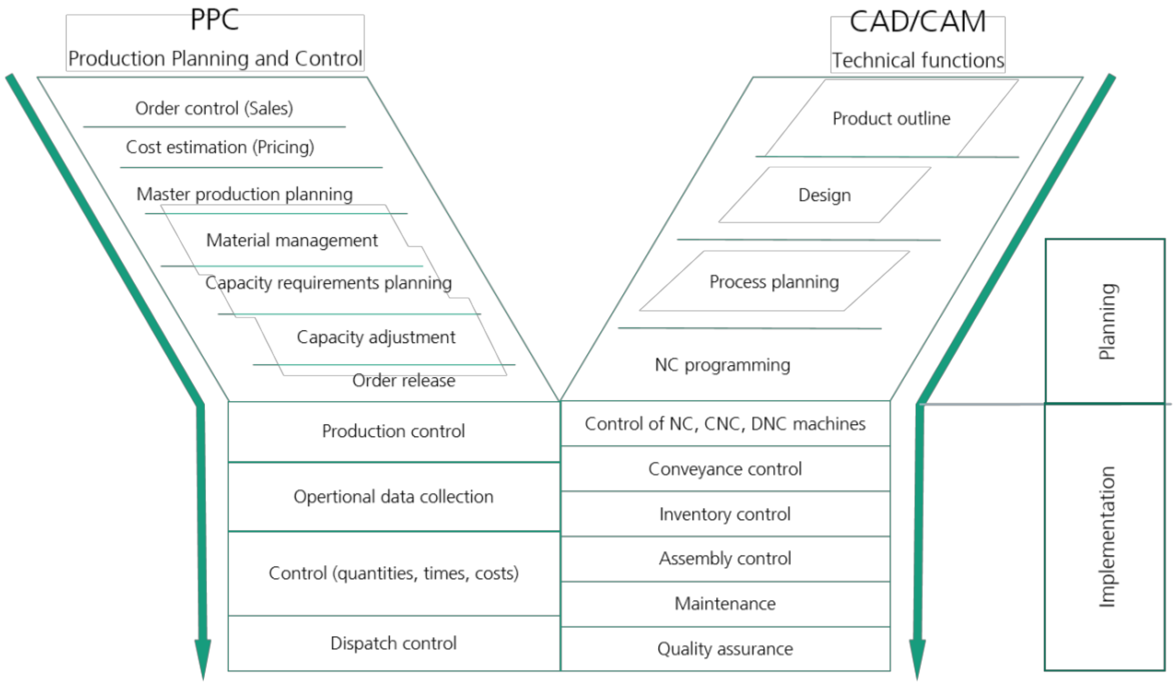


Figure 1: Information system in production, in accordance with [9]

So far, product configurator software has primarily been utilized as commercial sales configurators within order processing systems [10]. These configurators effectively handle products composed solely of pre-designed components. However, certain products require a combination of pre-designed, parametric, and customizable elements, such as specialty valves used in the process industry. In such cases, the engineering phase necessitates support both from a configurator and from other applications, such as CAD/CAM/CAE tools to ensure the seamless creation of a fully functional end product. Since these software depend heavily on user input, which in turn depends heavily on the business context, they are mainly operated by humans.

2.3 Technical process planning

The current state of the art in technical process planning for manufacturing preparation is to use 3D modelling and simulation-based planning software [11]. These methods allow processes to be virtually tested and optimized before being implemented in production. This can lead to greater efficiency, lower costs and shorter time to market or time to customer.

State of the art in supporting the technical process planning of order processing are computer-aided software. The goal is to improve process efficiency and accuracy by automating manual tasks. The technologies and methods mainly used in work preparation include [12]:

CAD (Computer-Aided Design): CAD software is used to create digital models of products. These models are used to create a virtual production environment in which production processes can be simulated and optimized. (E.g.: Autodesk Inventor, Dassault Systèmes SolidWorks, Siemens NX and many more)

CAM (Computer-Aided Manufacturing): CAM software is used to plan and control production processes. The software automatically generates work instructions and machine programs that control the production process. (E.g.: HCL Technologies CAMWorks, Dassault Systèmes SolidWorks CAM, Mastercam and many more)

PDM (Product Data Management) software manages and organizes production data. It provides a central source for storing and managing information about the product, including design data, bills of materials, work instructions, and manufacturing processes. (E.g.: Autodesk Vault, Siemens Teamcenter, Parametric Technology GmbH Windchill and many more)

ERP (Enterprise Resource Planning) software collects and integrates data from different business areas such as production, purchasing, sales and finance. These software enable seamless communication and coordination between the different departments. In the technical context they are mainly used for managing and/or creating work plans. (E.g.: SAP, Microsoft Dynamics NAV, Infor, proALPHA and many more)

Further developments in the field of technical process planning for manufacturing preparation include the integration of artificial intelligence (AI) and machine learning [15]. These technologies enable processes to be predicted and optimized even more accurately. In addition, AI systems can make decisions on their own and automatically adjust processes to achieve optimal results. Current research in this field is mainly related to deriving workflow sequences and work plans.

The general state of the art in technical process planning enables greater efficiency, flexibility and quality in manufacturing preparation. Using 3D modelling, simulation-based planning, advanced software solutions and AI enables companies to respond quickly to changes in the market and remain competitive.

3. Definition and components of the DesignChain

DesignChain describes a digital, automated and seamless technical end-to-end process chain from the recording of customer requirements to the handover to the shop floor. In its final stage of maturity, it will fully autonomously convert technical customer requirements into the relevant information of the product needed for production – still, it is currently more of a vision than a feasible solution. However, similar to the various levels of automating the driving functions in automobiles, DesignChain can already offer benefits even at lower levels of autonomy.

Current implementation ranges from systematically recording customer requirements using company-specific workflows to transferring a validated NC code to production. The focus lies on methodically organizing and controlling features, addressing gaps in the CAx chain, and discovering potential opportunities for cost savings [16]. In the Y-CIM model, DesignChain is intended to bring the upper "branches" of the Y closer together. Like a zipper pulled from the bottom to the top, the branches can be mutually integrated. In addition, DesignChain further extends the Y-CIM model. In the Y-CIM model, the perspective of automation and end-to-end integration is only considered to a limited extent. Looking at typical CIM process chains in companies today, it appears that only few of them are automated. Accordingly, continuous automation of process execution, availability of information and provision of information is not given. Thus the term “DesignChain” is used if there is a need for continuous automation of technical process planning.

DesignChain consists of five major building blocks:

1) Product configuration: Query and transfer of individual technical customer requirements into technical parameters and interpretation of the corresponding product structure according to customer requirements. Current implementations (e.g. Configure-Price-Quote-Software (CPQ)) focus on quick quoting and lack integration into product design. As a result, the scope of variants is limited, since the focus is clearly on customer guidance.
2) Quotation costing: In most cases, relevant information for the quotation process can already be derived from the customer configuration. If this is insufficient, the following modules, e.g., automated model construction, can add further detail. This process step provides an interface to the activities of business order processing. Currently, rigid cost rates are usually used, which estimate the cost of producing the component in advance for example on the basis of the volume or surface area.
3) Automated model construction: The technical planning and derivation of machine paths or even manual assembly processes, requires the creation of a 3D CAD model. With the set of rules for the company's product portfolio, these models can be built up in the CAD software based on rules and adapted to the customer-specific configuration derived in process step one [13]. These implementations still lack an end-to-end integration into the business aspects of a company. They require a high degree of human control and, by automating the technical task, are also bound by the rules established in the implementation.
4) Automated preparation of manufacturing information: The information relevant to manufacturing is derived from the 3D model, for example, the generation of an NC code. However, the 3D model can also be enriched with further information such as measuring points for an automated on-machine inspection [14]. Current implementations, with the help of feature and macro technologies, allow programming know-how to be saved for reuse or later application. This requires a predetermination of the manufacturing features already in the design, so that the CAM software can interpret them via standardized product and manufacturing information embedded in the 3D-model.
5) Process control: A higher-level process control system helps to connect, the individual systems in a chain. Depending on the company's internal requirements, this allows for considering the established process sequences. Optimal process sequences for the display of additional interfaces or output formats, e.g., for a sales-optimized 3D model, can also be integrated into the process chain. In addition to the automated model construction, the highest degree of individualization in DesignChain can be found in setting up process control. Furthermore, the process control is responsible for facilitating the information exchange through for instance XML- (Extensible Markup Language) or JSON-files (JavaScript Object Notation) and save them temporarily for further use (for example by the CAD-System) or save them long-term in the database (PDM). Current implementations of process control mainly focus on business processes. An extension to technical processes therefore means dealing with technical parameters and information.

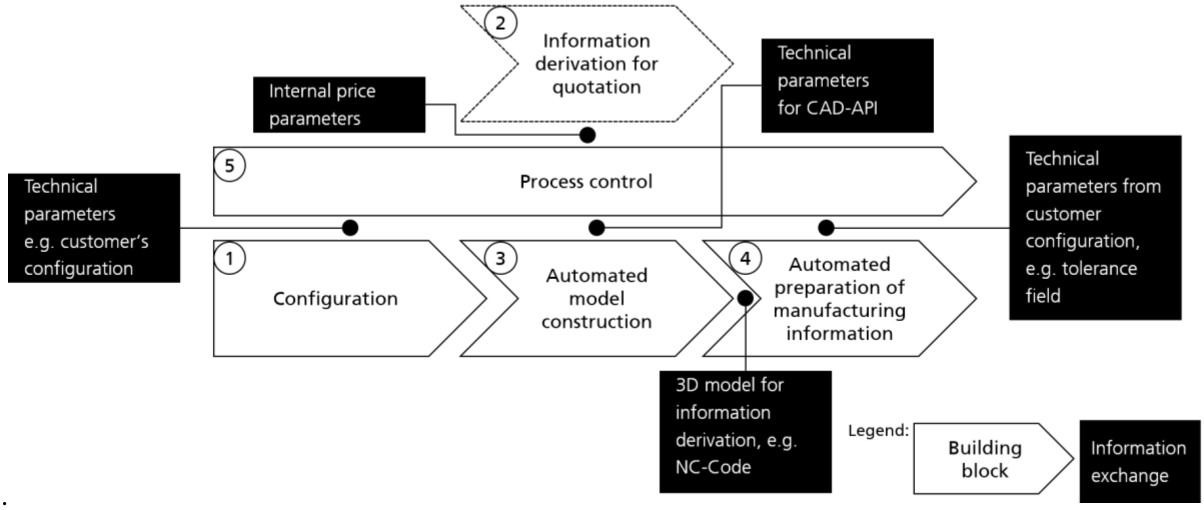


Figure 2: Building blocks of the DesignChain

4. Practical application

The first use cases in the industry are already showing promising results. As an example, with the help of DesignChain, the effort required for model creation in design in the construction industry could be significantly reduced. Now, individual assemblies are generated within a few minutes. With a user from the toolmaking industry, it was possible to build up a vision like the one shown in Figure 3. The area outlined in Green thus sets the limits for the scope of DesignChain and shows the interfaces from the company context. This means that steps one to three are within scope, and steps four to seven indicate possible interfaces to DesignChain. Step four represents the automated production of parts already designed and planned in DesignChain. The fifth step points out data acquisition on the shop floor. The data collected there can be used, for example to better coordinate order processing but also to offer added value to the customer, for instance through capacity-checked delivery dates. Step six, packaging and logistics, and step seven, the product delivery, complete the end-to-end customer-to-customer process.

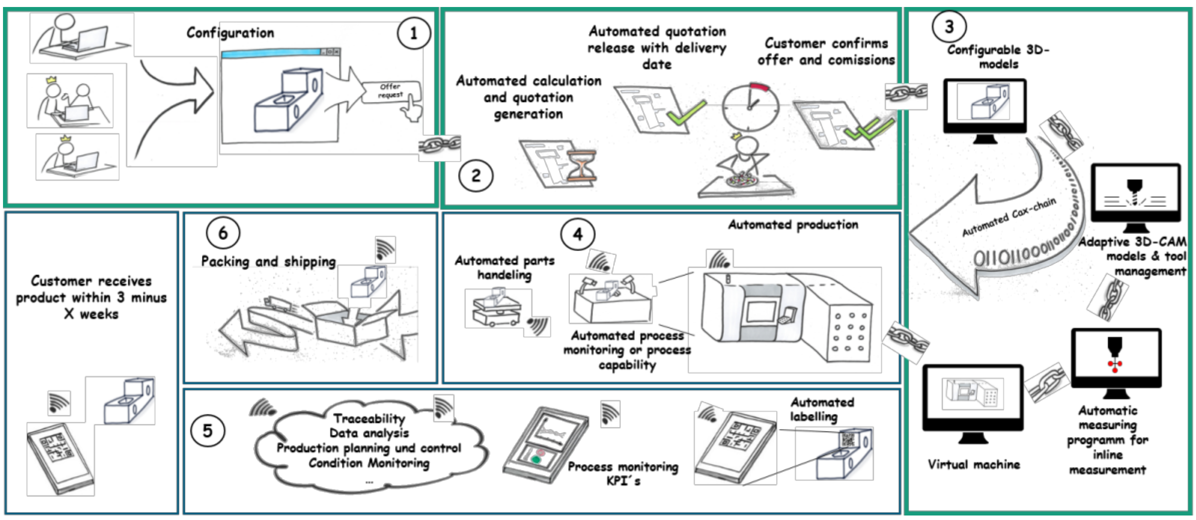


Figure 3: Implementation of an end-to-end process based on the example of Design-to-Order aimed at automating order processing [16]

In order to implement such a vision suitably into the corporate context, it is necessary to integrate the existing IT systems. The typical process chain of DesignChain utilizes the existing software in the company for technical process planning: CAD (2), CAM (3), PDM (4) and ERP (5). This process chain can be exemplified on a job shop for milled parts. First, customers enter their specific requirements for the desired milled part in the customer configurator (1). Assuming that the contract manufacturer does not accept externally created 3D models, customer requirements must be translated into technical parameters. As an example, the desired surface finish in conjunction with materiality may require specific cutting parameters. These technical parameters and customer requirements are stored in the PDM (4) with clear reference to the customer order. In the next step, the 3D model construction starts. The parameters are used to control the CAD (2) software, based on rules. The 3D model can be enriched using customer parameters, e.g., a tolerance class. The 3D model is then saved in the PDM (4) software and a bill of material (BOM) is derived. Then, the BOM can be transferred to the ERP (5) software via interface. To get the necessary information on the shop floor (6), machine paths and tools, for example are derived in the CAM (3) software. For this purpose, the 3D model is simulated in the CAM (3) software and enriched, for instance with the tool information from the ERP (5) software. Thus, at the end of the process chain, all information is available for production release and for manufacturing the product in the machine tool.

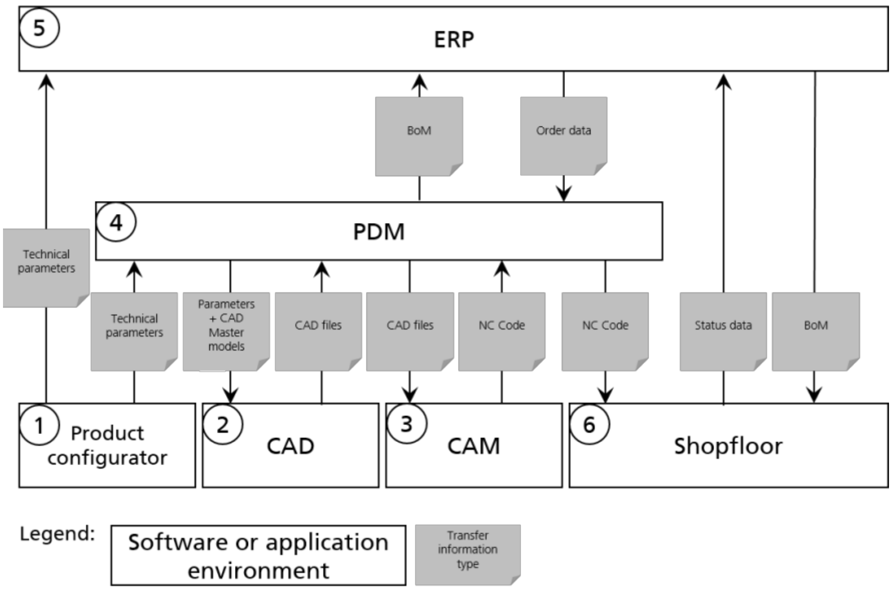


Figure 4: Typical IT-landscape in which DesignChain can be set up

With DesignChain, the functional areas are better linked, gaps in the CAx chain are closed, and potential cost savings are transparently displayed. Advantages of an implemented DesignChain include (1.) shorter throughput times, (2.) reduced effort, also in the indirect departments of the company (3) optimized information flow and (4) flawlessness of information generation. For a deeper understanding, the following paragraph elaborates on the benefits of DesignChain.

5. Key benefits of the DesignChain

By integrating DesignChain into their production, companies can streamline order processing and production processes. By consequently leveraging existing technologies such as computer-aided design (CAD), computer-aided manufacturing (CAM), and enterprise resource planning (ERP) software, businesses can efficiently manage customization requests, optimize production schedules, and reduce lead times. The benefits of DesignChain, are elaborated below:

1) DesignChain caters to individual customer needs and fosters higher levels of customer satisfaction. By offering personalized products, businesses can meet specific customer needs and preferences. Satisfied customers are more likely to become loyal brand advocates, leading to increased customer retention, positive word-of-mouth, and long-term business success.

2) DesignChain enables faster production throughput times, thereby improving the efficiency of order processing of customized products. As both technical process planning and design departments use DesignChain to derive information automatically, they move closer together, eliminating lengthy information searches.
3) DesignChain enables the potential for human error to be avoided in the provision of information through digital and automatic process flow. This ensures error-free information generation and transfer, even in hectic project business or when processing large amounts of data.
4) DesignChain automates recurring, previously manual processes in production preparation and thus relieves employees of recurring manual tasks. This enables information provision and derivation of variants with batch size one.
5) DesignChain uses the systems available in a company (CAD, CAM, PDM, etc.) to get started with automation and end-to-end consistency. This means these systems are still open for manual operations, and Engineer-to-Order (ETO) development processes can be performed in parallel and the product portfolio is further developed.

As elaborated above a potential user group that benefits most is the design department in a company. Recurring tasks customizing a product design can be adopted by the system and executed without errors. The error-free nature of the system also plays a major role for the work preparation personnel, who are also key users.

6. Discussion

Implementing DesignChain involves overcoming various challenges, such as managing a diverse range of customer preferences, ensuring the scalability of production processes, and coordinating multiple stakeholders effectively. Businesses must invest in robust systems, technologies, and training to address these challenges and seize the opportunities presented by customization. Especially in small and medium enterprises it is challenging to implement the necessary IT landscape. The development of DesignChain is also associated with a comparatively high initial effort. These frontloaded tasks consist of developing a set of rules, automating the individual systems and establishing integration - in the sense of a digitalized, automated end-to-end process. It remains to be seen how this initialization can be structured best and how, with the establishment of a digital and automated chain, a simple product structure can be created. So it is evident that DesignChain can offer a particularly large benefit when as many variants as possible run through DesignChain in order to offset the initial effort. In addition, another potential that has not been considered so far is to extend DesignChain to assembly and also have these scopes planned by an automated and digital chain.

7. Conclusion

Integrating DesignChain into order processing requires streamlining communication and collaboration between different departments and stakeholders. This integration enables efficient handling of customization requests, accurate production planning, and seamless coordination between design, manufacturing, and delivery processes. DesignChain ties in with the Y-CIM model, even if the business perspective has not been considered enough so far. Thus, DesignChain extends the established Y-CIM-Model and allows businesses to translate customer preferences into tangible products in a digitalized, automated and end-to-end integrated way. By involving customers at an early stage, companies can gather valuable insights, refine product concepts, and can ensure that the final product aligns with individual needs. This collaborative approach promotes innovation and enhances the overall customer experience. In conclusion, DesignChain serves as a catalyst for facilitating order processing of customized products. By effectively integrating and leveraging the DesignChain tool, businesses can meet the growing demand for customization. Thus, through the DesignChain production preparation effort can be reduced significantly as the degree of customization continues to increase.

References

[1] McKinsey & Company, 2019. The future of personalization – and how to get ready for it, last accessed on July 11th 2023, https://www.mckinsey.com/capabilities/growth-marketing-and-sales/our-insights/the-future-of-personalization-and-how-to-get-ready-for-it

[2] Boos, Wolfgang; Arntz, Kristian; Johannsen, Lars; Prümmler, Marcel; Wolbrink; Moritz; Wilms, Marcel; Horstkotte, Rainer, 2017. Erfolgreich Automatisieren im Werkzeugbau, Fraunhofer IPT, last accessed on July 11th 2023, https://www.ipt.fraunhofer.de/content/dam/ipt/de/documents/Studien/Studie_Automatisieren%20im%20Werkzeugbau.pdf

[3] Aldanondo, M., Vareilles, E. Configuration for mass customization: how to extend product configuration towards requirements and process configuration. J Intell Manuf 19, 521–535 (2008). https://doi.org/10.1007/s10845-008-0135-z

[4] Zhang, Linda L., 2014. Product configuration: a review of the state-of-the-art and future research. International Journal of Production Research 52 (21), S. 6381–6398 DOI: 10.1080/00207543.2014.942012

[5] Kreis, Alexander & Hirz, Mario. (2020). CAD-Automation in Automotive Development – Potentials, Limits and Challenges. 56-60. 10.14733/cadconfP.2020.56-60.

[6] Q. Huiying, "Research on NC Simulation Technology Integrating CAD/CAM/CAPP," 2014 7th International Conference on Intelligent Computation Technology and Automation, Changsha, China, 2014, pp. 551-554, doi: 10.1109/ICICTA.2014.139

[7] Tseng, Mitchell M., Yue Wang, Roger J. Jiao. (2017) Mass Customization. In: The International Academy for Produ, Laperrière L., Reinhart G. (eds) CIRP Encyclopedia of Production Engineering. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-35950-7_16701-3

[8] Wiendahl, Hans-Hermann, Fraunhofer IPA (2022) Schlanke, digitalisierte Auftragsabwicklung, Webinar (15.09. – 17.11.2022), Stuttgart

[9] Scheer, August-Wilhelm, 1994. CIM Computer Integrated Manufacturing: Towards the Factory of the Future. 3rd ed. Berlin, Heidelberg: Springer Berlin / Heidelberg. ISBN: 9783642789885.

[10] Yu Yang, Xiaodong Zhang, Fei Liu, Qiu Xie, An internet-based product customization system for CIM, Robotics and Computer-Integrated Manufacturing, Volume 21, Issue 2, 2005, Pages 109-118, ISSN 0736-5845, https://doi.org/10.1016/j.rcim.2004.06.002.

[11] Wiendahl, HH., Denner, T. (2020). Arbeitsplanung. In: Bauernhansl, T. (eds) Fabrikbetriebslehre 1. Springer Vieweg, Berlin, Heidelberg. https://doi.org/10.1007/978-3-662-44538-9_6

[12] Eversheim, Walter, 2002. Organisation in der Produktionstechnik 3: Arbeitsvorbereitung. 4th Edition, Berlin, Heidelberg: Springer. ISBN: 9783642563362

[13] Dassault Systèmes, 2011.Whitepaper: Kosteneinsparungen und höhere Rendite dank Konstruktions-Automatisierung.URL: https://www.solidworks.com/de/media/white-paper-using-design-automation-reduce-costs-increase-profitability , last accessed on 14.09.2023

[14] Krebs, J.; Roedel, L.; Mueller, G.: Computer Aided Inspection Planning For Automation Of On-Machine Inspection Of Customised Milling Parts. In: Herberger, D.; Hübner, M.; Stich, V. (Eds.): Proceedings of the Conference on Production Systems and Logistics: CPSL 2023 - 1. Hannover: publish-Ing., 2023, S. 758-766. DOI: https://doi.org/10.15488/13495

[15] Zhao, C., Melkote, S.N. Learning the manufacturing capabilities of machining and finishing processes using a deep neural network model. J Intell Manuf (2023). https://doi.org/10.1007/s10845-023-02134-z

[16] Fraunhofer IPA, 2023, DesignChain - Automating the CAx process chain, last accessed on July 16th 2023, https://www.ipa.fraunhofer.de/en/expertise/factory-planning-and-production-management/planning-manufacturing-systems/designchain_en.html

Biography

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.

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.

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.

Timo Denner (*1968) has been group leader of manufacturing systems planning at the Fraunhofer Institute for Manufacturing Engineering and Automation IPA in Stuttgart since 2002. His research focuses on requirements-based cost-optimal manufacturing concepts and implementations.

Prof. Dr.-Ing. Thomas Bauernhansl (*1969) has been director of the Fraunhofer Institute for Manufacturing Engineering and Automation IPA in Stuttgart since September 2011 as well as director of the Institute of Industrial Manufacturing and Management IFF at the University of Stuttgart. His research focuses on digital and biological transformation, production organization, factory planning, automation and robotics.

5th Conference on Production Systems and Logistics

Towards a Service-Oriented Architecture for Production Planning and Control: A Comprehensive Review and Novel Approach

Sebastian Behrendt[1], Florian Stamer[1], Marvin Carl May[1] , Gisela Lanza[1]
[1]*wbk Institute of Produciton Science, Karlsruhe Institute of Technology*

Abstract

The trends of shorter product lifecycles, customized products, and volatile market environments require manufacturers to reconfigure their production increasingly frequent to maintain competitiveness and customer satisfaction. More frequent reconfigurations, however, are linked to increased efforts in production planning and control (PPC). This poses a challenge for manufacturers, especially in regard of demographic change and shortage of qualified labour, since many tasks in PPC are performed manually by domain experts. Following the paradigm of software-defined manufacturing, this paper targets to enable a higher degree of automation and interoperability in PPC by applying the concepts of service-oriented architecture. As a result, production planners are empowered to orchestrate tasks in PPC without consideration of underlying implementation details. At first, it is investigated how tasks in PPC can be represented as services with the aim of encapsulation and reusability. Secondly, a software architecture based on asset administration shells is presented that allows connection to production data sources and enables integration and usage of such PPC services. In this sense, an approach for mapping asset administrations shells to OpenAPI Specifications is proposed for interoperable and semantic integration of existing services and legacy systems. Lastly, challenges and potential solutions for data integration are discussed considering the present heterogeneity of data sources in manufacturing.

Keywords

Service-oriented production; asset administration shell; service-oriented architecture; interoperability; Industry4.0

1. Introduction

The integration of modern information technologies into production systems, as proposed by concepts such as Industry4.0 [1], promises to be an answer to handle the increasing volatility in markets [2,3] and the need for more efficient, automated and adaptive manufacturing [4]. Although digitalization enables the continuous exchange of information between IT-systems and the shop floor for monitoring or control purposes, many processes in production planning and control (PPC) are still performed either manually or with software that only supports proprietary interfaces and often lacks automation and integration capabilities [5]. The trend towards more volatile, uncertain, complex, and ambiguous markets, as summarized by the VUCA world [6], emphasizes reliable planning as a crucial factor to get into production quickly, especially for low-volume products and complex product portfolios. Concepts such as reconfigurable manufacturing systems enable frequent and responsive adaption of system structure and logic to efficiently meet current customer demand [7,8] . However, frequent reconfigurations also increase the effort in PPC, motivating for digitalization and automation in this domain [9,10].

DOI: https://doi.org/10.15488/15271
ISSN: 2701-6277

In this sense, technological advances show potential for developing and integrating software solutions for planning and control of manufacturing systems that can interact in an interoperable way with each other and with the manufacturing system itself [11,12]. The availability of large amounts of data from a digitized shop floor enable the use of algorithms for analysis and planning, such as realistic simulation models for prognosis and analysis [13], optimization tools for capacity planning or layout planning [14], and machine learning for production control [15,16]. Although existing solutions could serve as components for a more automated and data-driven PPC, integrating them into company software architectures for automation poses a challenge in terms of data integration and algorithmic orchestration due to the variety of data sources [17] and the complexity of PPC [18,19]. To date, such algorithms and models are mostly implemented for specific use cases with proprietary tools and lack integration and generalization capabilities [20,21,5]. For example, material flow simulation models of manufacturing systems are mostly modelled by experts during production planning with manual parameter input and are not maintained and used over the life cycle of the later realized manufacturing system [13].

There have been great improvements in interoperable data exchange through technologies such as OPC UA, MQTT, or the asset administration shell (AAS). However, in sight of the volume and variety of data sources in manufacturing [17], a software architecture is needed that is manageable at large scales and prevents data silos and incompatibilities. The software-defined manufacturing (SDM) paradigm suggests to decouple software applications from the underlying manufacturing infrastructure through a control layer that simplifies the orchestration of information flows by abstraction, virtualization, and interface unification [22,23]. Developing solutions for tasks in PPC based on unified interfaces either through standardization or integration promises to increase their reusability and interoperability.

A related principle that is widely promoted in the areas of Smart Manufacturing [24], Cyber-physical Production Systems (CPPS) [11], Industry4.0 [1] or Cloud Manufacturing [25] is service-orientation. It is already the leading principle in many technologies such as OPC UA or web services and has emerged as a suitable architecture for a highly scalable orchestration of software systems [26]. In a software-oriented architecture (SOA), software components, i.e. services, are self-contained and modular units of functionality that communicate via standardized interfaces [27]. Due to the separation of interface and implementation, these services can interact with each other in complex scenarios without the need for mutual understanding of their underlying functionality [27]. The capabilities of SOA in terms of adaption, abstraction, and integration make it a suitable architecture to realize SDM in the domain of PPC. Therefore, we investigate how the principles of service-orientation can be applied to tasks in PPC to improve their potential for reusability, automation, and integration in an appropriate software architecture.

In the following, Section 2 reviews existing approaches in the literature that aim at digitalization of PPC and assesses their degree of service-orientation and integration capabilities. In Section 3, we will present an approach that aims at the servitization of PPC by describing PPC tasks as services with consideration of data integration theory. Moreover, we present a software architecture that considers SOA, SDM principles, and state-of-the-art technologies for a flexible, automated and data-based PPC. Thereby, special attention is given to the integration of existing legacy systems in manufacturing. Finally, Section 4 concludes the paper and provides an outlook for further research.

2. Related work

The goal of SOA is to organize networks of software systems in large scales while maintaining a flexible and maintainable system that enables interoperable data exchange between components [26]. According to Valipour et al. [27], services comprise of 3 components, i.e. protocol, interface, and implementation, and must implement the following 6 characteristics in SOA:

- **Discoverable and dynamically bound**: services can be discovered by consumers in registries

- **Self-contained and modular**: services are modular components that encapsulate specific functionality
- **Interoperable**: services are able to communicate and interact with each other using standard protocols and data formats
- **Loosely coupled**: a low and well-known number of dependencies between service consumers and service providers
- **Location transparent**: location of services is provided by registries at runtime allowing for simple load balancing
- **Composable**: services can be combined to applications or orchestrations due to their modular structure.

In order to evaluate existing concepts and approaches for digital planning and control of manufacturing systems, we classify their degree of service orientation based on the fulfilment of the aforementioned design principles of SOA. The literature review was thereby conducted based on the methodology of Mayring [28].

Services provide a distinct description how to interact with them by specifying their interface and protocol. The protocol denotes thereby how to interact with the service, e.g. covering authentication or payment, and the interface defines all possible requests of the service and their associated schema, i.e. the input and output data format of a request. However, data still needs to be right in the right format, i.e. data conforms the schema of these interfaces, to ensure interoperability when interacting with a service. Especially in manufacturing, interoperability is challenging due to legacy systems and a large variety of data sources [29,30]. The field of data integration deals with this problem by combining data from different sources to a unified view for the user [31]. Formally speaking, data integration can be described by the tuple $\langle G, S, M \rangle$, where a global schema G, i.e. the unified view, is obtained by applying a mapping M to a source schema S. The mapping M, responsible for translating between schemas S and G, aims to handle with data heterogeneity, both in terms of notational and conceptual heterogeneity [32]. Notational heterogeneity concerns communication protocol or language whilst conceptual heterogeneity is summarized by differences in schema or semantics of the used data models.

Besides the degree of service orientation, we assess the integration capabilities of existing approaches in the field of digital manufacturing based on the degree of data heterogeneity they can manage. In this literature analysis, we will not cover abstract architectures, like the RAMI4.0, as they miss the technical depth for a direct realization, as stated by Wang et al. [33]. Instead, we will concentrate on approaches that are either implemented and evaluated in case studies or concepts that provide enough detail for assessing their fit for a service-oriented PPC.

Lee et al. [34] motivate for the use of CPPS in Industry4.0 to control production operations and present therefore a 5-tier architecture, consisting of the levels: connection, conversion, cyber, cognition, and configure. They emphasize the importance of a tether-free method for exchanging data from various sources with consideration of needed data transformations. The architecture covers with its levels all relevant features of a CPPS but misses detail how to transfer this architecture directly to SOA and implement it with current technologies. A similar approach is proposed by Pérez et al. [35] with a model-based architecture for CPPS that enables vertical integration from the shop floor to the cloud. In this approach, they utilize existing standards and information models to represent manufacturing entities and exchange this information via OPC UA-based services.

Liu et al. [36] present and demonstrate a framework for CPPS that aims for reconfigurability of digital production systems by the use of digital twins and remote control. The authors motivate for a SOA to implement their CPPS and realize it with webservices and MQTT. To limit their efforts in regard of data integration, they use one unified domain ontology that ensures conceptual data homogeneity. A conceptually similar but technologically different approach is shown by Ye et al. [37] based on AAS for interoperable data exchange between cloud and edge software components. They utilize OPC UA for communication to assets and organize applications as AAS-based webservices. The authors note the importance of semantic integration of data for interoperability and ease of integration.

Table 1: Overview of approaches for architectures of digital manufacturing with consideration of production planning and control and service-orientation

	Service-orientation						**Data heterogeneity**	
Approach	Discoverable	Modular	Interoperable	Loosely Coupled	Location transparent	Composable	Notational	Conceptual
Lee et al. (2015) [34]	○	◐	◐	◐	○	○	◐	○
Pérez et al. (2015) [35]	○	●	◐	○	○	○	◐	○
Liu et al. (2020) [36]	○	●	●	○	○	◐	◐	○
Ye et al. (2021) [37]	◐	●	◐	●	●	●	◐	○
Wang et al. (2020) [38]	◐	●	◐	●	●	●	◐	◐
Biesinger et al. (2019) [39]	○	○	●	○	○	◐	◐	◐
Qiu et al. (2007) [40]	○	●	◐	●	○	○	◐	◐
Grassi et al. (2020) [41]	○	●	◐	◐	○	◐	◐	○

To enable digital PPC, Wang et al. [38] motivate to integrate different enterprise application, such as enterprise resource planning (ERP) or manufacturing execution systems (MES) for more collaborative and synergetic information exchange. In their proposed architecture, they utilize industrial internet of things (IIoT) for an interoperable information exchange with production resources. They emphasize the potential to disassemble monolithic applications into services to increase reusability and ease of integration. Yet, a clear explanation how data integration is performed, is missing.

Biesinger et al. [39] concentrate on this data integration by utilizing an enterprise service bus as a central integration entity that allows to connect to heterogenous data sources on the shop floor. They show how to utilize dedicated parsers to extract information in real-time from these data sources and integrate this information in other software systems.

Another approach is introduced by Qiu et al. [40] with a 3 layered architecture where production resources and their controllers are integrated by a service-oriented integration framework with enterprise business applications for planning and control of production. They use pre-defined data formats and protocols to perform the factory integration of heterogenous data sources by mapping the data to knowledge graphs. The demonstrate the approach in semiconductor manufacturing for process control and recipe management

Grassi et al. [41] are concerned with enabling orchestration of control in digital manufacturing. They argue for a decentralized control approach, that is able to handle complexity of manufacturing systems by abstraction of controllers. Yet, their architecture is a monolithic ERP application, that prevents realization of SOA on the application level.

To summarize the reviewed approaches, they all emphasize the importance of an interoperable and flexible information architecture to realize the potentials of digital manufacturing. Although the approaches follow different architecture paradigms and utilize different technologies, all architectures separate business applications from communication with production resource through a dedicated layer for integration, similar to SDM. Moreover, the approaches motivate for decentralized approaches to realize CPPS.

In recent surveys in the areas of smart manufacturing, cloud manufacturing or CPPS, enabling interoperability and information integration are seen as major challenges in realizing these concepts [42,24,43,44]. Although most of the reviewed approaches agree, they do not consider advanced data integration technologies that are scalable for notational and conceptual data heterogeneity. Instead, most approaches rely on tailored integrations or global data models that enable integration.

Another limitation of existing approaches is their degree of service-orientation. Although most of the reviewed approaches promote SOA, they fail to implement essential characteristics. Service discoverability and composability, that is important for SOAs to scale, are mostly not considered. Additionally, compatibility and consideration of existing SOA technologies is mostly not achieved. Lastly, the interoperability of approaches is mostly also limited since only one communication technology, such as OPC UA, is considered. To resolve existing limitations, the remainder of this paper aims to present an approach that considers all described key characteristics of SOA and allows to handle data heterogeneity considering notation but also concepts.

3. Approach to realize service-orientation in production planning and control

The approach considers at first (Section 3.1) how tasks associated with PPC can be described in terms of SOA. Building up on this logic, we describe a software architecture (Section 3.2) that implements the principles of SOA and allows for all data exchanges required to automate PPC. Section 3.3 gives thereby special notice to data integration in this architecture for integration of legacy systems.

3.1 Service abstraction for production planning and control

The aim of PPC is to efficiently and effectively operate production to satisfy customer demands [45]. To do this, a set of tasks is considered by PPC frameworks that are sequentially performed in iterations whereby each task contributes some aspects to the overall PPC solution. Typical tasks are, for example, capacity planning, shop floor scheduling or material requirements planning (MRP). There exist algorithms or models for many PPC tasks which shows the potential for automation. Yet, implementations are mostly done custom-tailored to specific use cases without possibilities for reuse.

To resolve this problem and also ensure that integration in software architectures is not prevented by incompatibilities, software implementations for PPC tasks should follow the design principle of services. Valipour et al. state that the "[…] most important aspect of SOA is that is separates the service's implementation from its interface." [27] This infers for PPC that the data required and produced when solving a PPC task should be separated from the algorithmic solution to solve this task. This makes it not only clear for service consumers how to use this service but also allows use of the service without knowledge of the algorithmic solution, i.e. the implementation. Additionally, implementing PPC tasks as services motivates for a use-case independent implementation with a parameterized interface.

To be precise, a PPC task can be seen as a function f, where $f\colon\ x \rightarrow y$. Thereby, x is data required to perform the PPC task and y the solution of the PPC task. For example, data required for performing MRP comprises of the production schedule and the bill of materials of all products in the schedule and the output covers cardinalities for material. Considering the contextual meaning of both x and y respectively in f, it is possible to define their schemas X and Y. Schemas for MRP would be clear definitions of the data models describing the production schedule or the bill of materials. With this formulation, a PPC task can be implemented as a service where its interface conforms X and Y and its implementation realizes f.

With this logic, it is possible to transfer the logic of service composition and orchestration to PPC for creation of planning pipelines in PPC. For example, we could define a service that is a composite of scheduling and MRP, where the input of the composite service are the placed orders of customers and the associated bill of materials. Output of this service would be a production schedule and cardinalities for all required materials.

Thus, we could abstract the sequential PPC logic, i.e. performing MRP after scheduling, in this service composition and thereby reduce complexity. Considering the orchestration capabilities of SOA, complex process models for PPC services could be realized for automation.

3.2 Software architecture to implement service-orientation in manufacturing

To realize an integration of PPC services and production data sources, a software architecture is required that is able to deal with the data heterogeneity of manufacturing and allows to orchestrate complex service networks for PPC tasks. Aligning with the concept of SDM [22] and the architectures discussed in section 2, our proposed architecture consists of three layers - infrastructure layer, reference layer and application layer – as shown in Figure 1.

The infrastructure layer is thereby a collection of data providers and consumers, i.e. production hardware and data bases, and their associated way of communication. The reference layer serves two purposes: data integration and service integration. At first, it aims for integrating the infrastructure to a more manageable representation by use of data integration technologies and providing the infrastructure's functionalities as services. Next, service integration is concerned with the registration, integration and orchestration of services in order to make them discoverable, compatible, and manageable. Lastly, the application layer comprises of the services itself and the configuration interfaces to control the components of the architecture.

In the data integration of the reference layer, data heterogeneity needs to be handled considering notations and concepts of data. There have been great advancements in terms of reducing notational data heterogeneity in shopfloors by middleware communication technologies. One example is the Eclipse BaSyx middleware (https://www.eclipse.org/basyx/) that allows to connect multiple industry protocols and make the information available in AAS. However, other integrations might be necessary besides the shop floor to data bases or enterprise applications such as MES or ERP systems (see Section 3.3), that are considered by integration services. The AAS serves as a promising technology to realize the target of data integration of the reference layer by making the data available in a manageable representation. It is a standardized description language with a service-oriented design that suits well for standardization of data formats. Currently, there exist many ongoing standardization procedures to create distinct domain models for AAS to ease integration.

Apart from its advantages, AAS technology is complex to use, and, unfortunately, not yet as compatible and mature as existing technologies for SOA and web services. Realizing data models with AAS requires precise knowledge of the AAS meta model, posing a high barrier to entry. Although AAS allow for the creation of schemas using templates, existing implementations for AAS currently do not provide any validation of these schemas. Technologies that support building an SOA like load balancers, health monitoring or data integration tools for services are not compatible with AAS. Instead they are widely compatible to existing solutions for describing web services. One example, the OpenAPI Specification, is a definition language that allows to describe, produce, consume, and visualize web services in a machine-readable form.

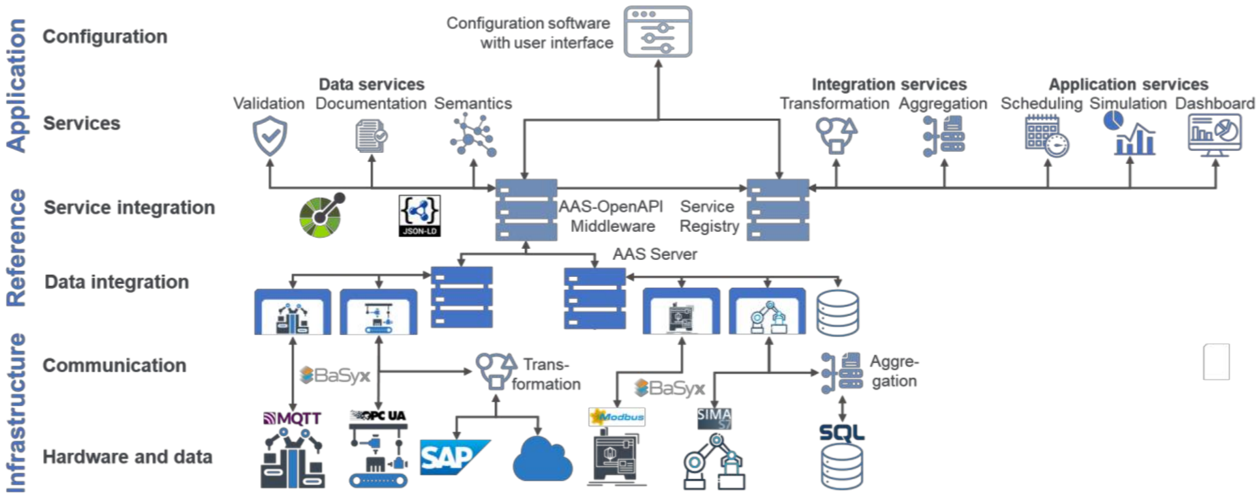


Figure 1: Visualization of the proposed architecture for realization of a service-oriented PPC

To make use of the benefits of AAS, i.e. standardized representation of data and compatibility to industrial data sources, and OpenAPI Specification, i.e. compatibility to SOA technologies and ease of use, we propose a middleware that integrates these languages. For this integration, we developed a mapping between the components of the meta models of AAS and OpenAPI schemas, as shown in Table 2. Note, that we considered only the most important components of both languages in this work. Extensions, however, to cover more aspects of the meta models are possible. Meta-information of schema and attribute names, necessary for this transformation, is specified within the DataSpecifications of the AAS. A more detailed explanation of this mapping based on a simple example can be found in the Appendix.

By considering these mapping rules, the AAS-OpenAPI middleware automatically transforms data between these two formats. To make the middleware useable, it provides a CRUD (create, read, update, and delete) REST API for its data models that is dynamically generated based on provided AAS or OpenAPI specifications. Queries against this CRUD interface are transformed and forwarded to the AAS and are transformed again upon return from the AAS interface. For an implementation of this middleware, refer to: [46]

Table 2: Mapping logic for transforming AAS to OpenAPI Specifications and vice versa

AAS Meta Model	OpenAPI	Mapping Transformation
Asset administration shell	object	ID, IDshort, and semantic ID are mapped as strings, submodels are mapped as attributes
Submodel	object	ID, IDshort, and semantic ID are mapped as strings, Submodel Element Collection are mapped as attributes
Submodel Element Collection	object	ID, IDshort, and semantic ID are mapped as strings, Submodel Element Collection are mapped as attributes
Submodel Element List	array	Values of the list entries are mapped to an array attribute
Property	string | number | integer | boolean	Value of the Property is mapped to the associated primitive data type attribute (either string, number, integer or boolean)
ReferenceElement	string	Value of the Reference Element is mapped as a string attribute

3.3 Data Integration and compatibility with legacy systems

The consideration of integration of legacy systems for PPC in this architecture is one essential component. The first step for integration is to ensure that these systems provide their functionalities as services, e.g. by wrapping their typical API in web services. Existing procedures are widely applicable and have been performed for many applications, such as in [30]. Although this allows to include legacy systems in the architecture, connecting them still requires data integration.

PPC tasks are strongly dependant on each other due to the sequential nature of PPC, input and output of different PPC tasks can have intersections or be subsets of each other. Let, for example, the output of scheduling service conform schema Y_S and let the input of an MRP service conform schema X_{MRP} that is an integration of a scheduling schema X_S and a bill of material schema X_{BOM}. Then, one would need to find a mapping M_S that integrates both scheduling schemas Y_S and X_S in order to integrate scheduling and MRP service.

Considering the number of tasks in PPC, the efforts for data integration with heterogenous interfaces can be huge. In fact, a worst-case scenario could require to define $\frac{1}{2}N(N-1)$ mappings for N schemas in a point-to-point integration [47]. However, concepts from data integration reduce this complexity by considering global or at least mediated schemas that reduce the number of necessary mappings in the best case N [31,29].

Semantically annotated data also has great potentials for data integration by use of schema matching technologies, automated semantic integration and ontology mapping [48,49]. Lastly, in case of missing semantics, one could employ existing machine learning approaches, or more specifically natural language processing, from other domains to automate the integration [50,51].

4. Conclusion and Outlook

This work aims to enable service-orientation in PPC by applying the principles of SOA to PPC and creating an architecture that allows the integration of such services with production data sources. At first, related approaches from literature are analyzed with consideration of their degree of service-orientation and their capabilities to handle heterogenous data sources. Analysis showed that the reviewed approaches either miss realization of some SOA principles or they rely on homogenous data sources. To close this deficit, we propose a concept that transfers theory from SOA and data integration to PPC frameworks, showing that PPC tasks can be described as services which are modular and composable. Based on this, an architecture is introduced that allows to synergistically use digital industry and SOA technologies for data exchange in production. It allows to orchestrate loosely coupled services to perform PPC tasks and to exchange data with production in an interoperable way. By integration of AAS with OpenAPI Specifications, the architecture achieves to handle notational data heterogeneity since the most common protocols and languages in practice can be interchangeably transformed. Lastly, special focus is given to handle legacy systems and conceptual data heterogeneity. Although the use of OpenAPI requires schema definitions of service interfaces, integrating these schemas is still linked to high efforts. To resolve this problem, integration with global schemas or use of automated approaches to find these schema mappings are recommended. In our future research, we will build up on this approach and demonstrate its effectiveness in use cases. Moreover, more detailed evaluation of the potentials of methods utilizing machine learning or semantics for data integration is focused.

Acknowledgements

The authors gratefully acknowledge financial funding from the German Federal Ministry of Economic Affairs and Climate Action and the European Union (grant no. 13IK001ZF) as well as organizational support by the VDI Technologiezentrum GmbH.

Appendix

In the following, we will explain the mapping defined in Table 2, for the integration of AAS and OpenAPI Specification schemas, based on a simple example. A reference implementation is available at [46]. The example is concerned with a data model (Figure 2a) that describes attributes of products that are required in typical PPC tasks, such as MRP or scheduling. The data model of the product specifies three attributes: an ID to identify the product, an attribute for required production processes and an attribute for its bill of material. The data model is depicted in Figure 2a as UML class diagram and an instance of the data model is shown in Figure 2b.

The result of applying the mapping logic between AAS and OpenAPI Specifications on this example is displayed in Figure 3. Here, the described data model is displayed in JSON-serialization for its representations conforming OpenAPI and AAS Meta model.

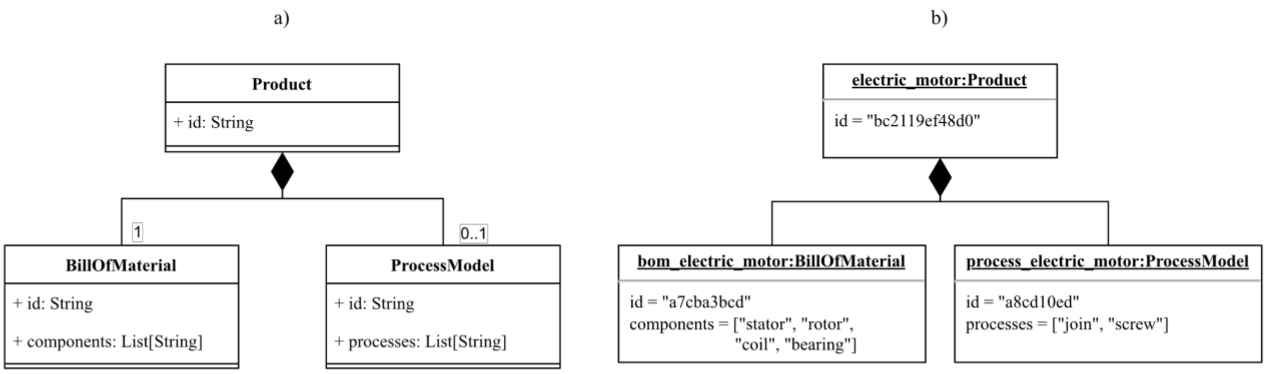


Figure 2: UML class diagram (a) and object diagram (b) of the exemplary data model of an electric motor

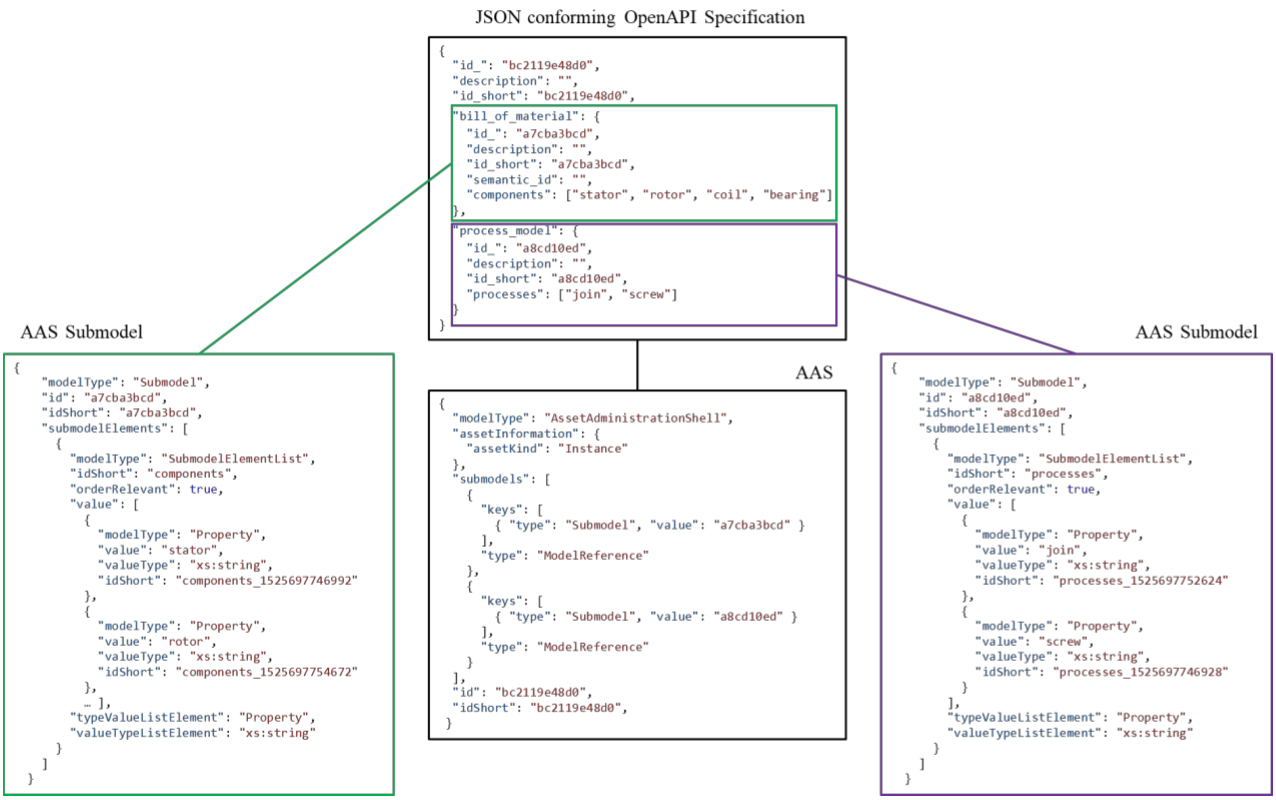


Figure 3: UML class diagram (a) and object diagram (b) of the exemplary data model of an electric motor

References

[1] Enke, J., Glass, R., Kreß, A., Hambach, J., Tisch, M., Metternich, J., 2018. Industrie 4.0 – Competencies for a modern production system: A curriculum for Learning Factories. Procedia Manufacturing 23, 267–272.

[2] Mack, O., Khare, A., Krämer, A., Burgartz, T. (Eds.), 2016. Managing in a VUCA world. Springer, Cham, Heidelberg, New York, Dordrecht, London, 259 pp.

[3] Millar, Carla C. J. M., Groth, O., Mahon, J.F., 2018. Management Innovation in a VUCA World: Challenges and Recommendations. California Management Review 61 (1), 5–14.

[4] 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.

[5] Oluyisola, O.E., Sgarbossa, F., Strandhagen, J.O., 2020. Smart Production Planning and Control: Concept, Use-Cases and Sustainability Implications. Sustainability 12 (9), 3791.

[6] Bennett, N., Lemoine, G.J., 2014. What a difference a word makes: Understanding threats to performance in a VUCA world. Business Horizons 57 (3), 311–317.

[7] ElMaraghy, H.A., 2005. Flexible and reconfigurable manufacturing systems paradigms. Int J Flex Manuf Syst 17 (4), 261–276.

[8] 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.

[9] ElMaraghy, H., Wiendahl, H.-P., 2014. Changeable Manufacturing, in: Laperrière, L., Reinhart, G., Chatti, S., Tolio, T. (Eds.), CIRP encyclopedia of production engineering. With 85 tables. Springer, Berlin, pp. 157–163.

[10] Saputra, N., Sasanti, N., Alamsjah, F., Sadeli, F., 2022. Strategic role of digital capability on business agility during COVID-19 era. Procedia Computer Science 197, 326–335.

[11] Monostori, L., 2014. Cyber-physical Production Systems: Roots, Expectations and R&D Challenges. Procedia CIRP 17, 9–13.

[12] Stark, R., Kind, S., Neumeyer, S., 2017. Innovations in digital modelling for next generation manufacturing system design. CIRP Annals 66 (1), 169–172.

[13] Overbeck, L., Le Louarn, A., Brützel, O., Stricker, N., Lanza, G., 2022. Comprehensive Validation Metrics and Precise Updating of Digital Twins of Production Systems. Simulation Notes Europe 32 (3), 135–142.

[14] Behrendt, S., Wurster, M., May, M.C., Lanza, G., 2023. Extended Production Planning of Reconfigurable Manufacturing Systems by Means of Simulation-based Optimization, in: 4th Conference on Production Systems and Logistics (CPSL 2023), Santiago de Querétaro, Mexiko. 2023. publish-Ing, Santiago de Querétaro, Mexiko, pp. 210–220.

[15] Kuhnle, A. Adaptive order dispatching based on reinforcement learning. Dissertation.

[16] Usuga Cadavid, J.P., Lamouri, S., Grabot, B., Pellerin, R., Fortin, A., 2020. Machine learning applied in production planning and control: a state-of-the-art in the era of industry 4.0. Journal of Intelligent Manufacturing 31 (6), 1531–1558.

[17] Yang, C., Lan, S., Wang, L., Shen, W., Huang, G.G.Q., 2020. Big Data Driven Edge-Cloud Collaboration Architecture for Cloud Manufacturing: A Software Defined Perspective. IEEE Access 8, 45938–45950.

[18] Tseng, M.-L., Tran, T.P.T., Ha, H.M., Bui, T.-D., Lim, M.K., 2021. Sustainable industrial and operation engineering trends and challenges Toward Industry 4.0: a data driven analysis. Journal of Industrial and Production Engineering 38 (8), 581–598.

[19] Wiendahl, H.-P., Scholtissek, P., 1994. Management and Control of Complexity in Manufacturing. CIRP Annals 43 (2), 533–540.

[20] 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.

[21] 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.

[22] Behrendt, S., Ungen, M., Fisel, J., Hung, K.-C., May, M.-C., Leberle, U., Lanza, G., 2023. Improving Production System Flexibility and Changeability Through Software-Defined Manufacturing, in: , Cham. 2023. Springer International Publishing, pp. 705–716.

[23] Lechler, A., Verl, A., 2017. Software Defined Manufacturing Extends Cloud-Based Control, in: Proceedings of the ASME 12th International Manufacturing Science and Engineering Conference. ASME 2017 12th International Manufacturing Science and Engineering Conference collocated with the JSME/ASME 2017 6th International Conference on Materials and Processing, Los Angeles, California, USA. 6/4/2017 - 6/8/2017, New York, N.Y.

[24] Phuyal, S., Bista, D., Bista, R., 2020. Challenges, Opportunities and Future Directions of Smart Manufacturing: A State of Art Review. Sustainable Futures 2, 100023.

[25] Adamson, G., Wang, L., Holm, M., Moore, P., 2017. Cloud manufacturing – a critical review of recent development and future trends. International Journal of Computer Integrated Manufacturing 30 (4-5), 347–380.

[26] Niknejad, N., Ismail, W., Ghani, I., Nazari, B., Bahari, M., Hussin, Ab Razak Bin Che, 2020. Understanding Service-Oriented Architecture (SOA): A systematic literature review and directions for further investigation. Information Systems 91, 101491.

[27] Valipour, M.H., Amirzafari, B., Maleki, K.N., Daneshpour, N., 2009. A brief survey of software architecture concepts and service oriented architecture, in: . 2009 2nd IEEE International Conference on Computer Science and Information Technology. 2009/08, pp. 34–38.

[28] Mayring, P., 2015. Qualitative Content Analysis: Theoretical Background and Procedures, in: , Approaches to Qualitative Research in Mathematics Education. Springer, Dordrecht, pp. 365–380.

[29] Oussous, A., Benjelloun, F.-Z., Ait Lahcen, A., Belfkih, S., 2018. Big Data technologies: A survey. Journal of King Saud University - Computer and Information Sciences 30 (4), 431–448.

[30] Sneed, H.M., 2006. Integrating legacy software into a service oriented architecture, in: . Conference on Software Maintenance and Reengineering (CSMR'06). 2006/03, 11-pp.-14.

[31] Lenzerini, M., 2002. Data integration: a theoretical perspective, in: . SIGMOD/PODS02: International Conference on Management of Data and Symposium on Principles Database and Systems, Madison Wisconsin. 2002/06/03. ACM, pp. 233–246.

[32] Genesereth, M.R., Keller, A.M., Duschka, O.M., 1997. Infomaster: an information integration system. SIGMOD Rec. 26 (2), 539–542.

[33] Wang, B., Tao, F., Fang, X., Liu, C., Liu, Y., Freiheit, T., 2021. Smart Manufacturing and Intelligent Manufacturing: A Comparative Review. Engineering 7 (6), 738–757.

[34] 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.

[35] Pérez, F., Irisarri, E., Orive, D., Marcos, M., Estevez, E., 2015. A CPPS Architecture approach for Industry 4.0, in: . 2015 IEEE 20th Conference on Emerging Technologies & Factory Automation (ETFA). 2015/09, pp. 1–4.

[36] Liu, C., Jiang, P., Jiang, W., 2020. Web-based digital twin modeling and remote control of cyber-physical production systems. Robotics and Computer-Integrated Manufacturing 64, 101956.

[37] Ye, X., Hong, S.H., Song, W.S., Kim, Y.C., Zhang, X., 2021. An Industry 4.0 Asset Administration Shell-Enabled Digital Solution for Robot-Based Manufacturing Systems. IEEE Access 9, 154448–154459.

[38] Wang, J., Xu, C., Zhang, J., Bao, J., Zhong, R., 2020. A collaborative architecture of the industrial internet platform for manufacturing systems. Robotics and Computer-Integrated Manufacturing 61, 101854.

[39] Biesinger, F., Meike, D., Kraß, B., Weyrich, M., 2019. A digital twin for production planning based on cyber-physical systems: A Case Study for a Cyber-Physical System-Based Creation of a Digital Twin. Procedia CIRP 79, 355–360.

[40] Qiu, R.G., 2007. A service-oriented integration framework for semiconductor manufacturing systems. International Journal of Manufacturing Technology and Management 10 (2-3), 177–191.

[41] Grassi, A., Guizzi, G., Santillo, L.C., Vespoli, S., 2020. A semi-heterarchical production control architecture for industry 4.0-based manufacturing systems. Manufacturing Letters 24, 43–46.

[42] Napoleone, A., Macchi, M., Pozzetti, A., 2020. A review on the characteristics of cyber-physical systems for the future smart factories. Journal of Manufacturing Systems 54, 305–335.

[43] Qu, Y.J., Ming, X.G., Liu, Z.W., Zhang, X.Y., Hou, Z.T., 2019. Smart manufacturing systems: state of the art and future trends. Int J Adv Manuf Technol 103 (9), 3751–3768.

[44] Trunzer, E., Calà, A., Leitão, P., Gepp, M., Kinghorst, J., Lüder, A., Schauerte, H., Reifferscheid, M., Vogel-Heuser, B., 2019. System architectures for Industrie 4.0 applications. Prod. Eng. Res. Devel. 13 (3), 247–257.

[45] Chapman, S.N., 2006. The Fundamentals of Production Planning and Control. Pearson/Prentice Hall.

[46] Sebastian Behrendt, 2023. aas2openapi v0.1.1, https://github.com/sdm4fzi/aas2openapi,. Zenodo, 10.5281/ZENODO.8209922.

[47] H. Mannaert, J. Verelst, Peter De Bruyn, 2016. Normalized systems theory : from foundations for evolvable software toward a general theory for evolvable design.

[48] Knoblock, C., Szekely, P., 2015. Exploiting Semantics for Big Data Integration. AI Magazine 36, 25–38.

[49] Mountantonakis, M., Tzitzikas, Y., 2019. Large-scale Semantic Integration of Linked Data: A Survey. ACM Comput. Surv. 52 (5), 103:1-103:40.

[50] Cappuzzo, R., Papotti, P., Thirumuruganathan, S., 2020. Creating Embeddings of Heterogeneous Relational Datasets for Data Integration Tasks, in: , New York, NY, USA. 2020//31/Mai. Association for Computing Machinery, pp. 1335–1349.

[51] Zhang, J., Shin, B., Choi, J.D., Ho, J.C., 2021. SMAT: An attention-based deep learning solution to the automation of schema matching. Advances in databases and information systems. ADBIS 12843, 260–274.

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).

Florian Stamer (*(1991) is a postdoctoral researcher and group leader at the Institute of Production Science (wbk) at the Karlsruhe Institute of Technology (KIT). He leads the Quality Assurance group, which focuses on intelligent quality control loops in production, with AI and advanced metrology as key enablers.

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

5th Conference on Production Systems and Logistics

Identification Of Investigation Procedures To Predict Work Roll Fatigue For Developing Machine Learning Applications – A Systematic Literature Review

Tobias Moser[1*], Johannes Seitz[1], Enes Alp[1], Bernd Kuhlenkötter[1]

[1]*Chair of Production Systems / Ruhr-Universität Bochum, Bochum, Germany*

Abstract

Machine learning approaches present significant opportunities for optimizing existing machines and production systems. Particularly in hot rolling processes, great potential for optimization can be exploited. Radial-axial ring rolling is a crucial process utilized to manufacture seamless rings. However, the failure of the mandrel represents a defect within the ring rolling process that currently cannot be adequately explained. Mandrel failure is unpredictable, occurs without a directly identifiable reason, and can appear several times a week depending on the ring rolling mill and capacity utilization. Broken rolls lead to unscheduled production downtimes, defective rings and can damage other machine parts. Considering the extensive recording of production data in ring rolling, the implementation of machine learning models for the prediction of such roll breaks offers great potential. To present a comprehensive overview of the potential influencing factors which are possibly relevant to the lifetime of mandrels, a systematic literature review (SLR) focusing on work roll wear in hot rolling processes is conducted. Based on the results of the SLR, a first selection of features and the used investigation procedures are presented. The insights can be used for the prediction of mandrel failure with machine learning models in further work.

Keywords

Radial-Axial Ring Rolling; Work Rolls; Fatigue; Systematic Literature Review; Machine Learning;

1. Introduction

Seamlessly formed, ring-shaped components with high required specifications, such as highly dynamic load capacity and high product variability, are necessary for many machines and systems in all branches of industry. Typical areas of application are rail transport, aerospace, the automotive industry, plant and energy plant engineering, and special machine construction. Radial-axial ring rolling (RARR) (see Figure 1) is an important process for the production of such components.[1] A currently not sufficiently explainable failure in the domain of RARR is the failure of the mandrel, which occurs unpredictably and without a directly identifiable reason. The large amount of influencing factors (e.g. rolling temperature, rolling pressure, rolling material)[2], which also have non-linear interdependencies, hinders the use of proven research methods to identify qualitative and quantitative influences that are related to failure.[3] In this context, machine learning algorithms offer a new approach for identifying and weighting the influencing factors and predicting the remaining lifetime of the mandrel. It has already been demonstrated by Fahle et al. that machine learning models are suitable for applications in the field of RARR.[4] Furthermore, comprehensive data recording is already available in many industrial companies, which is a basis requirement for the implementation of machine learning applications.[5]

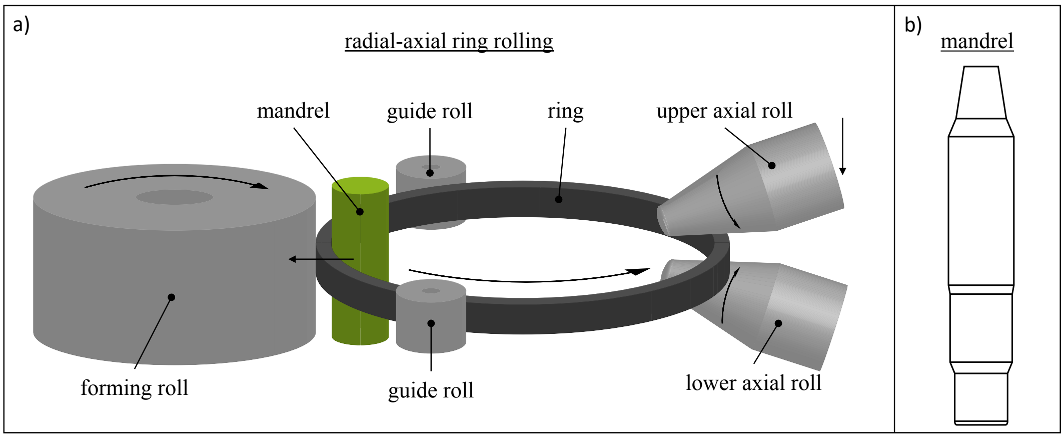


Figure 1: a) Scheme of the RARR process; b) illustration of the mandrel

To exploit the potential of machine learning algorithms effectively, it is beneficial to gain a fundamental domain knowledge about the conventional investigation procedures. However, given the limited availability of publications pertaining to the field of RARR, which were also included in this systematic literature review, it is not feasible to establish a scientifically robust investigation exclusively from the domain of RARR. Consequently, the scope of this study is broadened to encompass the broader domain of work rolls in hot rolling. In this field, it is well known that the service life of work rolls is mainly influenced by thermal stress, mechanical stress and wear. Consequently, the objective of this scientific paper is twofold. Firstly, a systematic literature search will be conducted which aims to classify the used research procedures and their limitation to investigate hot work roll wear. Second, the identified publications will be reviewed for potential capabilities in predicting work roll life. By accomplishing these goals, this study establishes a solid foundation for a well-informed machine learning application.

2. Structured Review Methodology

This chapter describes the literature search phase for the presented literature selection in Appendix 1. The literature selection was conducted using a combined approach by vom Brocke et al. [6] and Cooper [7] with the primary focus of identifying all relevant studies dealing with the investigation of factors affecting the wear and fatigue of work rolls in hot rolling. In addition, the approaches in the selected articles were examined for their ability to predict work roll life.

The Scopus database was used for the literature search as it provides a comprehensive international literature database from different research areas. The search was conducted in July 2023 using the search string shown in Figure 2 with the aim of presenting a literature review that was as comprehensive as possible in terms of the topic while still limiting the number of results to a controllable quantity. Specific filters were used to exclude irrelevant articles. The filters limited the search results to articles written in English or German, to articles from the subject area Engineering or Material Science and the document type Article or Conference Paper. Since many of the articles are dealing with the wear of bearings, rail wheels, gear, or cold rolling, these were also filtered out using keyword limitation.

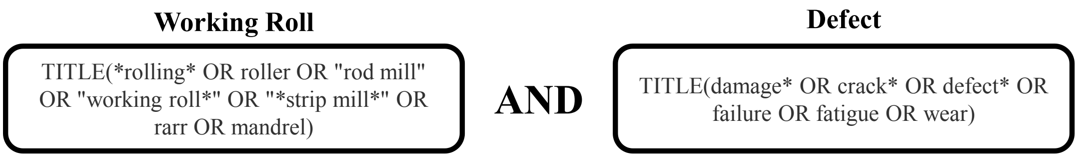


Figure 2: Search string

The search results as well as the outcomes of each filtering stage are shown in Figure 3. After performing all filtering stages, the initial number of 2,566 articles were reduced to 59. The selection of literature was limited to papers in which, firstly, the work rolls themselves are made of metallic material and, secondly, metallic materials are formed. Furthermore, the work rolls must perform forming work. This also includes backup rolls of strip steel mills, as they make an active contribution to the forming of the rolled material. Centering rolls, which mainly have a stabilizing role and do not contribute to the actual forming, are not considered. The effects of applied lubrication are also not considered since they play a minor role in the domain of RARR. Moreover, some studies were not considered, because it was not possible to clearly determine the influence factor for the defect that occurred. In addition, the selection has been reduced by papers where the conditions for increased wear of the work roll are not related to the forming process but to the manufacture of the work roll (e.g., development of internal stresses due to previous heat treatment of the working roll), as well as by papers where only the abstract, but not the full text, is available in English. Furthermore, in the case of a few papers, despite great efforts, it was not possible to gain access to the full paper.

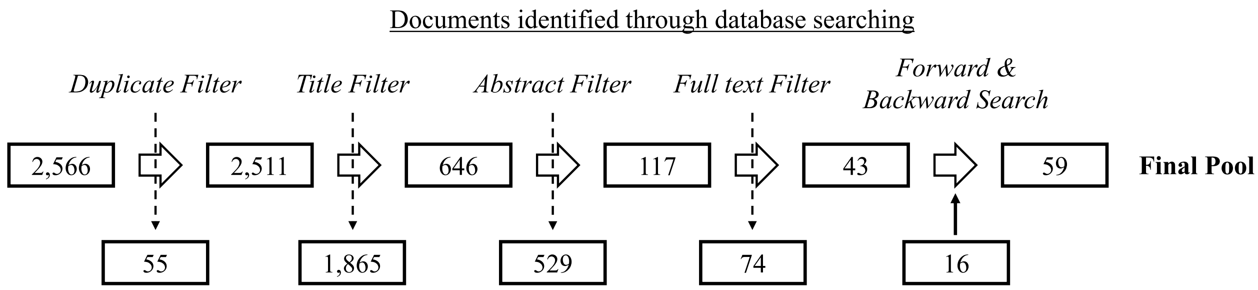


Figure 3: Levels of the systematic literature review

3. Summary of the Literature Review

3.1 Dimensions of the Analysis

In the following, the publications from the final pool are inspected in more detail. A list of the identified articles can be found in Appendix 1. The publications were divided into different categories in the areas of examined *influencing factors,* used *investigation procedure* and *investigation objective*. In the area of investigated *influencing factors,* a distinction is made between the categories *temperature*, which describes the effects on the rolls triggered by the high process temperatures, *material stress*, where the focus is on the forming forces required in the process and the associated stresses on the rolls, *material*, which inspects the material behavior, *process factors*, in which process variables, as well as influences of the system control and product properties are taken into account, and *roll design*, which describes the effects of different roll forms on wear. Within the area of *investigation procedure*, a distinction is made between *Simulation Approach, Experimental Approach, In-situ Analysis and Post process Investigation*. A closer description of the individual areas is given in the subsections of section 3.2. A more detailed look is also taken at the *investigation objective*. A distinction is made between a focus on general *wear* and a focus on the *end of service* of work rolls. End of service in this context means that either the roll has a defect which prevents the roll from being reused or the roll must be reworked within a maintenance. If the article focuses on the end of service, it is also checked whether methods for *predicting the end of service* are considered.

3.2 Publication Metadata Analysis

To identify trends and research priorities, an analysis of the metadata was carried out regarding the areas introduced above. In Figure 4, it is evident that the focus of research efforts is on simulation approaches and the application of an experimental approach, while the integration of in-situ analysis and the category post process investigation remains comparatively limited. In addition, the general importance of the topic is highlighted by the continuously increasing number of publications over the years. The limited number of articles in the years 2020-2023 can be justified by the fact that articles are often entered late in the databases and the year 2023 was not completed at the time of the literature search.

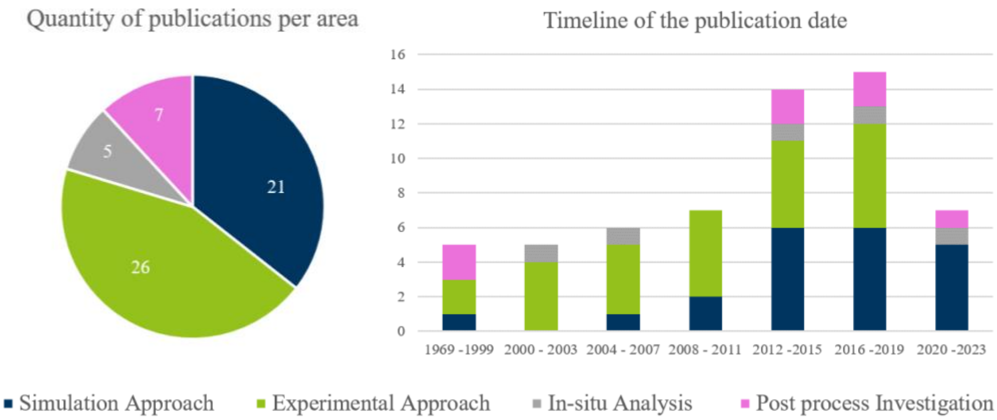


Figure 4: Superficial article analysis

Furthermore, with exception of the influencing factor roll design, all other categories in the articles were investigated with the same frequency (between 22 % and 26 %). The same applies to the investigation objective of the articles. 31 articles focus on the wear of the work rolls while 28 articles focus more on the end of service of the rolls. Six of the 28 articles also introduce new ways to predict end of service.

3.3 Summary of the Literature Review

In the following section, the publications identified by the literature review (see table in Appendix 1) are examined regarding the analyzed influencing factors within each publication. The articles are grouped according to the employed investigation approach. If a publication could be assigned to more than one investigation procedure, the one that accounts for the largest part of the paper was chosen. The respective category is highlighted in the table in Appendix 1. The assigned categorization can also be taken from the table. Due to page limitations, the publications are summarized briefly in the assigned categories. Nevertheless, all articles have been analyzed in detail and are referenced for further interested parties.

3.3.1 Simulation Approach

The category Simulation Approach includes all articles that deal with the development of models to replicate the wear and failure behavior of the work rolls without using real world data in the first place to create the model.

For this purpose, Dong and Cao created a finite element method (FEM) model that analyses the contact behavior of asperities in the strip mill. Especially in the asperity areas, increased stresses could be found, which support crack initiation and propagation.[8] Furthermore, Wu et al. developed an edge contact model to account for the time-varying contact strength of the surface of rolls. Through this work, a deeper understanding of the correlation between the vibration characteristics of rolls and roll wear could be generated.[9] A three-dimensional model dealing with the stress behavior of high-chromium work rolls was developed by Masoudi et al. Based on the stress behavior, the crack growth behavior can be modeled and the life of the roll can be predicted.[10] Further research regarding the possibility of calculating the service life of rolls was presented by Hu et al. Here, the thermoelastic and plastic behavior of high-speed steel (HSS) rolls were analyzed. The occurring residual stresses induced by thermal and mechanical influence were investigated by means of a FEM-Model, which allows to calculate the service life up to crack initiation on the rolls.[11] A FEM model for the development of internal fatigue fractures in bimetallic rolls induced by mechanical stresses is presented by Aridi et al.[12] The development of a model for the prediction of elliptically occurring cracks and fatigue phenomena in work rolls in continuous casting processes, which could be evaluated using FEM and experimental data, was presented by Tolcha et al.[13] Negahban Boron et al., on the other hand, investigated the effects and stress development triggered by thermal or mechanical loading or a combination of both types of loading in mandrel and main rolls in the RARR area. For this purpose, a FEM-Model was developed which reflects the stress behavior in the rolls.[14] For the investigation of thermal crack growth, Fedorciuc – Onisa and Farragia performed a FEM analysis, which can estimate roll life in terms of thermal fatigue.[15] Lundberg and Gustafsson developed a heat transfer model to determine thermal stresses based on the wear and friction behavior of rolling materials.[16] A model which is used to predict fatigue damage to backup rolls in strip mills is listed by Yuan et al. Based on the contact stresses that occur and taking into account the non-uniform wear of the rolls, fatigue phenomena can be predicted after the rolled material is fully formed.[17] Traino et al. developed a finite difference method (FDM) approach to predict the wear rate in strip rolling mills considering the friction path and the friction force in the deformation zone.[18] Song et al. developed a wear law by means of theoretical analysis and creation of FEM -Models to calculate the wear behavior of quenched and tempered rolls in the strip mill, which are mainly characterized by increased wear due to lack of lubrication and oxidation. The model was evaluated and verified in practice.[20,19] A development of a FEM-Model to investigate the wear load in hot strip mills for roll shifting strategies and changing rolling schedules was presented by Cao et al.[21] The investigation of rolling force and roll speed with respect to their influence on the wear of mandrel rolls was studied by means of FEM simulation by Behrens et al. In addition, the influence of lubrication was also investigated, although this is estimated to be low.[22] A consideration of roll wear in strip rolling mills, considering existing process factors and roll geometries, was carried out by both Guo et al. and Liu et al. Guo et al. also considered the existing roll geometry, roll material and friction coefficients.[23] Liu et al., on the other hand, considered the prevailing temperatures to calculate the wear rate.[24] An evaluation and comparison of different models for calculating and predicting the wear behavior in hot strip mills was presented by Souto et al. The models consider material hardness, material and roll geometry, and applied forces. Subsequently, the approach with the best results was implemented in an artificial neural network, again resulting in an improvement.[25] Qin et al. developed a theoretical model for damage development on backup rolls, taking into account the periodic reworking of the roll surface after its use.[26] A simulative consideration of abrasive wear caused by an oxidation layer forming on the surface of HSS rolls was developed by Phan et al. using the discrete element method.[27]

3.3.2 Experimental Approach

The Experimental Approach is concerned with the study of publications in which experimental studies were carried out either by means of test setups (e.g., twin disk rolls) or in the actual rolling mill.

Li et al. investigated the effects of temperature, rolling force and slip on the wear rate of HSS rolls used within strip rolling mills. The investigations were carried out by means of a self-developed test setup.[28,29] An investigation of different roll materials with respect to their wear behavior was implemented by Pelizzari et al. Within a twin disk roll test setup, high alloy HSS, cast iron and indefinite chill iron were analyzed. For the evaluability, a disk made of unalloyed C40 steel is heated to 700°C by induction and rolls against the sample with predefined contact pressure. In addition to the wear rate, the surface roughness of the specimens before and after the test run were determined.[30] The wear of HSS and nickel-grain iron based on the thermal fatigue property was analyzed by Ryu and Ryu. HSS showed much better fatigue properties in this case. The investigations were carried out by means of experimental setups as well as in the rolling mill.[31] To check the thermal fatigue and hot wear resistance of HSS materials, Tremea et al. developed two test setups that evaluated the specimens in terms of their correlation between the microstructure and the defects that appear.[32] Garza-Montes-de-Oca et al. studied the effects of the oxide layer on the wear rate on HSS rolls. Several tests were carried out at different temperatures and environmental conditions (water, both gaseous and liquid, and laboratory dry air). Due to the formation of a larger oxide layer, a higher wear rate occurred in the wet tests.[33] Based on the results, further studies were conducted regarding the formation of oxide layers and the emergence of cracks and spalling, taking into account the high-frequency thermal cycling of work rolls.[34]

Optimization of the thermal load was the focus of the research work by Raudensky et al. Temperature sensors were installed inside the roll and a relation was established between increasing roll speed and increasing heat flow. The knowledge gained enabled adjustments to be made in the rolling process, which led to a reduction in the peak temperature within the rolls.[35]

Some studies, which deal with the optimization of the roll material, could also be taken from the literature search. Zhang investigated the influence of deep rolling on the thermal fatigue performance of hot work tool steel.[36] Furthermore, Delaunois et al. examined various iron alloys regarding their suitability in rolling mills. Here, the focus was primarily on the characteristics of the developed oxide layers of the individual alloys. In particular, iron alloys which develop a fine oxide layer are suitable in rolling mills due to their low coefficient of friction.[37] Molinari et al. investigated the influence of matrix hardness in the thermal fatigue behavior of several HSS. The matrix hardness was varied by the tempering temperature.[38] Furthermore, Xiao-Feng et al. investigated the behavior of the hardness of Cr5 backup rollers under cyclic loading, where the hardness of the backup rollers decreases as the number of cycles increases and fatigue occurs.[39] Finally, a study by Flora et al. could be identified, which deals with the material behavior of 55NiCrMoV7, which is used as mandrel roll material in ring rolling mills. Different hardness grades were compared and evaluated with respect to their hot wear and thermal fatigue behavior.[40]

Other studies are concerned with the thermal fatigue behavior of work rolls. Ohkomori et al. investigated the occurrence of spalling on back-up rolls used within hot strip mills. The resulting spalling is due, on the one hand, to excessive contact stress at the roll ends and, on the other hand, to the thermal shocks experienced by the rolls.[41] Besides Sonoda et al investigated the cracking of high-speed steels using damaged work rolls. Experimental studies are presented for the identification of influencing factors, in which an independent consideration of mechanical and thermal cyclic loading took place. The main factor for crack initiation could be traced back to thermal stress. Crack growth, on the other hand, is significantly influenced by mechanical stresses.[42] Weidlich et al. calculated a coefficient for determining surface damage, taking into account cross-section reduction, material temperature and rolling speed. The coefficient correlates with the plastic strain of the rolls and can thus be used to determine service life. The design was developed using rolls from a pilot mill as well as industrial data.[43] A quantitative model to study the crack morphology of backup rolls mimicked by a twin-disc rolling machine was presented by Frolish et al.[44] An investigation of the backup roll of a steel strip mill was implemented by Dong et al. using FEM. Heterogeneous stress distributions lead to cracks and accelerate fatigue failure.[45] Based on the results, a more homogeneous distribution of contact stresses was aimed at and the geometry of the backup rolls was adjusted, thus reducing premature crack initiation.[46] Bombač et al. also conducted investigations on crack initiation in rolls due to cyclic heating. The investigation was carried out by means of a self-developed test rig, which heats a specimen conductively. The sample can be cooled in a controlled manner by means of a built-in cooling channel. Different temperature ranges were investigated, as well as different material compositions in a build-up study.[47,48] Drobne et al. investigated the fracture mechanics and fatigue crack growth of high chromium work rolls under thermal loading.[50,49] Belzunce et al. also analyzed the fracture toughness of rolled materials here the research focus was not only on thermal loading but also on mechanical loading.[51] Furthermore, Mercado-Solis et al. investigated the surface deterioration of HSS and carbon containing chromium steels. The study focuses on the progressive surface deterioration triggered by thermal fatigue. The investigation of the behavior of the steels is implemented by a standalone twin-disc simulation machine under conditions that are comparable to those of hot rolling of steel, which also takes into account cyclic thermal heating.[52] In addition, Akiyama et al. investigated the initiation of cracking due to thermal stress in mandrel rolls used to produce seamless rolled tubes. Real mandrel rolls were used for this purpose, but laboratory tests and FDM investigations were also carried out.[53] Further possibilities for the design of mandrel rolls were researched by Musa-Zade et al. The focus here was on adapting the geometry of the mandrel roller to reduce the wear rate.[54]

3.3.3 In-situ Analysis

In-situ Analysis contains publications that deal with the implementation of methodologies that monitor the wear of the work roll based on logger and production data in-situ during the process.

Two of these publications focus on determining the service life of the work rolls. Jiao et al. focused on calculating the remaining duration until the next maintenance of the roll. The prediction was based on neural networks that take into account the process factors of work rolls used in strip rolling mills.[55] Struin et al., on the other hand, dealt with the adjustment of control parameters to optimize the service life of mandrel rolls in tube mills.[56]

Other publications in the field of In-situ Analysis focus on the calculation wear rate of work rolls in different rolling mills. This includes the publication by Mohammed and Widell, which evaluated the possibilities of predicting the wear rate using two models. The focus was on the comparison of the two models regarding different rolling materials and stands in the strip mill. Industrial data as well as test campaigns were used for the investigation.[57] John et al., on the other hand, developed a roll force model which predicts the wear behavior of the work rolls in a strip mill on the basis of the available process factors.[58] Furthermore, a methodology for calculating the average friction wear rate of work rolls in hot strip mills was developed by Servin Castañeda et al. Process variables, the geometries of the rolls, and existing friction coefficients were considered. In addition, an evaluation using real-world data is presented.[59]

3.3.4 Post process Investigation

Post Process Investigation, publications were reviewed which examined the wear behavior of work rolls previously used in the rolling mill.

In this category, Nierkuziak and Kubinska investigated the wear behavior of work rolls in strip mills. Real-world process data and laboratory tests were considered for the analysis. This made it possible to calculate the wear rate of the rolls in use and to optimize the selection of roll materials for different production lines.[60] Investigations focusing on the assessment of the topography of rolls in plate mills were carried out by Bataille et al. Here, the main focus was on abrasive and adhesive wear as a function of rolling time.[61] Dobrik and Moiseenko, on the other hand, investigated under which conditions the treatment of work rolls by means of friction hardening contributes to an increase in service life.[62] Colás et al. investigated wear phenomena in work rolls using a scanning electron microscope. Colás et al. attributes the wear fatigue that occurs here to thermal fatigue and contact stresses that occur. The oxidation inside the cracks accelerates the wear rate.[63]

In addition, Palit et al. describes in a case study the breakage of two rolls in use, which can be attributed to different failure cases. Both failures indicate insufficient roll quality. The roll failure was attributed to an unsuitable microstructure and a defect caused in the manufacturing process.[64] Furthermore, broken work rolls were checked by ultrasonic measurement. The crack initiation was caused by exceeding the shear strength.[65] Another case study was carried out by Sinha et al. Here, the failure of an ICDP work roll, which was in use in a strip mill, was investigated. It was found that the extensive spalling that occurred on the roll surface was caused by a weak shell-core bond.[66]

4. Conclusion

Radial-axial ring rolling (RARR) is an important process to produce ring-shaped components across various industries. This study aimed to contribute to the understanding of mandrel failure to develop machine learning based approaches for failure prediction in further research. For this, a systematic literature review examined the current state of the art of publications, which dealt with the identification of influencing factors for determining the fatigue behavior of work rolls in hot forming. The analysis revealed that this field is attaining higher interest in recent years. An overview, of the results as well as the influencing factors analyzed in each publication, can be obtained from the table in Appendix 1.

In conducting this work, two major research gaps were uncovered that offer potential for future research. First, the articles found, mainly focus on optimizing the service life of the work rolls. Here, all influencing factors except for the roll design are equally researched. Optimization is mainly implemented by optimizing material properties and control parameters or avoiding errors in production. Prediction of service life is addressed in only a few research papers. In conjunction with online prediction, there is only one research paper that explores the possibility of predicting maintenance timing in strip mills. Jiao et al. applied neural networks to predict the remaining time until the maintenance of the roll.[55] However, transferability to RARR is not possible due to significant process differences. Hence, suitable methods for the prediction of the service life with consideration of production scheduling are still missing. A reliable prediction of the service life of work rolls in the domain of RARR could optimize the production system as a whole so that the coordination of upstream and downstream production steps can be enhanced while avoiding downtimes.[67] Besides, developing the capability of accurately predicting the lifetime of mandrels could also enable manufacturers of RARR machines to adopt data-based service activities and embrace innovative business models such as Product-Service Systems.[68] Second, our study revealed that there is only one additional article that deals with the field of machine learning algorithms. Souto et al. uses neural networks to improve already existing models for calculating and predicting wear behavior.[25] Nevertheless, none of these machine learning algorithms were specifically focused on the domain of RARR. This indicates that the potential of machine learning algorithms to identify influencing parameters within the RARR domain still remains unexplored, although a sufficient data infrastructure for employing machine learning already exists.[5]

In addition, due to the challenges of measuring various influencing factors in real processes, such as temperature distribution [16,35] or heterogeneous mechanical stress distribution (e.g. [8,45,46]) besides the costly implementation of measurement setups in industrial plants, many studies are using simulations or experimental approaches (see Figure 4). In this context, machine learning algorithms offer a promising approach for industrial research, as they allow the inclusion of significant influencing factors without direct measurements. This is achieved by extracting relevant information from other measurable variables with known correlations and then inferring the non-measurable information.

Based on the research results presented here, in further research, it will be the main focus to investigate the suitability of machine learning algorithms for the prediction of the service life to fracture of mandrels. In particular, the thermal and mechanical influences will be in the foreground. Due to the removal of finished rolled rings and the loading of the line with new blanks, downtimes occur after each rolling operation where the mandrel can cool down. For this reason, emphasis is placed on the number and characteristics of the thermal heating cycles. The machine learning model can acquire knowledge about the mechanical stress of the rolls by incorporating the forming forces, prevailing forming rate, and the material composition of the rings. This integration enables the machine learning algorithms to gain valuable insights into the process factors, thereby minimizing information redundancies right from the outset.

Acknowledgements

Funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – 464881255.

Appendix

Appendix 1 Results of the systematic literature review

Legend:

● : Contains elements of the category

○ : Contains elements of the investigation procedure though it is not the main focus

✓ : Contains elements of predicting end of service

Author	Influencing Factors					Investigation Procedure				Investigation Objective		
	Temperature	Mechanical Stress	Material	Process factors	Roll design	Simulation Approach	Experimental Approach	In-situ Analysis	Post process Investigation	Wear	End of service life	Predict end of service
Akiyama et al. (2000) [53]	●		●			○	●		○		●	
Aridi et al. (2022) [12]		●	●			●			○		●	
Bataille et al. (2016) [61]			●						●	●		
Behrens et al. (2014) [22]		●		●		●				●		
Belzunce et al. (2004) [51]	●	●	●				●			●		
Bombač et al. (2017) [48]	●						●				●	
Bombač et al. (2019) [47]	●		●				●				●	
Cao et al. (2011) [21]			●	●		●				●		
Colás et al. (1999) [63]	●	●	●						●		●	
Delaunois et al. (2018) [37]			●				●			●		
Dobrik and Moiseenko (1984) [62]									●		●	
Dong et al. (2015) [45]		●					●				●	
Dong et al. (2015) [46]		●			●		●				●	
Dong and Cao (2015) [8]		●		●		●				●		
Drobne et al. (2014) [50]		●					●				●	✓
Drobne et al. (2017) [49]		●					●				●	
Fedorciuc - Onisa and Farragia (2008) [15]	●					●						
Flora et al. (2009) [40]	●			●			●				●	
Frolish et al. (2002) [44]		●	●	●			●			●		
Garza-Montes-de-Oca and Rainforth (2009) [33]	●		●				●			●		
Garza-Montes-de-Oca et al. (2011) [34]	●		●				●			●		
Guo et al. (2012) [23]				●		●				●		
Hu et al. (2019) [11]	●	●	●			●				●	●	✓
Jiao et al. (2021) [55]	●	●		●				●			●	✓
John et al. (2006) [58]				●				●			●	✓
Li et al. (2002) [28]	●			●			●			●		
Li et al. (2008) [29]	●			●			●			●		
Liu et al. (2017) [24]	●			●	●	●				●		
Lundberg and Gustafsson (1994) [16]	●		●			●	○			●		
Masoudi Nejad et al. (2021) [10]		●				●	○				●	✓
Mercado-Solis et al. (2005) [52]	●		●	●			●			●		
Mohammed and Widell (2003) [57]				●				●	○	●		
Molinari et al. (2005) [38]	●		●				●			●		
Musa-Zade et al. (1969) [54]					●		●				●	
Negahban Boron et al. (2022) [14]	●	●	●			●					●	
Niekurzak and Kubinska (2022) [60]				●					●		●	
Ohkomori et al. (1988) [41]	●	●					●				●	
Palit et al. (2015) [64]			●						●		●	
Palit et al. (2019) [65]				●					●		●	
Pellizzari et al. (2005) [30]	●			●			●			●		
Phan et al. (2017) [27]			●			●				●		
Qin et al. (2014) [26]		●	●			●					●	
Raudensky et al. (2013) [35]	●			●			●			●		
Ryu and Ryu (2003) [31]	●						●			●		
Servin Castañeda et al. (2014) [59]		●	●	●				●		●		
Sinha et al. (2014) [66]			●						●		●	
Song et al. (2018) [20]		●		●		●				●		
Song et al. (2018) [19]		●		●		●	○			●		
Sonoda et al. (2009) [42]	●	●					●		○		●	
Souto et al. (2022) [25]		●	●	●		●			○	●		
Struin et al. (2019) [56]				●				●		●		
Tolcha et al. (2019) [13]	●	●				●	○				●	
Traino et al. (2013) [18]		●				●				●		
Tremea et al. (2006) [32]	●		●				●			●		
Weidlich et al. (2019) [43]	●	●		●			●				●	
Wu et al. (2014) [9]		●		●		●				●		
Xiao-Feng et al. (2016) [39]		●	●	●			●				●	
Yuan et al. (2023) [17]				●		●					●	✓
Zhang et al. (2013) [36]	●						●			●		

References

[1] Hoffmann, H., Neugebauer, R., Spur, G. (Eds.), 2012. Handbuch Umformen, 2., vollständig neu bearbeitete Auflage ed. Hanser, München, 769 pp.

[2] Spuzic, S., Strafford, K.N., Subramanian, C., Savage, G., 1994. Wear of hot rolling mill rolls: an overview. Wear 176 (2), 261–271.

[3] thyssenkrupp Rothe Erde. SixSigma Projekt zur Analyse der Lebensdauer von Dornwalzen bei Rothe Erde, in: , Fachausschuss Ringwalzen VDEh.

[4] Fahle, S., Glaser, T., Kuhlenkötter, B., 2021. Investigation Of Suitable Methods For An Early Classification On Time Series In Radial-Axial Ring Rolling. Hannover : publish-Ing.

[5] Fahle, S., Kuhlenkötter, B., 2020. A Framework for Data Integration and Analysis in Radial-Axial Ring Rolling, in: Proceedings of the 1st Conference on Production Systems and Logistics. CPSL 2020, pp. 127–136.

[6] 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. http://www.alexandria.unisg.ch/Publikationen/67910.

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

[8] Dong, Q., Cao, J., 2015. Contact Deformation Analysis of Elastic–Plastic Asperity on Rough Roll Surface in a Strip Steel Mill. J Fail. Anal. and Preven. 15 (2), 320–326.

[9] Wu, S., Wang, L., Shao, Y., Yuan, Y., 2014. Vibration characteristic analysis of twenty-high rolling mill with local defect on roll surface based on the time-varying contact stiffness. Engineering Failure Analysis 42, 297–310.

[10] Masoudi Nejad, R., Noroozian Rizi, P., Zoei, M.S., Aliakbari, K., Ghasemi, H., 2021. Failure Analysis of a Working Roll Under the Influence of the Stress Field Due to Hot Rolling Process. J Fail. Anal. and Preven. 21 (3), 870–879.

[11] Hu, K., Zhu, F., Chen, J., Noda, N.-A., Han, W., Sano, Y., 2019. Simulation of Thermal Stress and Fatigue Life Prediction of High Speed Steel Work Roll during Hot Rolling Considering the Initial Residual Stress. Metals 9 (9), 966.

[12] Aridi, M.R., Noda, N.-A., Sano, Y., Takata, K., Sun, Z., Takase, Y., 2022. Fatigue failure risk evaluation of bimetallic rolls in four-high hot rolling mills. Fatigue Fract Eng Mat Struct 45 (4), 1065–1087.

[13] Tolcha, M.A., Altenbach, H., Shunki Tibba, G., 2019. Modeling fatigue crack and spalling for rolling die under hot milling. Fatigue Fract Eng Mater Struct 42 (12), 2611–2624.

[14] Negahban Boron, A., Maracy, A., Livani, M., Nikouei, S.M., 2022. Prediction of work-rolls failure in hot ring rolling process. SCI 29 (2), 461–477.

[15] Fedorciuc – Onisa, C., Farrugia, D., 2008. Investigations into Roll Thermal Fatigue in Hot Rolling. Int J Mater Form 1 (S1), 363–366.

[16] Lundberg, S.-E., Gustafsson, T., 1994. The influence of rolling temperature on roll wear, investigated in a new high temperature test rig. Journal of Materials Processing Technology 42, 239–291.

[17] Yuan, T., Sun, W., Chen, S., Wu, Z., Chao, L., He, A., 2023. Fatigue-Damage Prediction Model of Backup Roll of Hot Strip Mills and its Applications. J Fail. Anal. and Preven. 23 (2), 880–893.

[18] Traino, A.I., Rusakov, A.D., Ogol'tsov, A.A., Mishnev, P.A., Golovanov, A.V., 2013. Application of the finite difference method for refining the model of the wear of work rolls in a broad-strip mill. Russ. Metall. 2013 (5), 332–335.

[19] Song, G., Yang, Q., Wang, X., 2018. Research on Wear Evolution Laws of the Work Rolls during Hot Temper Rolling Process. J Fail. Anal. and Preven. 18 (4), 912–919.

[20] Song, G., Wang, X., Yang, Q., 2018. Study on mathematical model of work roll wear in skin-pass rolling of hot steel strip. Int J Adv Manuf Technol 97 (5-8), 2675–2686.

[21] Cao, J., Liu, S., Zhang, J., Song, P., Yan, T., Zhou, Y., 2011. ASR work roll shifting strategy for schedule-free rolling in hot wide strip mills. Journal of Materials Processing Technology 211 (11), 1768–1775.

[22] Behrens, B.-A., Lütke-Verspohl, I., Bouguecha, A., Matthias, T., 2014. Numerische Berechnung des Verschleißes an der Dornwalze eines Ringwalzprozesses in Abhängigkeit prozessrelevanter Parameter. Mat.-wiss. u. Werkstofftech 45 (7), 591–599.

[23] Guo, Z.F., Hu, J.H., Sun, X.Y., 2012. Study on Roll Wear Model for Hot Strip Mill. AMR 535-537, 697–700.

[24] Liu, Z., Guan, Y., Wang, F., 2017. Model development of work roll wear in hot strip mill. IOP Conf. Ser.: Mater. Sci. Eng. 207, 12022.

[25] Souto, N., Marchand, E., Gay, A., Koont, Z., Legrand, N., 2022. Performance Analysis of Work-Roll Wear Models on Hot Rolling. KEM 926, 621–631.

[26] Qin, X., Dale, S., Xie, L., Li, Y., 2014. Subsurface Rolling Contact Fatigue Damage Distribution of Backup Roll After Periodic Dressing. J Fail. Anal. and Preven. 14 (4), 491–496.

[27] Phan, H.T., Tieu, A.K., Zhu, H., Kosasih, B., Zhu, Q., Grima, A., Ta, T.D., 2017. A study of abrasive wear on high speed steel surface in hot rolling by Discrete Element Method. Tribology International 110, 66–76.

[28] Li, C.S., Liu, X.H., Wang, G.D., Yang, G., 2002. Experimental investigation on thermal wear of high speed steel rolls in hot strip rolling. Materials Science and Technology 18 (12), 1581–1584.

[29] Li, C., Liu, X., Wang, G., 2008. New Method for Evaluating Thermal Wear of Rolls in Rolling Process. J. Iron Steel Res. Int. 15 (6), 52–55.

[30] Pellizzari, M., Molinari, A., Straffelini, G., 2005. Tribological behaviour of hot rolling rolls. Wear 259 (7-12), 1281–1289.

[31] Ryu, J.-H., Ryu, H.-B., 2003. Effect of Thermal Fatigue Property of Hot Strip Mill Work Roll Materials on the Rolled-in Defects in the Ultra-low Carbon Steel Strips. ISIJ International 43 (7), 1036–1039.

[32] Tremea, A., Biggi, A., Corbo, G., Cescato, D., Pellizzari, M., Molinar, A., 2006. Performances evaluation of high speed steels for hot rolling by wear and thermal fatigue tests. Proceedings of the Iron & Steel Technology Conference 2, 1–9.

[33] Garza-Montes-de-Oca, N.F., Rainforth, W.M., 2009. Wear mechanisms experienced by a work roll grade high speed steel under different environmental conditions. Wear 267 (1-4), 441–448.

[34] Garza-Montes-de-Oca, N.F., Colás, R., Rainforth, W.M., 2011. On the damage of a work roll grade high speed steel by thermal cycling. Engineering Failure Analysis 18 (6), 1576–1583.

[35] Raudensky, M., Horsky, J., Ondrouskova, J., Vervaet, B., 2013. Measurement of Thermal Load on Working Rolls during Hot Rolling. steel research int. 84 (3), 269–275.

[36] Zhang, L.L., Lei, L.P., Zeng, P., 2013. Investigation of the Influence of Deep Rolling on the Thermal Fatigue Cracking for AISI H13 Steel. AMM 457-458, 127–130.

[37] Delaunois, F., Stanciu, V.I., Sinnaeve, M., 2018. Resistance to High-Temperature Oxidation and Wear of Various Ferrous Alloys Used in Rolling Mills. MTA 49 (3), 822–835.

[38] Molinari, A., Pellizzari, M., Tremea, A., Biggi, A., Corbo, G., 2005. Effect of matrix microhardness on thermal fatigue behaviour of spincast high speed steels for hot rolls. Materials Science and Technology 21 (3), 352–356.

[39] Xiao-Feng, Q., Jiajun, R., Feng, L., Tie, W., Liyang, X., Qiong, W., Xingguo, Z., 2016. Degradation of Cr5 backup roll material under rolling contact fatigue. mat express 6 (4), 357–362.

[40] Flora, M.G. de, Pellizzari, M., 2009. Behavior at Elevated Temperature of 55NiCrMoV7 Tool Steel. Materials and Manufacturing Processes 24 (7-8), 791–795.

[41] OHKOMORI, Y., KITAGAWA, I., SHINOZUKA, K., MIYAMOTO, R., YAZAKI, S., INOUE, M., 1988. Cause and Prevention of Spalling of Backup Rolls for Hot Strip Mill. ISIJ Int. 28 (1), 68–74.

[42] Sonoda, A., Hamada, S., Noguchi, H., 2009. Analysis of small spalling mechanism on hot rolling mill roll surface. Memoirs of the Faculty of Engineering. Kyushu University 69, 1–14.

[43] Weidlich, F., Braga, A.P.V., Del Silva Lima, L.G.B., Júnior, M.B., Souza, R.M., 2019. The influence of rolling mill process parameters on roll thermal fatigue. Int J Adv Manuf Technol 102 (5-8), 2159–2171.

[44] FROLISH, M.F., FLETCHER, D.I., Beynon, J.H., 2002. A quantitative model for predicting the morphology of surface initiated rolling contact fatigue cracks in back-up roll steels. Fatigue Fract Eng Mat Struct 25 (11), 1073–1086.

[45] Dong, Q., Cao, J., Li, H., Zhou, Y., Yan, T., Wang, W., 2015. Analysis of Spalling in Roughing Mill Backup Rolls of Wide and Thin Strip Hot Rolling Process. steel research int. 86 (2), 129–136.

[46] Dong, Q., Cao, J., Wen, D., 2015. Spalling Prevention and Wear Improvement of Rolls in Steel Strip Hot-Rolling Process. J Fail. Anal. and Preven. 15 (5), 626–632.

[47] Bombač, D., Gintalas, M., Kugler, G., Terčelj, M., 2019. Thermal fatigue behaviour of Fe-1.7C-11.3Cr-1.9Ni-1.2Mo roller steel in temperature range 500–700 °C. International Journal of Fatigue 121, 98–111.

[48] Bombač, D., Kugler, G., Markoli, B., Terčelj, M., 2017. Hot work roller surface layer degradation progress during thermal fatigue in the temperature range 500–700 °C. International Journal of Fatigue 104, 355–365.

[49] Drobne, M., Vuherer, T., Samardžić, I., Glodež, S., 2014. Fatigue crack growth and fracture mechanics analysis of a working roll surface layer material. Metalurgija 53, 481–484.

[50] Drobne, M., Klančnik, U., Terčelj, M., Fajfar, P., 2017. Thermal crack propagation during hot rolling and its influence on cast iron work roll degradation, in: . METAL 2017 - 26th International Conference on Metallurgy and Materials, Conference Proceedings. TANGER Ltd, pp. 408–413.

[51] Belzunce, F., Ziadi, A., Rodriguez, C., 2004. Structural integrity of hot strip mill rolling rolls. Engineering Failure Analysis 11 (5), 789–797.

[52] Mercado-Solis, R., Beynon, J.H., 2005. Simulation of thermal fatigue in hot strip mill work rolls. Scandinavian Journal of Metallurgy 34, 175–191.

[53] Akiyama, M., Tsubouchi, K., Tsumura, M., Hori, H., 2000. A study of the mechanism of crack initiation on a mandrel bar for mandrel mill rolling in a seamless tube. Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology 214 (2), 179–187.

[54] Musa-Zade, M.M., Mamedov, K.K., Aliev, I.P., Guseinov, K.R., Podzharskii, B.I., Guseinov, K.A., 1969. Effect of design parameters of mandrels on their service life. Metallurgist 13 (11), 713–715.

[55] Jiao, R., Peng, K., Dong, J., 2021. Remaining Useful Life Prediction for a Roller in a Hot Strip Mill Based on Deep Recurrent Neural Networks. IEEE/CAA J. Autom. Sinica 8 (7), 1345–1354.

[56] Struin, D.O., Toporov, V.A., Panasenko, O.A., P'yankov, A.G., P'yankov, K.P., Shkuratov, E.A., 2019. Increasing the Service Life of Continuous Rolling Mill Mandrels. Metallurgist 63 (7-8), 684–689.

[57] Mohammed, T., Widell, B., 2003. Roll Wear Evaluation of HSS, HiCr and IC Work Rolls in Hot Strip Mill. steel research int. 74 (10), 624–630.

[58] John, S., Sikdar, S., Mukhopadhyay, A., Pandit, A., 2006. Roll wear prediction model for finishing stands of hot strip mill. Ironmaking & Steelmaking 33 (2), 169–175.

[59] Servin Castañeda, R., Equihua Guillen, F., Torres Gonzalez, R., Facundo Arzola, I.A., 2014. Development of simple equation for calculating average wear of hot strip mill work rolls. Ironmaking & Steelmaking 41 (5), 369–376.

[60] Niekurzak, M., Kubińska-Jabcoń, E., 2022. Assessment of the Impact of Wear of the Working Surface of Rolls on the Reduction of Energy and Environmental Demand for the Production of Flat Products: Methodological Approach. Materials (Basel, Switzerland) 15 (6).

[61] Bataille, C., Luc, E., Bigerelle, M., Deltombe, R., Dubar, M., 2016. Rolls wear characterization in hot rolling process. Tribology International 100, 328–337.

[62] Dobrik, A.V., Moiseenko, I.I., 1984. An analysis of failures of hot rolling mill rolls and the development of methods of increasing their life. Mater Sci 19 (4), 357–360.

[63] Colás, R., Ramírez, J., Sandoval, I., Morales, J.C., Leduc, L.A., 1999. Damage in hot rolling work rolls. Wear 230 (1), 56–60.

[64] Palit, P., Jugade, H.R., Jha, A.K., Das, S., Mukhopadhyay, G., 2015. Failure analysis of work rolls of a thin hot strip mill. Case Studies in Engineering Failure Analysis 3, 39–45.

[65] Palit, P., Patel, S.N., Mathur, J., Shenoy, S., 2019. Analysis of a Progressive Failure of a Work Roll in Hot Strip Mill. J Fail. Anal. and Preven. 19 (5), 1297–1303.

[66] Sinha, P., Indimath, S.S., Mukhopadhyay, G., Bhattacharyya, S., 2014. Failure of a Work Roll of a Thin Strip Rolling Mill: A Case Study. Procedia Engineering 86, 940–948.

[67] Dreyfus, P.-A., Kyritsis, D., 2018. A Framework Based on Predictive Maintenance, Zero-Defect Manufacturing and Scheduling Under Uncertainty Tools, to Optimize Production Capacities of High-End Quality Products, in: Moon, I., Lee, G.M., Park, J., Kiritsis, D., Cieminski, G. von (Eds.), Advances in Production Management Systems. Smart Manufacturing for Industry 4.0, vol. 536. Springer International Publishing, Cham, pp. 296–303.

[68] Leonardo Silva Teixeira, E., Tjahjono, B., Crisóstomo Absi Alfaro, S., Manuel Soares Julião, J., 2012. Harnessing prognostics health management and product-service systems interaction to support operational decisions. Jnl of Manu Tech Mnagmnt 24 (1), 78–94.

Biography

Tobias Moser (*1994) is a research associate at the chair of production system at the Ruhr-University of Bochum since 2021. He earned a bachelor's and master's degree in mechanical engineering at the Ruhr-Universität Bochum. His primary research topics are machine learning, time series and radial-axial ring rolling.

Johannes Seitz (*1996) is a research associate at the chair of production systems at the Ruhr-University Bochum. He studied mechanical engineering at the Ruhr-University (B.Sc.) and the University Duisburg-Essen (M.Sc.). In his research he is using methods of machine learning and data mining for processes in the domain of forming technologies.

Enes Alp (*1993) is a research associate at the Chair of Production Systems (LPS) at the Ruhr-Universität Bochum. His primary research interest is in the area of simulation-based hyperheuristic optimization of the operative service delivery planning and scheduling within the context of Product-Service Systems. He also follows work on the use of Artificial Intelligence in production systems.

Bernd Kuhlenkötter (*1971) was responsible for product management and technology at ABB Robotics Germany until 2009. In 2009, Bernd Kuhlenkötter took over the professorship for "Industrial Robotics and Production Automation" at the Technical University of Dortmund. Univ. Prof. Dr.-Ing. Bernd Kuhlenkötter has held the professorship for "Production Systems" at the Ruhr University Bochum since 2015.

5th Conference on Production Systems and Logistics

The Job Role As A Reference Category For The Design Of Continuing Education In Production Companies

Pia Mozer[1], Bernd Dworschak[2]

[1]Institute of Human Factors and Technology Management/ Stuttgart University, Stuttgart, Deutschland
[2]Institute for Industrial Engineering / Fraunhofer, Stuttgart, Deutschland

Abstract

For effective Continuing Vocational Education and Training (CVET), a field of reference is needed. This can either be established through the concept of occupation (CO) or the actual job role. The concept of occupation can sociologically be understood as a community of practice of specialized people with particular qualifications and competences and therefore perform subtasks of larger groups and communities. "Members of this specialized community of practice gain knowledge about work processes, how to optimize procedures, and develop specific tools" [1]. Occupations are defined as social forms, whose members are similar to each other and different from others [2]. Organizational professions are understood as bundles of skills. The Standing Conference of the Ministers of Education and Cultural Affairs of the Länder in the Federal Republic of Germany (Kultusministerkonferenz, KMK) suggests a Concept of Capacity to Act (CCA) which can serve as an instruction for further vocational education. It is described as the individual's willingness and ability to behave in professional and social situations in an appropriately thought-out and individually and socially responsible manner [3] The CCA comprises the components of professional, social and personal competence, linked by methodological, learning and communication competence. These competence dimensions denote a leitmotif for the professional learning activities and processes. The occupation serves as a frame of reference for further education and training activities in the case of the professional community of practice, which is based on a group of people working in the field, with identical or very similar training and similar experiential process knowledge. These parameters can be used as a basis for the instructional design of competence development. Many jobs – most commonly in the field of academic positions in companies and organizations – are not defined by the CO, but by the actual job role. In production companies, employees who need to be addressed by the job role tend to work in fields like Research and Development or product design, whereas jobs that are structured by the CO can be found in production or logistics. People who execute a certain job role have various courses of study, professional experience, and competences. In contrast to jobs referring to the concept of vocation, there is no reference framework which can be used as a reference to design CVET. This has a direct impact on the didactics and instructional design, the skill and competence development in CVET. Due to the variation of knowledge and previous education, it is not possible in these cases to refer to a common training content. In these cases, CVET is not standardized in the same way as in the case of the occupations. Therefore, competence development goals cannot be structured in the same way. This raises the question on application of didactic and learning-theoretical basic categories to the conception of further training formats for this group of employees. However, it is still unclear if the job role as a category can be used as a frame of reference for CVET in a similar way as the CCA. The impact of the CCA and the job role on the learning theory and instructional design of CVET programs and competence development is evaluated in this article.

Keywords

Continuing vocational education and training; competences; occupation; job role; competence development

DOI: https://doi.org/10.15488/15314
ISSN: 2701-6277

1. Work structured by the concept of occupation versus job roles

Working conditions, working environments and working requirements are changing more rapidly with the accelerated release of new technologies, as well as with cultural and societal changes. This makes CVET and lifelong learning essential for organizations, companies, and individuals. For CVET, a field of reference is essential to establish the frame of the training and define a starting point of the training. In this paper, we look at two different reference approaches: The CO and the concept of the job role. The core of the CO is the dual apprenticeship. The dual apprenticeship is a unique training system in the vocational education and training in the German speaking countries (Germany, Austria, Switzerland and Lichtenstein). Apprentices learn and practice during their apprenticeship (usually two to three years) at two different training locations: The company and the vocational school (VS). Training in the companies takes place three to four days a week, with vocational school days on one or two days. This dual system with theoretical inputs from the school lessons and practical learning parts in the companies, is reflected in the CO. This concept means that the dual education is structured by recognized training occupations and prepares for specific activities. In this context, occupations can be understood as communities of people who have specialized qualifications and competences and therefore perform subtasks of larger groups and communities. *"Members of this specialized community of practice gain knowledge about work processes, how to optimize procedures, and develop specific tools [1].* In the field of production, jobs which are structured by the CO often are so-called blue-collar jobs. Many employees who are carrying out jobs on the shop floor are specialists with completed recognized training occupations.

In contrast to the CO, the concept of the job role is defined by the job description, which outlines the respective assignments, functions and tasks in a certain work area. There is no defined education and training way into a job role, it can be performed by people with numerous backgrounds.

Vocational education and training is strictly regulated for certain job roles and thus, occupations develop along the actual requirements of work. Changes of the work requirements are integrated into the training framework curricula of the dual apprenticeship to guarantee the innovation process within vocational education [4]. Thus, vocational learning is subject to continuous adaptation to labor market requirements and new technologies. Through vocational training, current knowledge from the work is carried directly into the training. The CO serves therefore as a central reference category for competence development and occupational communities of practice structure of the labor market and communities of practice, which allows identification with fields of action, work tools and a group of people [5].

2. Occupationally and academically structured fields of work

The occupation is a central category for CVET activities that can be initiated by the group members themselves. It is often related to the content of the working area. Thus, it serves as a central category for the didactic design of CVET activities. The competence orientation and the preceding contents of the dual apprenticeship provide a content-related and formal framing. Additionally, a relative homogeneity of the learning group can be assumed due to the similar learning biographies. These determinants provide a framework for the didactic design and content orientation of CVET activities [5]. Regarding the learning trajectory the fields of work structured by occupations contrast with fields of work that are mainly structured by job roles, which are supplemented by – predominantly academic – training paths. As a rule, academic training paths are independent from work and business processes.

Academic studies are integrated into the scientific processes of specialized disciplines. Conveying content in academic fields is based on a higher level of abstraction, with a focus on basic research. Basic curricula consist of fundamental subjects such as mathematics and the natural sciences. For example, an aspiring production engineer has to focus on mathematical and scientific studies before specializing on applied content in advanced studies. Training for the actual job role is predominantly independent from academic studies. Thus, design and structure of CVET is subject to other premises than jobs that are structed by the CO.

In the following section, the central reference points for competence development in training occupations, both structured by the CO (Chapter 3) and by job roles (Chapter 4)) are described. Finally, indications for the design of CVET in production are contrasted and summarized (Chapter 5).

3. Frame of Reference Concept of Occupation

The Concept of Occupation consists of the following core aspects:

- The Concept of the Capacity to Act (CCA, *berufliche Handlungsfähigkeit*),
- The community of practice
- The shared occupational and learning biography.

Below, abovementioned aspects and a discussion of their relevance to CVET are described.

3.1 Concept of the capacity to act professionally

The CCA allows apprentices to acquire "vocational skills, knowledge and abilities that are necessary to do qualified occupational work in a changing world and to acquire the necessary work experience" [6]. The CCA is a fixed element of the dual apprenticeship by the German Vocational Training Act (Berufsbildungsgesetz 2005).

The Concept of Competence (CoC) is central to the CCA. While there are several approaches to define the CoC, this paper focuses on the concept of The Standing Conference of the Ministers of Education and Cultural Affairs of the States in the Federal Republic of Germany (KMK) as the central actor within vocational education and training. The CoC simply means that actions are divided into different types of skills and abilities to execute them. Competences can be understood as the ability to apply learning outcomes adequately in a defined context which may be work, education or personal areas [7].

CCA comprises the components **of professional, social and self-competence**, linked by **methodological, learning** and **communication competence (KMK)**.

Vocational training – with a focus on professional skills – aims to develop skills in everyday professional life.

Professional competence within the KMK´s concept is defined as the "willingness and ability to solve tasks and problems in a goal-oriented, proper method-oriented and independent manner on the basis of professional knowledge and skills and to assess the result" [3] . **Self-competence** is "the disposition to clarify, think through and assess development opportunities, demands and limitations in family, work and public life, to develop personal talents and to formulate and develop life plans" (Federal Ministry of Education and Research (*Bundesministerium für Bildung und Forschung*, BMBF)). This includes qualities such as independence, critical thinking, self-confidence, reliability, and sense of responsibility. It also includes the development and self-determined commitment to well-thought-out ethical values. **Social competence** represents the willingness and ability to live and shape social relationships, to grasp and understand affections and tensions, and to engage and communicate with others rationally and responsibly. This includes the development of social responsibility and solidarity.

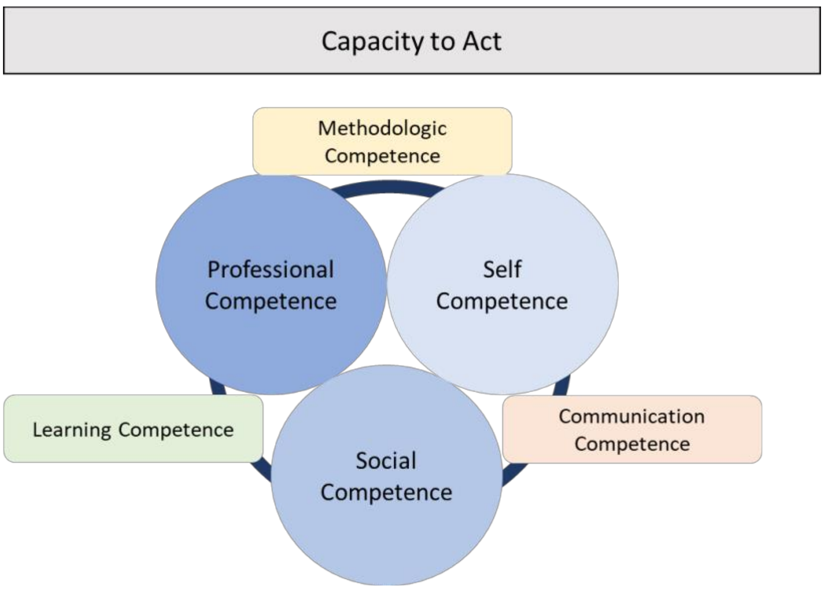


Fig.1 BMBF Concept of Professional Competence [8]

Cross Cutting Competences consist of the communicative competence, the learning competence and the methodic as cross-cutting competences. **Communicative competence** is the willingness and ability to understand and shape communicative situations [3] This includes the ability to think critically and develop an own opinion, being aware of needs and intentions as well as communicating them to others in a understandable way. But also, the comprehension of the thoughts and needs of others is meant by the communicative competence.
Learning competence is the willingness and ability to understand and evaluate information about facts and contexts independently and together with others. To classify information in mental structures and patterns. Learning competence also includes the ability and willingness to develop learning techniques like metacognitive strategies to observe which learning strategies work well. The application of those techniques on the job and beyond the job sector and to use them for lifelong learning are comprised within the learning competence as well. **Methodological competence** is a key competence that refers to the ability to use different methods to obtain, structure and analyze information. Methodological competence also means recognizing connections and deriving solutions from these structures [7].

Within the KMK framework CCA is described a blend of knowledge and skills. It is defined as the ability and willingness to work independently on professional tasks and to solve problems in a professionally appropriate and methodical manner – CCA includes the ability to assess the outcome and to derive patterns or re-evaluate workflows. A person's professional competence enables them to successfully master certain tasks, problems or challenges in his or her field of expertise [3].

Vocational actions can be fully structured and translated into training objectives, utilizing the conceptualized vocational action processes as defined within the CCA. In this way, requirements that arise (e.g. due to innovative technologies) are integrated into vocational training. This enables the restructure of training with content that responds to the changing work requirements in the various areas. In addition, the CCA enables the content to be organized and structured according to a system that emphasizes the progression of competence development from vocational novice to expert in professional work. Content can be organized by components of qualification, consisting of coherent sets of knowledge, skills and competences. A unit can be the smallest part of a qualification that can be assessed, transferred and, possibly, certified [7].
Vocational education and training provide a framework through the competence development goals, that represent an organizational framework for CVET. The learning content for further training can be designed along or complementary to the training regulations specified by the fields of action.

3.2 Community of Practice

The second aspect of the Concept of Professionalism, which can serve as a reference for instructional design for CVET, is the so-called *communities of practice* with their shared training and working experience. This leads to common ways of thinking and acting, as well as similar rituals. This enables the development of templates for thinking and action that can be applied in similar situations, while at the same time allowing for the integration of innovation. Due to the steady renewal of vocational training (see section above), as well as the identification with and affiliation to a vocational community of practice, the dual apprenticeship contributes to a high innovation potential. German small and medium-sized enterprises (SMEs) with their high level of training have the highest values in the EU for self-developed innovations, as well as innovations in sales, organization, and production (EU 2010). The strength of German industry therefore lies in the large number of skilled employees, who can contribute to optimized working processes and innovation through the CCA [9].

Therefore, the CCA is embedded in larger contexts than just the immediate wage-earning function. It connects a business and social context that cannot be reduced to the profit orientation of the employing or qualifying companies. Early on, this function was defined as an "inner vocation" or contribution to identity formation. It is based on the assumption of social tasks, which goes back to the original social division of labor and to which professions can still be assigned today [2].

Members of a professional community resemble each other based on shared collaborative experiences that impact them. This causes an alignment between one another and a difference in relation to the others. “These considerations again make a strong point, how into the occupation-relevant knowledge and ability certain personality structures are embedded, here in the form of certain handling forms with itself (its personal past, its experiences, fears and hopes) in addition, in the form of certain argumentation styles, ways of understanding the world, forms of thinking and consciousness" [10]. Occupations are to be understood as social forms that emerge in certain regions and cultures and as subcultures of a society, "formative on those who enter them and those who deal with them" [2].

This is useful when designing CVET programs: The members of the community have a similar understanding of their work processes and the goals of their work. They have a similar understanding of materials and dangers involved with their working process. For example, welder share a common experience related to working materials and have common knowledge about how to deal with problems that might come up during work processes. All of this can be presupposed by the instructor when elaborating the didactic design.

3.3 Identification through training and professional biography

Considering the community of practice and the sense of identification with the profession that comes with it, people have a similar training biography, which represents an additional identification factor: occupational and learning biography.

The feeling of identification with the community of practice is strengthened by the fact that people working in these professions have similar training histories. This represents another identification factor. Both, structural and individual characteristics, contribute to the formation of identification with the respective professional field.

With the development of CCA, a professional identity is formed. The nature of professional requirements and the willingness to solve and master them are essential for the development of identification with professional tasks. This desire forms a common basis among the learners.

In addition, there is the socialization through the trainees' institutions. The trainees are shaped by the same experience of attending both places of learning, (vocational) school and company, and learning together in theory and practice. They learn on practical and theoretical exams and thus develop similar learning heuristics. This shared influence creates a sense of identification with each other and, ideally, with the profession in terms of professional ethics.

Such a sense of professional responsibility – as an expression of professional ethics as action-reflective knowledge – is an essential prerequisite for responsible professional action and thus for professional design competence [11]. This is shared among the trainees. Ideally, ethics goes closely together with the desire to maintain and improve the professional environment in terms of work design [11]. On the one hand, this can be conducive to the design of further education formats since the learners bring their own concerns in terms of content and concept. Furthermore, it simplifies the didactic design of further education since a group with similar learning requirements can be assumed.

The concept of competence-oriented training with practical components in the company, the community of practice and the shared learning biographies enable a targeted and tailor-made further training design, that can be strictly oriented towards the needs of the learners.

4. Job role reference frame

In areas of production that are design and development oriented, there are many fields of activity that are carried out by people whose work and training are not governed by the CO, but by job descriptions or job roles. The lack of a CO means that employees have different, mostly more abstract qualifications. They only get to know the job requirements while working. Fields of activity that require academic education are therefore not filled with people who have had reproducible training. They often learned more abstract, non-specific content with a strong focus on methods that can be used in various fields of application. The abovementioned reference points for CVET must be reconsidered at this point. In these cases, the knowledge and skills relevant to the activity are located differently and the training and biographies of those carrying

out the work differ considerably. This has a direct impact on the didactic design of learning, education and competence development processes in work-related CVET. In these cases, it is not possible to refer to the CCA, the community of practice or the common learning experiences in vocational training.
CVET cannot be standardized in these use cases in the same way as for training professions. Therefore, other learning theories and basic categories must be applied to create effective training for this group of employees.

4.1 Analysis of tasks within the job role

To be able to conceptualize further training needs in these fields of work, the work tasks and job descriptions as well as the company are considered as central reference points for the didactic design of job-related further training. The work tasks and activities usually merge into the job role. When determining the objectives of the further training programs, the importance of the company is in the foreground, as the corporate strategy sets direction and content of the further training. In order to design the learning objectives, the current specific activities, i.e., the job role of the person carrying out the work, must be seized accordingly. The basis of this analysis can be the competence assessment and survey. This involves looking at the work tasks that employees in a particular job role are currently performing. These work tasks serve as an anchor for the development of further training activities. In contrast to the classic work and requirements analysis, it is not the content of the individual tasks (the "what") that is relevant, but how they can be mastered in a goal-oriented and successful manner (the "how") [12]. To determine the goals of continuing education activities, it is usually important to align them with strategic corporate goals. The analysis of a work environment with the modeling and design of competence building activities is described, for example, in the Competence Compass developed at Fraunhofer IAO.

4.2 The Fraunhofer Competence Compass as an instrument for analyzing work tasks and the design of continuing training

The Fraunhofer Competence Compass describes an approach for identifying the goals of CVET through strategy linkage by the identification of competences and their development of competences through training activities. The Fraunhofer Competence Compass can be used to identify competence needs in organizations [13]. It offers a systematic approach for strategic competence management with the analysis, design, and balancing of continuing training needs and strategic competence development as well as continuing education planning for organizations.

For all stakeholders involved, such as employees and managers, it is necessary to schedule sufficient time for the competence needs assessment. Depending on the focus, the assessment can be carried out, for example, in the form of interviews, employee discussions, management discussion rounds, etc. This applies not only to the actual time required for the competence needs assessment, but also to the planning, introduction and follow-up for all stakeholders involved in the process.

Orientation of the further training activities
The first step is to determine the goal of the CVET. In order to design training activities in a didactically meaningful way, the goal of the activities must first be determined. This can be done, for example, by holding workshops with subject matter experts and executives to derive specific fields of action from the corporate strategy and to identify areas of activity that the company will need to master in the future. This is followed by the specification of tasks in the fields of action that the company, its departments or employees will have to master in the future. In an internally or externally moderated workshop with relevant representatives of the company, the current situation of the company can be systematically examined, and future developments and strategic targets can be reflected upon. Strategic learning objectives for further training can be derived from this.

Competence assessment
The competence assessment ensures that the required competences are available for all important work tasks in organizations and that employees are optimally qualified for current and future tasks. Therefore, the

second step is the systematic structuring and specification of a model considering the work context. To create a competence model, competence classes must first be selected according to which the competence requirements assessment is to be structured. A competence model includes competence classes (*Which competences do we want to consider?*), the scope of the model (*A model for the whole organization or only for certain functions?*), assessment levels or competence levels (e.g. beginner-expert) and the specification of competence profiles (*Existing competences today? Important competences in the future?*). A competence model also defines key terms for the organization and creates a common understanding among all stakeholders [14].

Competence Measurement

The decision of a competence model for the fields of work for which further training activities are designed, is followed by the third step. The third step is to measure and assess the existing competences within the framework of the competence model and a competence requirement assessment. In measuring and assessing competences, it is necessary to answer the question of which competences exist today and at what level, and which competences need to be developed or acquired in the future. Methods of measuring existing competences are for example, self-assessment and external assessment of employees, observation of work processes, interviews and questionnaires, and, if necessary, further assessments.

The measurement results in the *ACTUAL* competences of the employees. These *ACTUAL* competences can now be contrasted with the required *TARGET* competences of the strategic corporate, divisional and departmental goals from step 1In this way, "gaps", which contain the goals of the further training activities become visible. The contents of the gaps represent the contents of the CVET.

Competence development

This also represents the fifth step in the competence compass. This step is about the way in which competences can be built up and (further) developed.

Depending on the training objective, a specific method is suitable. For example, a self-learning phase or trainer input may be well suited to impart knowledge. For building specific skills or developing a specific behavior, other methods like business simulation games, simulations, or role plays, are better choices [15]. The proximity or remoteness of the training to the workplace also depends on the objective of the measure [16]. Should the learning activities take place in the process of work in order to learn as close to the application as possible or are cross-situational competences addressed that are initially learned outside of an everyday work situation. The type and content of the build-up measure are derived from the respective objective. In addition, it must be determined whether the measure is more concerned with the development of a specific behavior or rather with the transfer of knowledge. It must also be determined which employee groups are to be addressed and to what extent.

For a meaningful and targeted design for a successful implementation, a competence needs assessment requires clear responsibilities for the design and implementation of the activities and acceptance by all stakeholders. This can be achieved, for example, through planned change management.

Competence reassessment

The activities can be assessed in a fifth step to evaluate wether they have been successful in the sense that the competences have been developed or if the need to be adjusted.

5 Conclusion

The two approaches different core concepts of competence development show that both, the CO and work in the sense of the job role, can serve as a field of reference for the design of curricula and the didactic structure of CVET. The argumentation explicitly shows that the orientation towards occupations offers a more structured framework. It allows an orientation towards existing competence frameworks and qualifications when creating CVET offers.

The communities of practice serve as a framework because they enable the reintegration of work changes, and work experiences into the curricula. Therefore, curricula are always up to date, allowing for state-of-the-art training- and CVET. Similar learning biographies allow instructors to find familiar learning formats. Additionally, instructors benefit from homogeneous prior knowledge of learning methods within the group.

Regarding the non-occupationally organized fields of activity, it is first necessary to identify the existing qualifications and competences. A structure for competence development needs to be elaborated in the different work contexts. This provides a basis for determining which skills can be assumed. Once the skills have been analyzed, they can be a starting point for the didactic design of further education, like in the occupational fields.

Communities of practice can be replaced by identification factors such as the product or the job family. In many cases, a similar learning biography cannot be assumed for activities organized by job role. During the academic study, it would be worth considering whether the increased emphasis on methodological competences, as well as the socialization processes can be treated as similarities in learning biographies.

The two approaches to the design of continuing education and training show that both occupation and work in the sense of the job role can serve as a reference field for determining competences and designing continuing education and training. In this way, the job role or work as a reference field for continuing education has similar orientation factors as the occupation. In general, however, it can be stated that vocational education is more pre-structured, and this simplifies the didactic design of continuing education and training.

Nevertheless, there are also many cases in which both, vocationally and academically trained employees, need to build up competences, e.g., through the introduction of a new technology. It should be noted that the needs of both groups must be considered to ensure successful competence development.

References

[1] Fischer-Elfert, H.-W., 1997. Berufliche Bildung und Ausbildung im alten Ägypten, in: Liedtke. M. (Ed.), Berufliche Bildung - Geschichte, Gegenwart, Zukunft, pp. 27–52.

[2] Schapfel-Kaiser, F., 2008. Beruf und Zeit: Pilotstudie zum Zeiterleben in Erwerbsberufen am Beispiel von Hebammen, Straßenbahnfahrern, leitenden Angestellten und Künstlern. Bertelsmann, Bielefeld, 335 pp.

[3] KMK, Sekretariat der Kultusministerkonferenz Referat Berufliche Bildung, Weiterbildung und Sport (Ed.), 2021. Handreichung für die Erarbeitung von Rahmenlehrplänen der Kultusministerkonferenz für den berufsbezogenen Unterricht in der Berufsschule und ihre Abstimmung mit Ausbildungsordnungen des Bundes für anerkannte Ausbildungsberufe.

[4] Frank, I., Hackel, M., 2016. Neu geordnete Ausbildungsberufe nach BBiG/HwO: Begriffe, Sonderfälle und Empfehlungen. Bundesinstitut für Berufsbildung, Bonn, Online-Ressource.

[5] Krikler, K., 2017. Zielgruppenspezifische didaktische Gestaltung von Weiterbildungsmodulen: Eine Befragung von Fachkräften und Alumni. Hochschule und Weiterbildung (1), 99–105.

[6] Berufsbildungsgesetz 2005: § 1 Abs. 3 BBiG.

[7] European Centre for the Development of Vocational Training., 2017. The changing nature and role of vocational education and training in Europe.Volume 1, Conceptions of vocational education and training : an analytical framework. Publications Office.

[8] BMBF, Bildungsministerium für Bildung und Forschung. https://www.prueferportal.org/de/.

[9] Bosch, G., 2016. Ist die industrielle Ausbildung ein Auslaufmodell? Denk-doch-mal.de: Online-Magazin für Arbeit - Bildung – Gesellschaft (1), 1–7.

[10] Beck, U., Brater, M., Daheim, H., 1980. Soziologie der Arbeit und der Berufe: Grundlagen, Problemfelder, Forschungsergebnisse. Rowohlts deutsche Enzyklopädie, in: , Rowohlts deutsche Enzyklopädie, Reinbek bei Hamburg.

[11] Heinemann, L., Rauner, F., 2008. Identität und Engagement: Konstruktion eines Instruments zur Beschreibung der Entwicklung beruflichen Engagements und beruflicher Identität. A+B Forschungsberichte (1).

[12] Kauffeld, S., Paulsen, H.F.K., 2018. Kompetenzmanagement in Unternehmen: Kompetenzen beschreiben, messen, entwickeln und nutzen. Verlag W. Kohlhammer, Stuttgart, 1 Online-Ressource.

[13] Bauer, W., Dworschak, B., Zaiser, H., 2017. Weiterbildung und Kompetenzentwicklung für die Industrie 4.0, in: Vogel-Heuser, B., Bauernhansl, T., Hompel, M. (Eds.), Handbuch Industrie 4.0. Springer Vieweg, Wiesbaden, pp. 125–138.

[14] North, K., Reinhardt, K., Sieber-Suter, B., 2018. Kompetenzmanagement in der Praxis: Mitarbeiterkompetenzen systematisch identifizieren, nutzen und entwickeln, 4., überarb. u. erw. Aufl. ed. Springer Gabler, Wiesbaden.

[15] Blaha, C., 2021. Bildungs-Controlling: Wir müssen Personalentwicklung messen, um sie weiterentwickeln zu können, in: Eschenbach, R., Baumüller, J., Siller, H. (Eds.), Funktions-Controlling. Springer, Wiesbaden, pp. 65–84.

[16] Karapidis, A., Becker, T., Zimmermann, V., 28. Novmber - 30. Dezember 2005. Knowledge Work and Learning at the Workplace - Key Issues and Solutions. 13th International Conference on Computers in Education, 28. Novmber - 30. Dezember 2005, Singapore.

Biography

Pia Mozer has been a researcher of the Institute for Vocational Education and General Pedagogy (IBAP) at the Karlsruhe Institute of Technology. Since 2022 she works at the Institute of Human Factors and Technology (IAT) at the Stuttgart University in the field of Competence Management. She is also a member of the German Society for Higher Education Didactics (DGHd).

Bernd Dworschak 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.

5th Conference on Production Systems and Logistics

Application Of The Dynamic Tolerancing Approach To The Assembly Of Fuel Cell Stacks

Andreas Aichele[1], Oliver Mannuß[1], Alexander Sauer[1,2]

[1]*Fraunhofer Institute for Manufacturing Engineering and Automation IPA, Stuttgart, Germany*
[2]*Institute for Energy Efficiency in Production, University of Stuttgart, Stuttgart, Germany*

Abstract

The proton exchange membrane fuel cell (PEM-FC) makes it possible to provide electrical energy for a wide range of applications without polluting emissions as a by-product. However, various challenges need to be overcome before widespread use of this technology is possible. In addition to optimizing its performance and lifetime, a key challenge is to reduce production costs. Production processes significantly affect these three objectives. Tighter manufacturing tolerances on the main components, membrane exchange assembly and bipolar plate, for example, can improve the functions above. However, manufacturing to tighter tolerances usually leads to higher production costs. To resolve the contradiction between 'tight tolerances' and 'low costs', the principle of dynamic tolerancing was developed. So far, this principle has only been implemented for a shaft-hub connection. The approach presented here applies the principle to the assembly process of a stack for a PEM-FC and shows how the channel offset within a stack can be reduced without increasing the requirements for individual part tolerances.

Keywords

Manufacturing technology; Assembly process; Cost reduction; Manufacturing tolerances; Stack assembly

1. Introduction

Fuel cells are becoming increasingly important as a source of energy. They convert chemical energy, provided in the form of fuel and an oxidant, into electrical energy. The fuel cell technology discussed in this paper is the polymer electrolyte membrane (PEM) fuel cell, which runs on hydrogen. It is the most common type. Compared to other fuel cells, the PEM fuel cell offers high (electrical) efficiency, low reaction temperatures, good quick-start capability, availability and handling of the fuel, and a high level of technological maturity [1].

1.1 Research issue

An essential criterion for the suitability of fuel cells for mass production, besides available infrastructure [2] and acceptance [3], is cost. It includes not only fuel costs but also the costs of producing the fuel cell. The manufacturing costs of fuel cells are currently higher than those of combustion engines of the same size. The largest share of manufacturing costs is attributed to the assembly of the fuel cell stacks, in particular for composing the bipolar plates (BPP) and membrane exchange assemblies (MEA) [4]. As some of this work still needs to be done manually, it represents a quality- and time-critical bottleneck in production [5]. The long-term goal is to further develop the production processes to allow for automatic mass production of the fuel cell and thus reduce production costs [6] and improve quality. A major influence on the quality of the fuel cell stack is geometry [2]. For constant and consistent functionality, the geometries must be

DOI: https://doi.org/10.15488/15318
ISSN: 2701-6277

manufactured reproducibly within narrow tolerance limits. This can be achieved by very tight tolerances on the individual components and by high accuracy of the systems involved in the process. Both measures lead to higher manufacturing costs, which contradicts the goal of reducing production costs.

1.2 Objectives and tasks

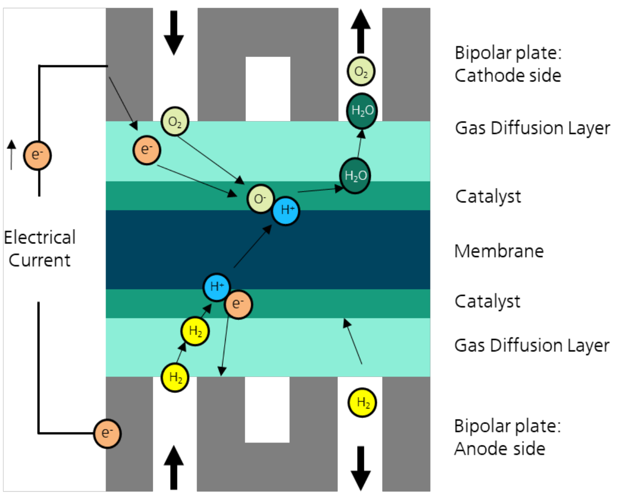
Lorenzoni was able to resolve the contradiction of high quality vs. larger tolerances with his approach of dynamic tolerancing using a shaft-hub connection (Lorenzoni et al., 2019). Since a fuel cell stack is different from a shaft-hub connection, this paper aims to examine a possible application of dynamic tolerancing and to develop it further, if possible. Therefore, the paper addresses the following issues: Section 2 of the paper presents the necessary fundamentals. These are, in overview, the PEM-FC, the fuel cell stack including the manufacturing process, the geometric quantities relevant to quality, and Lorenzoni's dynamic tolerancing approach. Section 3 presents the developed approach. Section 4 gives a short summary and an outlook on further objectives for research on this topic.

2. State of the Art

The following gives an overview of the functionality and structure of a PEM-FC. It explains the stack and points out where applying dynamic tolerancing offers potential. Then, the most important geometric parameters influencing the characteristics of a PEM-FC are mentioned, and the approach of dynamic tolerancing is presented.

2.1 PEM-FC

As mentioned above, PEM-FC converts the chemical energy of hydrogen into electrical energy by adding an oxidizing agent. The essential components are two electrodes separated by two gas diffusion layers, two catalysts, and a semi-permeable membrane. The two electrodes, anode and cathode, are bipolar plates in the PEM-FC. On the anode side, hydrogen oxidizes to cations. On the cathode side, oxygen reduces to anions as an oxidant and can react directly with the hydrogen ions diffused through the membrane to form water (see Figure 1, left side). The voltage generated in this process is insufficient for most applications. Therefore, several cells are arranged in a stack and connected in series [3]. The bipolar plates act on one side as an anode for a single fuel cell and on the other side as a cathode for the next single cell of the stack. In addition, the gas diffusion and the catalyst layers are usually applied to the MEA. This structure is complemented by a current collector and an end plate at each end of the stack (see Figure 1, right side) [4].



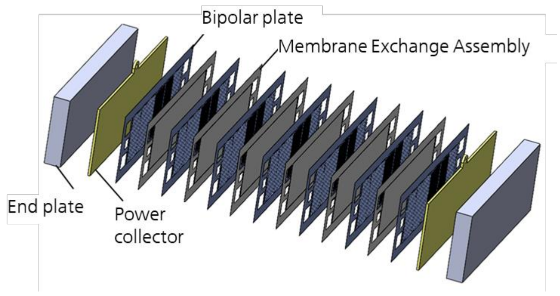


Figure 1: Left: design and function of a PEM-FC based on [4]; above: schematic structure of a fuel cell stack [5]

The stack assembly starts with pre-assembling the lower-end plate and the lower current collector. Then, the MEAs and BPPs are alternately placed on the stack. After depositing the required number of MEAs and BPPs, the upper current collector and the upper-end plate are placed next. Guide elements are used to ensure the exact alignment of the individual components of the stack (see Figure 2). [9]

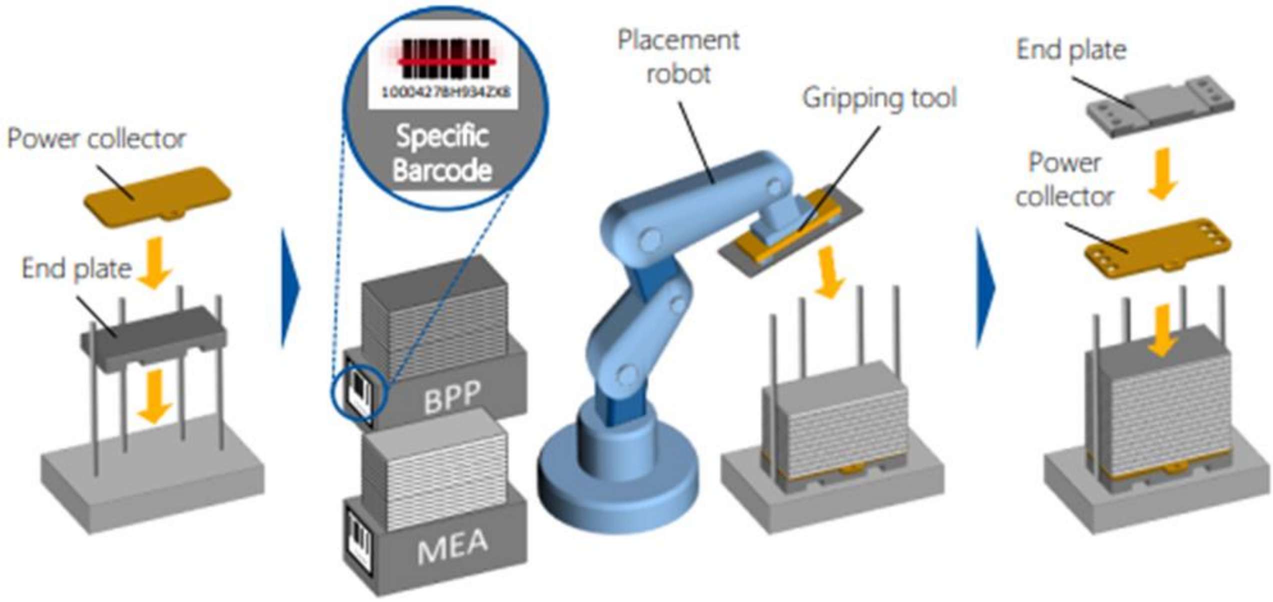


Figure 2: Illustration of the stacking process [9]

2.2 How geometrical sizes of the fuel cell stack and its components affect the target sizes of the PEM fuel cell

A literature search prior to this paper identified a number of important geometric variables for fuel cell performance [2]. Power and lifetime of a fuel cell, for example, were assumed as relevant performance criteria. 'Flatness of the stack', 'different channel depths', 'channel offset', and 'channel cross-section' were identified as influencing geometric variables [10,7,6,8,9]. The focus of this paper will be on the 'channel offset': In a stack, opposite BPPs are arranged mirroring each other. The aim is to achieve an exact match of the opposing flow fields so that the individual channels of the two flow fields coincide. If they do not coincide, this is referred to as a channel offset (see Figure 3). Aichele shows that this misalignment affects various functions of a PEM-FC and reduces the performance and lifetime of a PEM-FC [2]. The misalignment is production-related and can have the following causes:

- Variations in the spacing of the channels (absolute and with respect to parallelism) of the BPP during primary forming and welding of the plates [11]
- Varied position of the flow field to the reference points of the stack, depending on how the individual BPP is cut from the coil [12]
- Varied stacking positions in assembly due to inaccuracies of the robots and fixtures used [13]

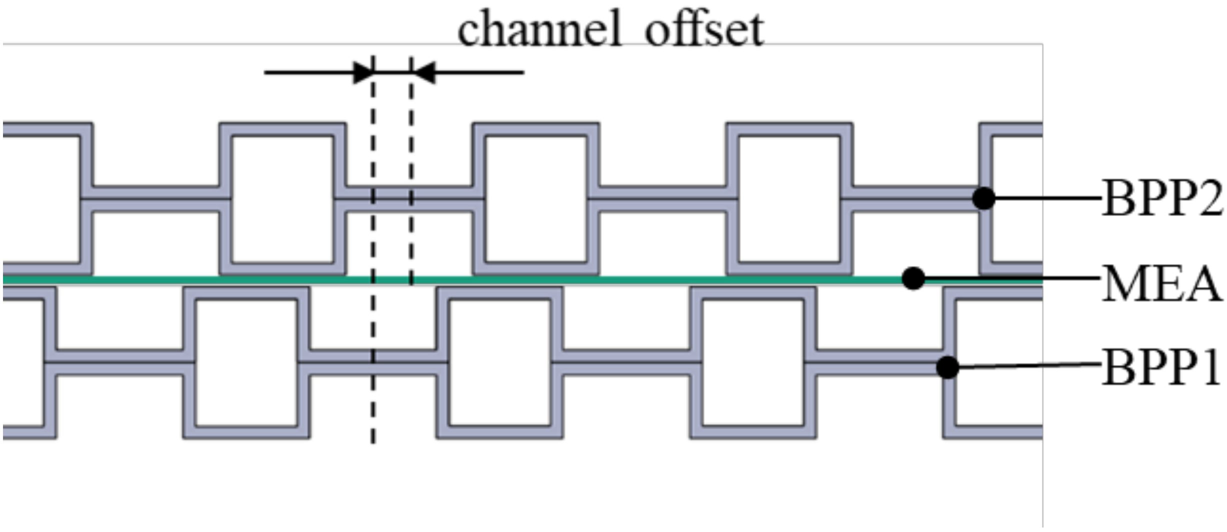


Figure 3: Schematic representation of two superimposed BPPs with channel offset based on [14]

2.3 Dynamic Tolerancing

The dynamic tolerancing methodology involves manufacturing two components of a fit function in sequence and logistically combining them in an assembly. In the first step, the first component of the assembly is manufactured. In the next step, the geometric size required for the fit function is measured and documented. The target value of the geometric size of the second component relevant to the fit function is calculated based on the actual value of the first component. The second component is then manufactured to these specifications (see Figure 4). The matched components are then assembled. The advantage of this method is that it eliminates the need to divide the tolerance field available for manufacturing between two components. Instead, it can be used either for manufacturing processes with lower tolerance requirements, thus saving costs. Or, it can be used to achieve higher accuracy and thus higher quality of the fit function for the same manufacturing cost. [15,16]

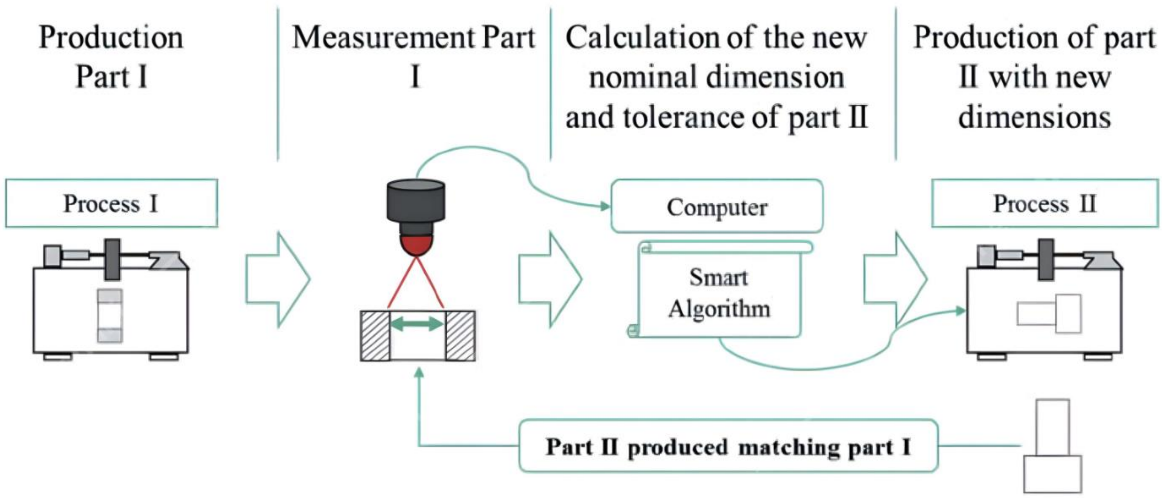


Figure 4: Basic approach of dynamic tolerancing [16]

3. Approach

A straightforward application of the dynamic tolerance approach described in Section 2.3 to channel misalignment in a fuel cell stack is not practical. In the case of hydroformed BPP, it is not possible to adjust the channels without significantly increasing the cost. Therefore, the dynamic tolerance approach must be applied in a different way. The first part of this chapter develops a basic scheme for doing this. The second section provides further details, including an example calculation. Section 3 integrates the concept into the overall stack assembly process.

3.1 Transfer of the basic idea

Although in a different manner, the basic idea of dynamic tolerancing can also be applied to stack assembly. Dynamic tolerancing consists of three building blocks: Information, criteria, and options. Information represents the actual value of the first component. Criteria is the fitting function to be fulfilled. Together, information and criteria are used to derive the options, i.e., the target dimension, including the tolerances for the second component that still needs to be produced.

To apply this concept to the stacking process, we also need information, criteria, and options but in a different sequence: Information indicates the actual values of the geometric quantities of the BPP to be stacked. Instead of criteria, options come first, implying alternative stacking options. With actual values and alternative stacking options, it is possible now to check how the criterion can best be fulfilled for a BPP to be joined. To create alternative stacking options, several stacks can be stacked in parallel in the process. On the other hand, a point-symmetrical design enables an additional stacking option rotated by 180°. Assuming that two stacks are stacked in parallel and a point-symmetrical design is present, four stacking options are available (see Figure 5).

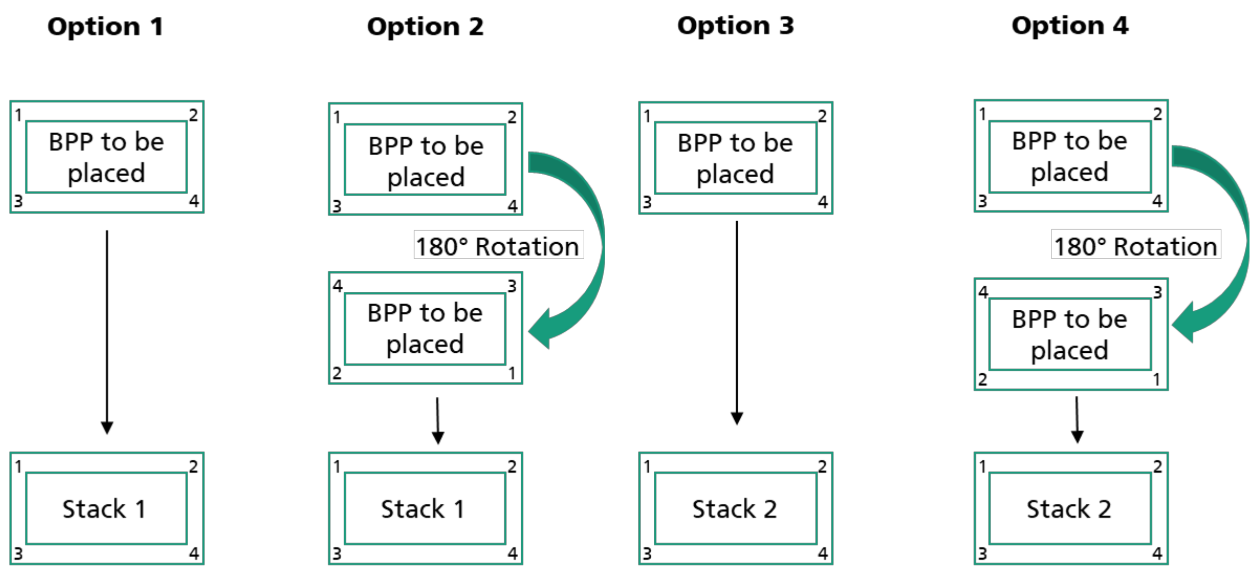


Figure 5: Placement options for the next BPP to be placed. The numbers in the corners indicate the orientation of the respective BPP.

3.2 Marginal conditions and sample calculation

For the further detailing of the approach the following marginal conditions have to be considered:

1. With regard to the causes of channel misalignment to be considered (see section 2.2):
   - Due to the tool-bound process of hydroforming in the production of the BPP, the variances in the distances between the channels (absolute and with regard to parallelism) are minimal and thus negligible [17].
   - The channel offset caused by inaccuracies of the robots and fixtures used, only arise during assembly. The approach of dynamic tolerance uses dimensions that arise before assembly.

   It follows that only the varying position of the flow field in relation to the reference points of the stack can be considered in the dynamic tolerance approach.
2. A relevant deviation of the flow field occurs only in the x-direction, since this can be caused by the cutting process. No offset is to be expected in the y-direction, since this is only influenced during hydroforming and, as mentioned, this is a dimensionally stable process.
3. The joining edges for the stack are two outer edges: one each in x- and y-direction (see Figure 6).
4. From 2. + 3. follows: The possible deviation from the position of the flow fields can be represented by the dimensions dx1 and dx2 between the joining edge and the flow field (see Figure 6).
5. The nominal distance dx is 50.00 mm and its tolerance is ±0.125 mm (typically for hydroforming) [11].
6. The actual size of the dimensions is normally distributed.
7. The BPP is point-symmetric.
8. two stacks are stacked in parallel with one robot.

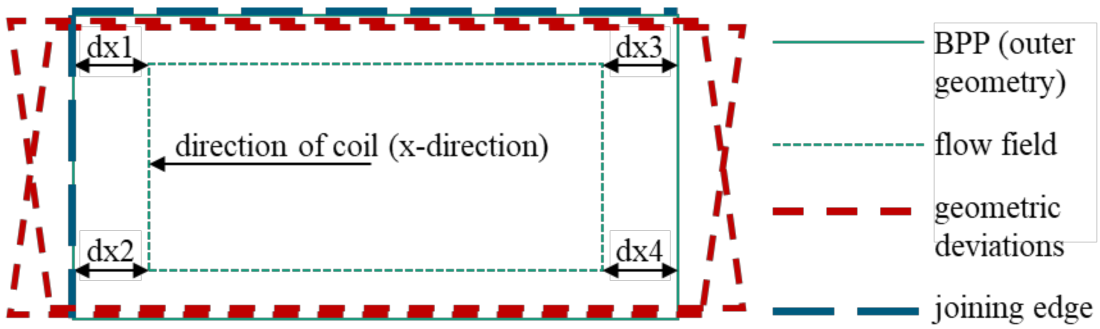


Figure 6: Schematic representation of the flow field on a BPP

To obtain a result concerning the channel offset from the deviations of the flow field, it is necessary to determine the maximum value of dx1 and dx2 of the BPP on the stack ('BPP Stack') and the BPP to be joined ('BPP 2'). Due to the marginal conditions shown above, the maximum value is the relevant value for offset of the flow fields and accordingly for the channel offset in the stack. The maximum values of the BPP to be joined and the BPP on the stack must then be subtracted from each other (see formula 1). If a point-symmetric BPP additionally allows for a 180° rotated placement, dx3 and dx4 of BPP 2 must be considered instead of dx1 and dx2. Then, the resulting channel offset is calculated according to formula 2. If the desired overlap of the flow field is as high as possible, i.e., there is a very low channel offset, the difference is as close to 0 as possible. To create an optimal channel offset with several delivery options, the minimum difference must be selected (see Formula 3).

$$CO_{BPP2-BPP\ Stack} = max(dx1_{BPP\ 2};\ dx2_{BPP\ 2}) - max(dx1_{BPP\ Stack};\ dx2_{BPP\ Stack}) \quad (1)$$

$$CO_{BPP2-BPP\ Stack} = max(dx3_{BPP\ 2};\ dx4_{BPP\ 2}) - max(dx1_{BPP\ Stack};\ dx2_{BPP\ Stack}) \quad (2)$$

$$min(|CO_{Option1}|;\ |CO_{Option2}|;\ |CO_{Option3}|; \dots) \quad (3)$$

An example calculation illustrates the approach presented below. According to Figure 6, there are four stacking options: Positioning on stacks 1 and 2, each at 0° and 180°. BPP 1 is on stack 1, and BPP 2 is on stack 2 in the 0° position. BPP 3 is now to be joined with as little channel offset as possible. The necessary dimensions are found in Table 1. These are used for calculating the channel offset for each stacking option (see Table 2). The best option for this example is to select tray option 4. BPP 3 should therefore be added to stack 2 and rotated by 180°. It allows for achieving a flow field offset of 0.01 mm. This is a 66% improvement compared to stacking options 2 and 3 and an 80% improvement on stacking option 1.

Table 1: Relevant values of the BPPs

BPP	d_{x1} [mm]	d_{x2} [mm]	d_{x3} [mm]	d_{x4} [mm]
1	50,05	50,02	49,97	49,95
2	50,02	50,03	50,01	49,97
3	50,00	49,98	50,02	49,95

Table 2: Example calculation for an optimized channel offset

Stacking option	description	$max\begin{pmatrix} dx1_{BPP\ Stack}; \\ dx2_{BPP\ Stack} \end{pmatrix}$	$max\begin{pmatrix} dx1_{BPP\ 3}; \\ dx2_{BPP\ 3} \end{pmatrix}$	$max\begin{pmatrix} dx3_{BPP\ 3}; \\ dx4_{BPP\ 3} \end{pmatrix}$	CO
1	BPP 1; 0° BPP3	50,05	50,00	not relevant	0,05
2	BPP 1; 180° BPP3	50,05	not relevant	50,02	0,03
3	BPP 2; 0° BPP3	50,03	50,00	not relevant	0,03
4	BPP 2; 180° BPP3	50,03	not relevant	50,02	**0,01**

3.3 Integration into the stack assembly

The basic applicability of dynamic tolerancing has been demonstrated in sections 3.1 and 3.2. However, the successful integration of a stack into the assembly process with a robot requires further steps. For this purpose, the stack assembly process presented in section 2.1 is applied. For stacks 1 and 2, pre-assembly of the bottom end plate and the bottom current collector is performed first, followed by the placement of one BPP per stack. This is where the dynamic tolerance approach from section 3.2 comes in. The relevant dimensions of the already placed BPP are recorded and stored. The next BPP to be placed is measured and the measurement data is stored. The recorded data can now be used to calculate and realize the optimal placement position according to section 3.2. Depending on the selected position, new measurements must be stored for Stack 1 or Stack 2 and an MEA must be placed on it. The process must be repeated until the required number of BPPs and MEAs are placed on a stack. Finally, the top current collector and top end plate are added to the stack, closed, and removed from the assembly area by the robot. The process begins again at the location of the ejected stack (see Figure 7).

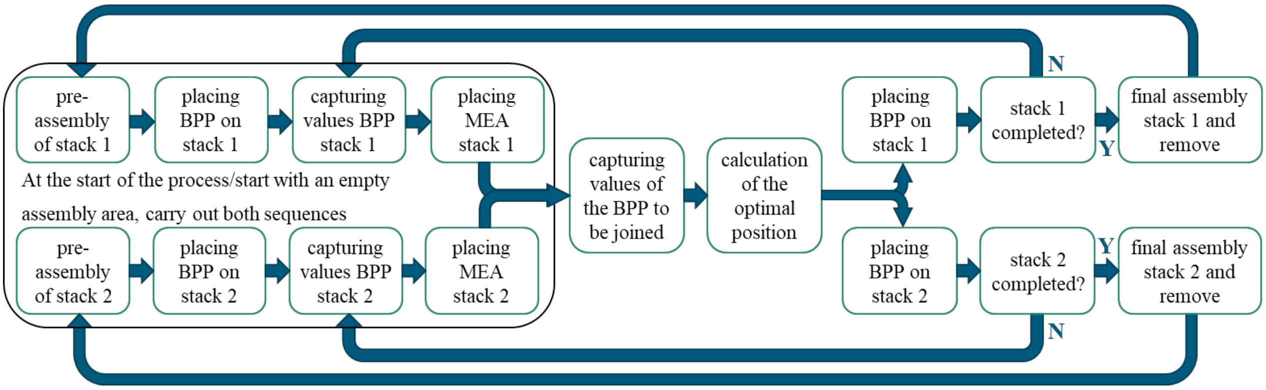


Figure 7: Sequence in a stack assembly with integration of the dynamic tolerancing approach

4. Conclusion

The presented approach demonstrated that applying and implementing the dynamic tolerance approach for the channel offset in stack assembly is possible. The exemplary calculation for joining two BPPs significantly improved the channel offset. However, in order to improve not only the channel offset, but also the characteristics of a fuel cell, more research is needed. For example, the extent to which performance and lifetime are improved by reducing tolerances needs to be demonstrated. It is also important to note that the dynamic tolerance approach does not only improve the channel offset. Other geometric quantities are the geometric variables of channel depth, cross-section, and flatness (mentioned in section 2.2). The parallel application to several quantities may require the development of a meta-model. This would enable the assembly of the best possible stacks, taking into account the individual approaches.

Acknowledgements

This work is part of the project 'Demonstrator-Pilotanlage für die Produktion von Brennstoffzellen'/ 'H2FastCell' and has received funding from the Ministry of Economics, Labour and Tourism of the State of Baden-Württemberg under the funding code BW1_0114/07. The authors are responsible for the content of this publication. Corresponding author is Andreas Aichele.

References

[1] Mekhilef, S., Saidur, R., Safari, A., 2012. Comparative study of different fuel cell technologies. Renewable and Sustainable Energy Reviews 16 (1), 981–989.

[2] Aichele, A., 2023. Geometric parameters influencing the characteristics of a stack of a PEM-FC, in: Annual World Conference of the Society for Industrial and Systems Engineering (12 : 2023 : Munich), Society for Industrial and Systems Engineering (Eds.), Proceedings of the 12th Annual World Conference of the Society for Industrial and Systems Engineering. 2023 SISE Munich. 09.-10.10.2023.

[3] Kurzweil, P., 2013. Brennstoffzellentechnik: Grundlagen, Komponenten, Systeme, Anwendungen, 2., überarbeite und aktualisierte Auflage ed. Springer Vieweg, Wiesbaden, 248 pp.

[4] Schmidt, V.M., 2003. Elektrochemische Verfahrenstechnik. Wiley.

[5] Beyer, U., Porstmann, S., Baum, C., Müller, C., 2022. Produktion der PEM-Systeme, Hochskalierung, Rollout-Konzept, in: Neugebauer, R. (Ed.), Wasserstofftechnologien. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 297–330.

[6] Li, W.Z., Yang, W.W., Zhang, W.Y., Qu, Z.G., He, Y.L., 2019. Three-dimensional modeling of a PEMFC with serpentine flow field incorporating the impacts of electrode inhomogeneous compression deformation. International Journal of Hydrogen Energy 44 (39), 22194–22209.

[7] Irmscher, P., Qui, D., Janßen, H., Lehnert, W., Stolten, D., 2019. Impact of gas diffusion layer mechanics on PEM fuel cell performance. International Journal of Hydrogen Energy 44 (41), 23406–23415.

[8] Taymaz, I., Benli, M., 2010. Numerical study of assembly pressure effect on the performance of proton exchange membrane fuel cell. Energy 35 (5), 2134–2140.

[9] Zhang, L., Liu, Y., Song, H., Wang, S., Zhou, Y., Hu, S.J., 2006. Estimation of contact resistance in proton exchange membrane fuel cells. Journal of Power Sources 162 (2), 1165–1171.

[10] Hoppe, E., Janßen, H., Müller, M., Lehnert, W., 2021. The impact of flow field plate misalignment on the gas diffusion layer intrusion and performance of a high-temperature polymer electrolyte fuel cell. Journal of Power Sources 501, 230036.

[11] Bell, C., Corney, J., Zuelli, N., Savings, D., 2020. A state of the art review of hydroforming technology. Int J Mater Form 13 (5), 789–828.

[12] Kampker, A., Ayvaz, P., Schön, H.C., Reims, P., Krieger, G., 2020. Produktion von Brennstoffzellenkomponenten, 1.th ed. VDMA Eigendruck, Aachen.

[13] Liu, D., Peng, L., Lai, X., 2010. Effect of assembly error of bipolar plate on the contact pressure distribution and stress failure of membrane electrode assembly in proton exchange membrane fuel cell. Journal of Power Sources 195 (13), 4213–4221.

[14] Qiu, D., Peng, L., Lai, X., Ni, M., Lehnert, W., 2019. Mechanical failure and mitigation strategies for the membrane in a proton exchange membrane fuel cell. Renewable and Sustainable Energy Reviews 113, 109289.

[15] Lorenzoni, A., 2020. Methodik zur dynamischen Tolerierung am Beispiel einer Welle-Nabe-Verbindung. Dissertation, Stuttgart.

[16] Lorenzoni, A., Tielemann, C., Sauer, A., 2019. Reducing manufacturing costs: the dynamic tolerance system. Cogent Engineering 6 (1).

[17] Porstmann, S., Wannemacher, T., Drossel, W.-G., 2020. A comprehensive comparison of state-of-the-art manufacturing methods for fuel cell bipolar plates including anticipated future industry trends. Journal of Manufacturing Processes 60, 366–383.

Biography

Andreas Aichele (*1989) is a research associate in the Quality Department at the Fraunhofer Institute for Manufacturing Engineering and Automation IPA, Stuttgart,. He works in the field of technical risk analysis and process optimization with a focus on quality issues. He is a facilitator for quality tools and Six Sigma Black Belt, both in research as well as in operational application.

Oliver Mannuß (*1969) is group manager of Quality and Reliability Engineering. He has done more than 100 risk analyses in industrial projects in automotive, machinery, and medical/pharma branches. His research fields are machinery availability, and the process analysis of geometrical and processual influence factors on product characteristics.

Alexander Sauer (*1976) is head of the Fraunhofer Institute for Manufacturing Engineering and Automation IPA, Stuttgart. Prof. Dr.-Ing. Alexander Sauer is also head of the Institute for Energy Efficiency in Production at the University of Stuttgart.

CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
CPSL 2023-2

5th Conference on Production Systems and Logistics

Proposing A Solution For A Self-Managed Data-Ecosystem In Production: Use-Case-Driven IT-OT-Integration With An Event-Driven IT-Architecture

Sebastian Kremer[1], Christian Mennerich[2], Max-Ferdinand Stroh[1], Günther Schuh[1]
[1]*FIR e.V. at RWTH Aachen University, Aachen, Germany*
[2]*synyx GmbH & Co. KG, Karlsruhe, Germany*

Abstract

With the development of publicly accessible broker systems within the last decade, the complexity of data-driven ecosystems is expected to become manageable for self-managed digitalisation. Having identified event-driven IT-architectures as a suitable solution for the architectural requirements of Industry 4.0, the producing industry is now offered a relevant alternative to prominent third-party ecosystems. Although the technical components are readily available, the realisation of an event-driven IT-architecture in production is often hindered by a lack of reference projects, and hence uncertainty about its success and risks. The research institute FIR and IT-expert synyx are thus developing an event-driven IT-architecture in the Center Smart Logistics' producing factory, which is designed to be a multi-agent testbed for members of the cluster. With the experience gained in industrial projects, a target IT-architecture was conceptualised that proposes a solution for a self-managed data-ecosystem based on open-source technologies. With the iterative integration of factory-relevant Industry 4.0 use cases, the target is continuously realised and validated. The paper presents the developed solution for a self-managed event-driven IT-architecture and presents the implications of the decisions made. Furthermore, the progress of two use cases, namely an IT-OT-integration and a smart product demonstrator for the research project BlueSAM, are presented to highlight the iterative technical implementability and merits, enabled by the architecture.

Keywords

Event-Driven IT-Architecture; IT-OT-Integration; Data-Ecosystem; Self-Managed; Industry 4.0

1. Introduction

Since its conception in 2011, the term Industry 4.0 defines the digital revolution of industry and proposes a target vision for digitalisation activities for production environments [1]. While developments of the last decade have achieved the realisation and validation of Industry 4.0 use cases in both research demonstrators and integrations into commercial system solutions [2], the overall state of digitalisation in the industry has, in experience, remained poor. While the realisation of a true data-driven ecosystem, as proposed in Industry 4.0, poses a challenge, a previous investigation proposes the perceived problems to derive from an IT-architectural point of view and has identified event-driven IT-architectures to be a suitable fit for the application in and realisation of Industry 4.0 [3].

The adaption of event-driven architectures (EDA) as an overall IT-architecture for production addresses the need for a multi-agent, real-time, data-driven ecosystem while retaining a manageable complexity due to modularity, decentralisation, and decoupling [4,5,3]. While businesses from a broad range of branches have already identified event-driven IT-architectures as an efficient tool to self-manage business operations via

DOI: https://doi.org/10.15488/15268
ISSN: 2701-6277

digital services in a distributed way [6,7], the adaption in industry is limited to a few prominent examples, mainly from the automotive industry [8–10]. In experience, the industry's interest in such an architecture in production is quite high, yet only few decided to undertake such a transformation. The is mainly due to the uncertainty of success in the face of high initial effort; the proposed long-term benefits are undermined by the short-term expenditures. Furthermore, the philosophy of self-managing IT-architecture development and digitalisation still poses a barrier despite the existence of publicly available, powerful software solutions.

To solve this stalemate, the decision was made to undertake such an endeavour within the research environment of the Cluster Smart Logistics in Aachen. The research institute FIR partnered with the IT-expert synyx to transform the Demonstration Factory Aachen (DFA) into an event-driven smart factory. The factory is subject to various research entities and partners acting and developing in the production environment, which induces heterogenous IT-solutions with secluded data spaces and uncertain organisational responsibilities, resulting in an IT-landscape comparable to commercial productions. The goal of the transformation lies in the creation of a unified data space for enhanced data availability and for the DFA to regain control and independence in the management of its complex IT-landscape. To address the DFA's IT-strategy in creating a self-managed data-ecosystem, a target vision was conceptualised, and its iterative realisation addressed along use cases, generating a tangible benefit.

2. State of the art and design principles

The conceptualisation and realisation of a self-managed, event-driven IT-architecture intends to establish sustainable digital sovereignty. The aspiration for the executing parties is to reach this goal both efficiently and effectively, which is pursued by value-creating development increments in an agile manner and the utilisation of a CI/CD process for streamlining deployments. The following chapters present the principles of event-driven architectures, digital sovereignty, agile software development and the CI/CD process.

2.1 Event Driven Architectures

Event-driven architecture (EDA) describes an architecture in which components communicate asynchronously through the exchange of events via a middleware (= broker). Such events can be described as a data package communicating, for example, a state change of a component or the attainment of information by a service. Events consist of a payload carrying event-relevant data that is contextualised by specifying an action that this data has occurred in (e.g., an end of operation or a measurement). The transmission of events is conducted by a component publishing/producing an event in a specific topic (analogous to a directory) of the broker and recipients actively subscribing/consuming events by topic from the broker. The overall design principle of distributed systems entails eventual consistency (possibility of data not being known to all systems at a single point in time) and possible loss of events that is to be dealt with accordingly in application design. [11–14]

Because this architecture enables the interconnection of distributed functionality and various systemic domains, event-driven architectures have historically evolved from a central design principle for operating system to a backbone for complex software solutions [11]. With the availability of industrially proven open-source broker software, like Apache Kafka, this design principle can now be extrapolated to the scale of corporate data-driven IT-architectures, to interconnect business domains in a manageable decoupled manner.

2.2 Digital Sovereignty

Digital sovereignty describes the extensive control of a company over its own data. This logically extrapolates towards control over the software and hardware that process such data, and ultimately implies complete control of their value chain. This provides valuable insights into mission critical business processes or can reveal indicators on how to execute them more reliably or efficiently. Digital sovereignty thus can support making the right business decisions towards business evolution, growth, or expansion into new markets. [15]

To achieve digital sovereignty, a transformation, or digital evolution, of a company is necessary. Digital processes are not a simple replacement for existing ones, but become the essence of the value chain, and thus move in the centre of the organisation [16,17]. Thus, Conway's Law [18] applies: The organisational structure of a company is necessarily reflected in any digital design. This relation is isomorphic, and thus the companies' organisational structure and digital value chain are interdependently related [19]. Adoption of modern software development methodologies are the means to facilitate this evolution. This includes agile methodologies borrowed from e.g. DevOps to streamline teams around a common vision. EDA as an architecture style can help uncover communication flows in the company, between departments or parts of a facility. These can then be analysed with modern sociological approaches e.g. Luhmann's system theory [20], and the complex interplay of requirements engineering and recent trends in modern software development be combined and tackled.

2.3 Agility and agile software development

Agile software development has become the state-of-the-art methodology of modern software development. Since the publication of the agile manifesto in 2001 [21], methodologies like SCRUM, Kanban or Extreme Programming have become the de-facto standard in professional software development. Agile focusses on customer satisfaction with working software as the highest goal and accepts that the world is permanently unpredictably changing requirements. This is tackled by continuously learning, and results in development employing frequent increments, inspect and adapt patterns, fail fast philosophy, and short feedback cycles. Techniques from domain-driven design (DDD) [22] experience increased awareness as integration into agile software development processes (elaborated in appendix). These techniques are event-centred and focus on communication flows, thus comply with EDA naturally.

Ultimately, agile is a characteristic of an organisation's vision and mindset, not it's IT department. Agile organisations are more viable in free markets by the ability to adopt to everchanging environments and regulations [16]. In experience, agility is not a buyable off-the-shelf tool for incorporating or outsourcing software development but needs cross-functional software teams to be embedded in agile organisations (or projects). Often, this means to introduce a new mindset in an organisation and comes along with the complexity of change management and associated challenges. If not addressed properly, the boundaries between the agile (software) development teams and rigid organisation structures become bottlenecks for communication flows and prevent efficient decision-making processes, as stated, again, by Conway's law.

2.4 CI/CD – Continuous integration and development/deployment

In Experience, modern software systems are subject to frequent changes that need to be releasable into production on a regular basis on short time scales, in case of mission-critical bugs within hours or even minutes. To have control and knowledge about the components that run in production, proper versioning of every software service is inevitable. Versioning systems like git are widely used in combination with integrated platforms like GitLab or GitHub that provide DevOps methodologies. These systems offer mechanisms for automating the release process of software into test, staging and production environments and, at the same time, ensure compliance with defined quality standards.

Preferably, this is an automated process that deploys the new (or any other stable wanted) version into production environments: continuous integration and development/deployment (CI/CD). At best, every successfully implemented feature (i.e., feature that passes the quality gate) triggers an automated deployment. That way, software development teams can release features into production several times per day. High deployment cycles (at least to test and staging environments) and short lead time for changes are valuable, as they enforce high quality software and keep the teams trained, thus increasing confidence and reducing cognitive load [17]. Automated CI/CD pipelines in general serve several purposes which are further discussed in the appendix.

3. Proposed solution

The implementation of an event-driven IT-architecture in a production environment is not to be understood as a general solution to Industry 4.0 use cases. The selection of an IT-architecture is a strategic decision that must match the requirements and prospects of the concerned company [3]. The applicability of EDA for the Demonstration Factory Aachen (DFA) was identified as a solution to address the challenges specific to the situation of multiple stakeholders acting in one factory (refer details in appendix). With the decision of EDA to be the central design principle for the DFA, the IT-architecture was then specified along the by experience relevant architecture dimensions *technology*, *organisation*, *data,* and *applications*.

3.1 Technology Dimension

The foundation of an event-driven architecture is a central entity accepting and making contextualised data packages available [11]. In the scope of an IT-architecture, such a central entity is often implemented using a message broker to integrate all components within the network. From experience gathered in industry projects, the realms of IT (e.g., IT-Systems, Applications) and OT (e.g., PLCs, machines, sensors) have different demands towards the central connectivity: IT-systems conventionally expect data persistence as in query-able master records, OT puts more demands on real-time availability. Consequentially, the allocation of two dedicated interconnected brokers is proposed, providing technologies that complement and serve IT and OT separately. The developed technical IT-architectural is visualised in Figure 1.

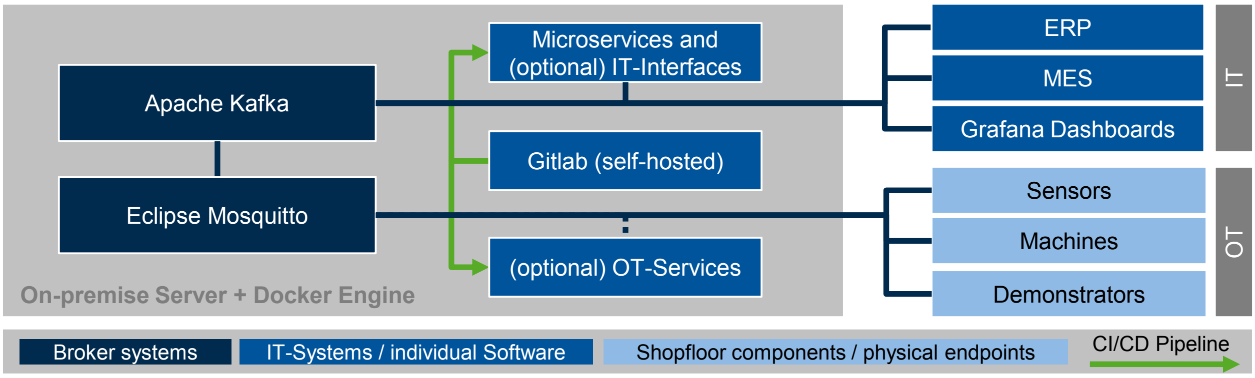


Figure 1: IT-Architectural overview of the EDA concept for the Demonstration Factory Aachen

Regarding limited resources in the transformation process and retaining an overall independence in the DFA's research environment, the choice of broker systems focuses on publicly available open-source solutions. The chosen technologies are Apache Kafka and Eclipse Mosquitto. Kafka offers valuable scalability and persistence capabilities for IT on top of the TCP based Kafka messaging protocol. Mosquitto is based on the IoT standard protocol MQTT and provides real-time and lightweight interconnectivity for OT. Even though the industry standard OPC-UA does offer plug-ins to support publish/subscribe patterns, the decision was made to focus on MQTT, due to its reduced complexity, broader support for IoT-sensors and the enhanced flexibility to individually structure event on different abstraction levels (for e.g. custom services) [23]. Ultimately, OPC-UA natively employs 1:1 data-querying, which in the context of DFA both risks maintainability and does not inherently fulfil the contextualisation of data in events. Prospectively, a more production-robust OT-solution will be evaluated with commercial products that offer convenience functionality for integration (including OPC-UA endpoints). IT- and OT-endpoints that do not natively connect to the brokers, will be integrated via a dedicated service and eventually a technical solution for physical endpoints. The broker software is planned to be deployed on-premise on dedicated servers within the network of the DFA, accessible for all relevant resources. The deployment of the broker software and subsequently developed services that interface network-components or implement specific logic, is handled via CI/CD, using a locally maintained Gitlab instance and a docker container runtime.

3.2 Organisation Dimension

From an organisational point of view, the main challenge lies in combining various demands regarding functionality and available datapoints into a single consistent model and governing adherence, which is required for the functioning of distributed systems [12]. To align demands in the central data structures and corresponding responsibilities, the architectural orchestration is proposed as a change management process. Any request for change regarding data access and the centralised data model is funnelled through designated architects, who align them with the architectural vision and derive specific measures. These measures are communicated to the corresponding owners that are then responsible for implementation. From a technical perspective, each endpoint is required to manage its own connector to the broker, if not already defined within the standard stack of interfaces provided by central organisation. Adherence to correct usage of devised models will be governed with access control and schema validation. The management of services, interfacing endpoints and implementing specific logic components is handled via CI/CD that serve as a quality gate for the software and ultimately install deployable artifacts into production environments.

3.3 Data Dimension

Managing distributed systems in a centralised data space requires the definition of a standardised data model, to be adhered to by contributing components [12]. The overlying philosophy is defined to be "finding data instead of searching for data". This philosophy is expected to harmonise with the nature of EDA to contextualise data by specifying the context in a topic that the event is published within. The data dimension of the architecture focuses on designing a coherent structure for the topics that allows a user to find data by matching its context against the literal topic. Furthermore, the data dimension specifies top level segments designated for production, development and third parties, to structurally decouple these domains and allow for an effective management of authorisation.

Hence, the top level of the topic tree defines the domains *dfa* (DFA, as the main productive domain), *dev* (development) and *ext* (external) – the domain *fir* was later added for production unrelated research projects by FIR. The *dev* and *ext* branches define subtopics named after use cases and external company name, respectively. The *dfa* topic partitions subtopics into both specific and abstract business objects. For in depth reference, Table 1 presents an overview of the topic structure envisioned for the EDA.

The topics define a tightly scoped context that allows for specification of strict responsibilities. The base topic of each business object contains general events regarding the resource; further segmentation (e.g., identifiers for individual orders) and specific data points (e.g., sensor data of a machine) are placed in individual subtopics. For potential direct interaction with a domain, a "request" subtopic is defined for topic necessitating such a functionality. Data schemas transported via the topics are still in development, as they will be defined according to the requirements of implemented use cases and hence are omitted in this paper.

Table 1: Topic structure within the broker based on business objects

Business Object	Topic structure	Potential Owner [1]	Description
OT-Device	dfa.ot.<id>	Respective device	Status updates of shopfloor machines, sensors, or robots
IT-System	dfa.it.<id>	Respective system	Proprietary (not adhering defined model), but relevant data produced by IT-systems [2]
Microservice (Business Functionality)	dfa.svc.<id>	Respective service	Results and heartbeats of microservices managing logic, data transformation, and analysis
Order	dfa.order	e.g. ERP	Updates on production orders
Operation	dfa.operation	e.g. MES	Updates on shopfloor operations
Transport Order	dfa.transport	e.g. EWM, FTS, MES	Updates on intralogistics orders
Warehouse	dfa.warehouse	e.g. EWM	Warehouse inventory
Product	dfa.product	e.g. PLM, ERP	Assembly status of parts / product
Master Record	dfa.rec.<record>	e.g. ERP, MES, EWM, CRM	Persistence for e.g. material specifications, packaging lists, worker info or customers
Development Domain	dev.<use case>	Respective use case / service	Data space for use case specific developments by research entities
External Domain	ext.< name>	Respective partner	Data space for partners for integration and testing of individual IT and OT
FIR Services	fir.svc.<id>	*Analogous to dfa.svc.<id>*	
FIR Devices	fir.dev.<id>	*Analogous to dfa.ot.<id>*	

3.4 Application Dimension

The application dimension in the IT-architectural design focuses on the definition of standard applications and their integration into the IT-landscape. While the DFA has specific IT-systems defined for required functionality (e.g., an ERP), EDA does not require for a specific system to be set as a standard application. In fact, the architectural design allows for the expected heterogenous IT-landscape to incorporate multiple IT-Systems reading and writing data from and to the centralised broker.

Nevertheless, the specific role of existing IT-Systems and general applications within the DFA's IT-landscape need to be defined, to manage responsibilities regarding provided data. By applying a contextualised data space as proposed in 3.3, the distribution of responsibilities regarding these data spaces can be determined and retained. Data-producing applications are bound to their respective service or business object in accordance with Table 1 in appendix. Prospectively, standard applications will be defined for developing dashboards, interfaces, and low-code / no-code logic with the aim to accelerate the utilisation of the architecture by new stakeholders.

4. Implementation and validation of proposed solution

Having proposed a concept for the IT-architecture's dimensions, the goal was set to pursue its implementation. Like experienced in the industry, the risk of implementing an unverified concept with a lack of ample resources hinders the extensive implementation at once. Hence, the advancement was decided to derive from actual realisable increments with a tangible benefit that iteratively pay into the overall vision of

[1] Likely candidates. Any designated service can own a topic to abstract interfacing one or even multiple IT-systems.
[2] Business-object-relevant data is either directly published to the domain-topic or handled via a topic-designated service.

the IT-architecture. This iterative approach suits the design of an EDA [3] and allows to consecutively add new requirements and adapt the choices made during the design phase in an agile manner.

Derived from user stories in agile development, the basis for these realisable, beneficial increments are use cases within the environment of the Cluster Smart Logistics. Relevant use cases for and with a self-managed data-ecosystem were identified in discussion with stakeholders like the DFA and research entities, and in regard of demonstrators for active research projects. Subsequently, a roadmap was designed by breaking down use cases with an adequate benefit to effort ratio into sprints with a priority on creating a minimum viable product first. The two use cases implemented by the time of this paper are a case of machine data acquisition for transparency and a demonstrator for smart products further discussed in 4.2 and 4.3 respectively. Section 4.1 first presents an overview on the current state of implementation.

4.1 State of Implementation

The DFA's current EDA solution is deployed on dedicated on-site Linux servers. A single Mosquitto Broker (MQTT) handles both IT and OT to rationalise complexity in the early stage of development. A self-hosted GitLab instance is used for software version control and serves as the environment for CI/CD pipelines. Microservices, mainly written in Rust, interface the broker and enable the use cases functionality by gathering data from endpoints like machines and sensors, feeding data to endpoints like databases and dashboard, abstracting endpoints into digital interfaces and executing logic.

These services are developed and maintained in a GitLab project that is CI/CD enabled and defines pipelines that trigger project build, test, and image creation. For now, a manual containerisation and deployment step is necessary to start the service into the production environment with Docker. At a later stage of the transformation, a container orchestration tool like Docker swarm or Kubernetes will be used to maintain the overall operations infrastructure, and pipelines will be extended to directly deploy into production environments. Such container orchestration platforms also offer means to comply with requirements to the availability of services, via health checks and monitoring, including automatic restarts and dynamic scaling.

4.2 Validation: Machine data acquisition – Tracking inert gas usage for laser cutting process

The first developed use case developed into the EDA addresses an uncertainty that the DFA faces regarding the consumption of inert gas for a laser cutting process. While the material processing is mainly unconcerned from the eventual exchange of gas containers during the process, personnel had no way to estimate the remaining useful levels for short term planning or estimate required volumes for specific orders. This impaired the scheduling of resupplies, predicting the order-specific cost and fine planning operations. The target was hence to achieve transparency in the inert gas usage and predictability regarding orders.

The realisation of the use cases first focused on attaining real-time process data (unbuffered, 1 Hz – 10Hz) from the laser cutting machine. This was achieved by a stack of flow sensors and relay-states feeding into an IoT-Box[3], a component attached to the machine and establishing connectivity. The data was then pulled into the centralised broker via a dedicated microservice, continuously fetching the data from the IoT-Box and posting it into the machine specific topic *dfa.ot.trumpflaser* and respective sensor subtopics. Moreover, the service enriched the forwarded data by determining the operation state of the machine into a predefined, factory-wide data format. To achieve the first benefit the data was then written into a time-series database via a dedicated second microservice, to allow the implementation of a simple Grafana dashboard for the end users. Thus, workers were able to match the usage of gas to the periods of corresponding operations and ultimately the consumption of inert gas per type of operation. To automate the matching of process to order data, a microservice similar to the connection of the OT device will then interface the ERP's API and post current order data into the topic *dfa.order* with subtopics specifying the order id. This data will both serve

[3] Based on an HPE Edgeline EL300 with OT Link

to generate a workers' dashboard of active order (that is required in another use case) and feed into a microservice mapping the integrated consumptions to produce estimates per known type of order.

The realisation of this use case allows to validate certain assumptions made with the pursuit of an EDA in a production environment. The integration of the laser cutting machine via an IoT-Box showed that the architecture is robust against various types of endpoints in context of specific protocols and formats or it being a server or a client. By the utilisation of a dedicated microservice the integration did not need to rely on the machine proactively posting its data but could remain a passive endpoint. Furthermore, the architecture provided excellent availability and usability of the machine data, without the necessity of gateway systems like MES or third-party platforms. At last, the scope of the deployed microservices were precise, which allowed for a clear identification of responsibility and introduction of changes along the development process. Yet, as stated in 2.2, the implementation required direct confrontation with technical challenges and hence expertise in the technical solution design and development of software-components.

4.3 Validation: Demonstrator for research project BlueSAM – Realisation of a smart product

The second use case substantiated itself in the planned demonstrator for the publicly funded research project BlueSAM[4]. The research project aimed to construct **Blue**prints for **S**mart product **A**rchitecture **M**anagement that derive relevant IT-architectural components for the pursuit of individual use cases with the application of a smart product. In the project a method was developed and build into a publicly accessible webtool[5] which helps users identify relevant smart product use cases and learn among others about functional requirements a respective IT-architecture must fulfil. As part of the research project, the method was tested with a digitalised espresso machine (specified as DE1) as an exemplary smart product to (analogously) demonstrate digital use cases on handcraft with industrial machines. The espresso machine already offered Bluetooth capabilities and a local interface for operation but needed to be upgraded to realise the envisioned smart product use cases of assisting the user in the operation of the machine, offering data analytic capabilities to the user, and upgrading the provided digital services on data-based learnings.

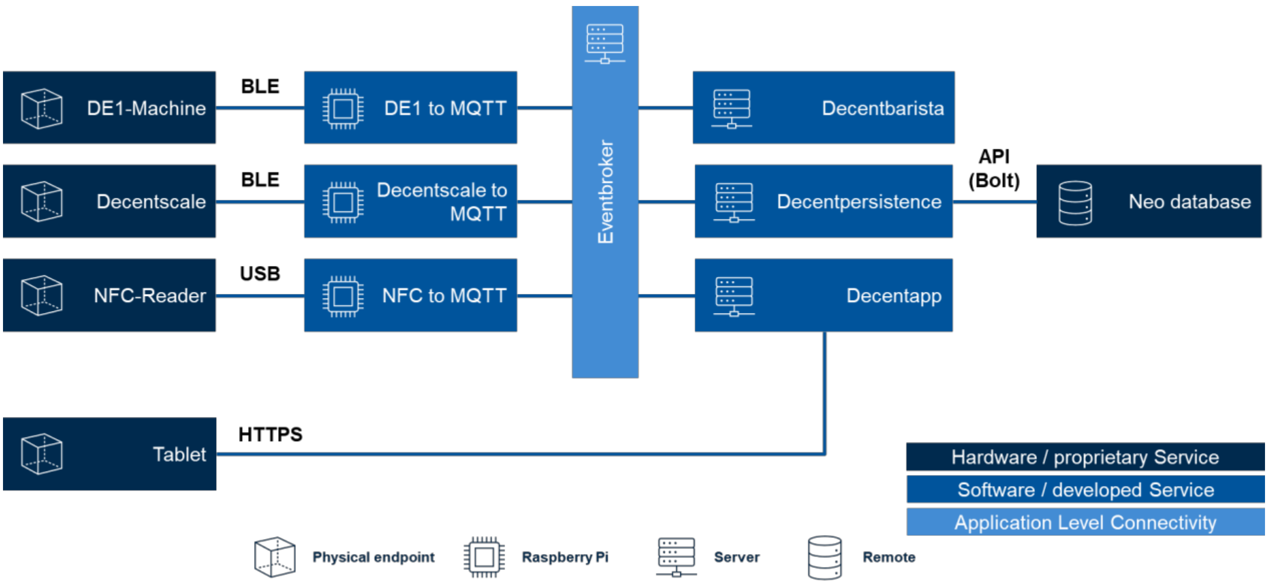


Figure 2: Smart product architecture of the BlueSAM demonstrator utilising the centralised event broker

The realisation (as illustrated in Figure 2) first focused on the digital interfacing of the machine. This was achieved by creating a service running on a Raspberry Pi situated at the espresso machine that both interfaces the machine via Bluetooth and directly communicates with the centralised broker. This way status updates

[4] IGF/CORNET no. 303 EN
[5] Webtool is available at bluesam-tool.fir.de

by the machine were published in the topic *fir.dev.de1* (specifying *dev* for device instead of *ot*) while listening for direct requests to the machine on the topic *fir.dev.de1.request*. The demonstrator required the integration of two more devices handled likewise by the Raspberry Pi, namely an USB NFC sensor for user identification (*fir.dev.de1-nfc*) and a Bluetooth weighing scale for the espresso making process interface (*fir.dev.decentscale*). Three further digital services required for full operation were then iteratively added and incorporated into the EDA and deployed on an on-premise server: A service to supervise the espresso extraction process and command the DE1-machine to stop on a specific weight (*fir.svc.decentbarista*); a service to interface a remote Neo4J database to store and provide process and configuration data (*fir.svc.decentpersistence*); and a user application to provide a web-application as an user interface to a tablet mounted on the machine (*fir.svc.decentapp*). All services were designed to strictly interact only via the broker, reacting to event data and if necessary, placing requests into each other's topics.

The resulting demonstrator was not only capable of realising all use cases envisioned within the research project BlueSAM, but with EDA also offered further non-functional benefits. The services could be adapted independently and deployed anywhere without the need for reconfiguration of the entire system. This not only benefitted the role of the demonstrator to represent a smart product that is situated in the field and is hence mobile. It also allowed for multiple instances of user application to be accessed and used remotely for testing and demonstrating vendor-supervision with each instance receiving live data from the machine. The incorporated responsive design induced by the EDA also deemed to be essential during error fixing. Anecdotally, the remote database crashed in the week of project conclusion and demonstration. Even though the functionality of saving and loading process and configuration data was thus lost, the application and machine control did not seize to respond correctly to the otherwise usual operation. Furthermore, the database functionality was then easily and fully restored by setting up a new local database from a backup and linking the responsible *decentpersistence* service to the new database endpoint. Whereas in conventional software/application design a reconfiguration of any service using the database would have been necessary, the decoupled design induced by EDA reduced the outage and maintenance to a precise and limited scope.

5. Conclusion and Outlook

The introduction of EDA in the production environment of the DFA and its surrounding research environment was conducted along the implementation of two use cases as an iterative increment towards the proposed architecture target. In the scope of the use cases the EDA was an effective tool to precisely scope the development of new components within the network and achieve high data availability. With adherence to the design principles of EDA, the developed solutions offered good decoupling and hence robustness in the case of errors. As the achieved state of realisation for now only focuses on two use cases in a small development team, the effectiveness of multiple top level domain design (*dfa*, *dev*, *ext*, *fir*), of the architectural governance via the change management process and the overall management of authorisation in the broad data space could not yet be validated.

For now, the overall applicability of EDA regarding the DFA is perceived as good. The diverse environment at the Cluster Smart Logistics offers availability of expertise for technical enquiries, software development, IT infrastructure and process knowledge, which proof to be of great value in the self-managed development of a data ecosystem. Even in its infancy the project has gained prominence and broad interest within the Cluster, which stems from the promise of high data availability and the reactive, real-time design.

The overall applicability in the context of other production depends both on the heterogenous nature of the environment and the willingness to develop and self-manage such an ecosystem. From experience even small factories offer enough complexity due to organisational divisions, which fulfil the heterogeneity of interest in the scope of a shared data set. The willingness itself is dependent on the individual IT-strategy of a company. A pursuit of event-driven IT-architecture is not advisable if the IT-strategy does not include own digital expertise and organisational adaptability or a third-party market solution in its standard does suffice.

The continuation of the project will focus on the concurrent iterative addition of use cases into the EDA of the DFA. The current roadmap includes the integration of order data via a microservice interfacing the ERP, the creation of worker terminals for active orders and the implementation of external data spaces with use cases from external partners of the Cluster's Center Connected Industry CCI and Center Integrated Business Application CIBA.

Acknowledgements

Part of this report is the scientific result of a research project BlueSAM undertaken by the FIR at RWTH Aachen University (Germany) and Sirris (Belgium). The research project was carried out in the framework of the industrial collective research programme (IGF/CORNET no. 303 EN). It was supported by the Federal Ministry for Economic Affairs and Energy (BMWi) through the AiF (German Federation of Industrial Research Associations e.V.) based on a decision taken by the German Bundestag

Appendix

Addition on 2.2 Digital Sovereignty: **Technical dimension on digital sovereignty**

When it comes to technical solutions to achieve digital sovereignty, operation of the IT solutions must be thoroughly considered. Usually, different parts of a complex (naturally distributed) ecosystems have different requirements to availability, resilience, and fault tolerance. Thus, these components can, in principle, be operated, with different SLAs. By buying or outsourcing crucial components of the digital infrastructure, full data sovereignty must be secured in the operations by contracts. The danger of disadvantageous vendor lock-in and reliability on third parties resides. Open-source solutions and on-premise operations are a way out to achieve complete control but come with the cost to secure the knowledge and work power in the organisation to guarantee stable operations and demanded SLAs.

Addition on 2.3 Agility and agile software development: **Domain driven design (DDD)**

DDD centres the development around a model and language common to developers and domain experts, strengthening the cross-functional character of and incorporating communication into the development process [24]. With DDD collaborative modelling techniques arose like domain-story telling [25] or event storming [26]. These incorporate sociological/sociotechnical and psychological research [27–29] and bring together different stakeholder groups to make the most of shared knowledge.

Addition on 2.4 CI/CD – Continuous integration and development/deployment: **Software Development process**

Following the agile philosophy, software is developed in short iterations, each delivering small, valuable increments, developed on small, short-lived feature branches within the version control system. These branches are merged into one common main branch that always needs to be stable and releasable (in the current as well as in all former versions). During the software development process, developers ensure that the software meets certain functional requirements by writing and maintaining sets of tests that describe aspired quality standards. Successful tests serve as the quality gate and are integrated in the development process via test-driven or behaviour-driven development to ensure correctness of both, technical and business-behaviour of the service, at best always including stakeholders in the process. So-called pipelines run these tests automatically before merging a new feature into the stable main branch. Once the pipeline succeeds, the new version of the software can be released into production.

Addition on 2.4 CI/CD – Continuous integration and development/deployment: **Automated Pipelines**

Automated Pipeline enforce documented and repeatable processes, decrease error rates and shorten mean time to restore by automating rollbacks (i.e., deployments of known stable versions). Failures in a pipeline prevent faulty versions to be rolled into production, and thus enable fast feedback cycles by braking builds. This enables highly endorsed continuous learning processes [30]. The term ‘DevOps’ is often used for this set of methodologies. From the DevOps culture and DevOps topologies ultimately Team Topologies arose [17], ideas on how to streamline development teams along the value chain to enable for fast development, improvement of production software and maintenance of the software development and production infrastructure. Agility and adoption of a DevOps mindsets need to be embedded in the core of an organisations value chain to make it efficiently work. Again, Conway’s law applies - digitalisation at full scale that aims to achieve digital sovereignty, demands a structure that is fully organised around their digital value chain.

***Addition on* 3 Proposed solution: Information on the Demonstration Factory Aachen (DFA)**

The DFA represents the practical test ground within the Cluster Smart Logistics in Aachen. While being an independent organisation executing individual production to order, it offers capabilities to develop, test and demonstrate applications and technologies related to Industry 4.0 within a genuine production environment. Stakeholders of such demonstrators are research entities at the cluster as well as partners using the environment for individual development. Over time, this environment has evolved into a heterogenous IT-landscape with numerous isolated solutions that are organisationally, and hence functionally, unrelated. To centrally organise the development of solutions within the DFA, and to allow for implemented solutions to build on each other regardless of their owner, the introduction of an IT-architecture that focuses on digital sovereignty for the DFA as the de facto central entity was deemed necessary. Having a broad spectrum of capabilities available at the Cluster, the self-reliant technical conventionalisation and implementation of digital solutions does not present an obstacle. EDA offers a suitable solution to manage multiple stakeholders acting within a data ecosystem with heterogenous solutions, by abstracting interfaces into a centralised, collaborative dataspace to reduce organisational and technical dependencies [3].

References

[1] 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.

[2] BMWK, 2022. Mittelstand Digital - Demonstrationsorte. https://www.mittelstand-digital.de/MD/Navigation/DE/Praxis/Demonstrationsorte/demonstrationsorte.html. Accessed 15 December 2022.

[3] Kremer, S., Konrad, L., Stroh, M.-F., Schuh, G., 2023. Event-driven IT-architectures as enabler for Industry 4.0. Hannover : publish-Ing.

[4] Duggan, D., 2012. Enterprise software architecture and design: Entities, services, and resources. Wiley, Hoboken, N.J., 482 pp.

[5] Jahn, U., 2021. Verteilte Systemarchitektur für mobile Roboter. Dissertation, Bielefeld.

[6] 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.

[7] 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.

[8] Confluent, Inc., 2022. Confluent-Kunden: Echtzeit-Event-Streaming für alle Branchen | DE. https://www.confluent.io/de-de/customers/. Accessed 31 January 2022.

[9] 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.

[10] 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.

[11] Bruns, R., Dunkel, J., 2010. Event-driven architecture: Softwarearchitektur für ereignisgesteuerte Geschäftsprozesse. Springer, Berlin, 241 pp.

[12] Hastbacka, D., Kannisto, P., Vilkko, M., 2018. Data-driven and Event-driven Integration Architecture for Plant-wide Industrial Process Monitoring and Control, 2979–2985.

[13] 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.

[14] 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.

[15] Hummel, P., Braun, M., Tretter, M., Dabrock, P., 2021. Data sovereignty: A review. Big Data & Society 8 (1), 205395172098201.

[16] Forsgren, N., Humble, J., Kim, G., 2018. Accelerate: The science behind DevOps : building and scaling high performing technology organizations. IT Revolution, Portland, Oregon, 257 pp.

[17] Skelton, M., Pais, M., 2019. Team Topologies: Organizing Business and Technology Teams for Fast Flow. IT Revolution Press, California, 5 pp.

[18] M. E. Conway. How Do Committees Invent? 1967.

[19] Lise Hvatum, Allan Kelly, 2016. What do I think about Conway's Law now?: Conclusions of a EuroPLoP 2005 Focus Group.

[20] Mennerich, C., Meseck, F., 2020. Systemtheorie und Softwaredesign: Wie Soziologie und Softwareentwicklung zusammenspielen können 4, 48–53.

[21] Kent Beck, 2001. The Agile Manifesto. https://agilemanifesto.org/. Accessed 29 July 2023.

[22] Evans, E., 2004. Domain-driven design: Tackling complexity in the heart of software / Eric Evans. Addison-Wesley, Boston, London.

[23] Biedermann, E., 2023. OPC UA versus MQTT: Gelingt der direkte Vergleich? WEKA Industrie Medien GmbH, January 1.

[24] Vernon, V., 2013. Implementing domain-driven design. Addison-Wesley, Harlow.

[25] Hofer, S., Schwentner, H., 2022. Domain storytelling: A collaborative, visual, and agile way to build domain-driven software. Addison-Wesley, Boston, 1 online resource.

[26] Alberto Brandolini, 2021. Introducing EventStorming: An act of Deliberate Collective Learning. https://leanpub.com/introducing_eventstorming. Accessed 3 July 2023.

[27] Kahneman, D., 2012. Thinking, Fast and Slow. Penguin Books, London.

[28] Syed, M., 2016. Black Box Thinking: Marginal gains and the secrets of high performance, First published in paperback ed. John Murray (Publishers), London.

[29] Taleb, N.N., 2007. The Black Swan: The impact of the highly improbable. Random House, New York. N.Y.

[30] Humble, J., Farley, D., 2011. Continuous delivery. Addison-Wesley, Boston, Mass., London.

Biography

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.

Dr.-Ing., Dipl-Inf. Christian Mennerich (*1981) has studied computer sciences with a focus on theory and implementation of database systems. He started working with synyx GmbH & Co. KG in 2013. Here, he is occupying himself with NoSQL and message-oriented distributed systems. Mennerich talks at conferences and user-groups, writes articles and occasionally edits books. Since 2022, he is lives in England and establishes synyx UK.

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.

CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
CPSL 2023-2

5th Conference on Production Systems and Logistics

A Control Architecture For Energy Systems With Multiple-Energy Carrier Devices

Kerim Torolsan[1], Mirja Mannigel[1], Janosch Hecker[1], Alexander Sauer[1,2]
[1]Institute for Energy Efficiency in Production EEP/University of Stuttgart, Stuttgart, Germany
[2]Fraunhofer Institute for Manufacturing Engineering and Automation, Stuttgart, Germany

Abstract

As energy systems become increasingly complex with integrating multiple-energy carrier devices, there is a growing need for advanced energy management systems that can effectively coordinate and control the diverse elements within the system. This paper presents a novel architecture for energy management systems explicitly designed for energy systems with multiple-energy carrier devices. The proposed control architecture encompasses three distinct levels: the device level, the subsystem level, and the system level. Each level incorporates operation models that are the foundation for implementing use cases in operation targets. The overall concept combines a bottom-up and top-down approach, where operational goals are transferred from the upper to the lower levels and, conversely, the lower levels communicate state adjustments to their respective upper levels, enabling feedback based on the established goals. A unified input-output data exchange is introduced to increase the control architecture's applicability. The interaction between the individual levels of the control architecture makes it possible to implement use case-dependent operation targets. Their execution is carried out through dedicated operation models representing devices and logical control structures capturing state-change processes. This paper provides a comprehensive overview of the proposed control architecture by applying it to the energy system of the industrial research platform WAVE-H2, with multiple energy carriers, heat, hydrogen, and electricity. This work highlights the proposed architecture's potential for adaptability regarding complex energy systems and facilitating efficient operation.

Keywords

Hierarchical control architecture; Multiple-energy carrier devices; Complex energy systems; Logical control structures; Unified input-output

1. Introduction

The increasing energy demand and the requirement for sustainable and efficient energy systems have led to the widespread use of multiple-energy carrier devices (MEDs). These devices, such as electric heat pumps, fuel cells, electrolyzers, and energy storage systems, couple a variety of energy carriers, such as heat, hydrogen, and electricity, and allow them to be integrated into a single holistic system. This enhances the performance and flexibility of the energy supply compared to conventional single-energy carrier systems whose sectors are treated independently [1,2].

However, the integration and control of these MEDs present significant challenges due to their heterogeneous characteristics, diverse operational constraints, and complex interactions, e.g., implementing optimal energy scheduling in the presence of uncertainties, e.g., variable prices or uncontrollable energy

DOI: https://doi.org/10.15488/15279
ISSN: 2701-6277

demands [3].To address these challenges, the development of an effective control architecture is necessary. Such an architecture should provide an intelligent control framework that ensures the synergistic operation of the MEDs while considering the dynamic changes in energy supply and demand. Interactions with the outside world and between the various energy networks are important aspects of the multi-energy carrier system (MES). Furthermore, the system size can range from building-level to entire countries [2,4]. The interaction points between MEDs are referred to as energy hubs, where different energy carriers are transformed, converted, and stored [2,5].

Optimization objectives of MESs are typically based on reducing system operation costs or pollutant emissions, improving the stability and quality of the energy supply, increasing system reliability and minimizing outage duration, or increasing overall system efficiency [6–9].

Several topologies of control architectures are used in different contexts and applications. The most common topologies are described below, although variations or combinations of the topologies can also be found.

- Centralized control architecture: A central authority is responsible for monitoring and managing all the relevant energy data within a system in this topology. It involves centralized decision-making, control, and coordination of energy generation, distribution, and consumption. This topology lacks efficiency and flexibility, as it must be modified to integrate additional devices and has extensive computational costs [10,11].
- Decentralized control architecture: This topology distributes decision-making and control authority to multiple subsystems within a system. Each subsystem has a degree of autonomy in managing energy resources and optimizing energy consumption. A decentralized control architecture is primarily employed in distributed energy systems and microgrids [12,13], often with respect to isolated energy carriers [14].
- Hierarchical control architecture: This topology is based on a structured multi-level architecture. It divides energy management tasks and decision-making into distinct levels, each with its own set of responsibilities and objectives. This topology enables coordinated decision-making at multiple levels, from long-term strategic planning to short-term operational control. Hierarchical control architectures are commonly applied in MESs, where different energy carriers and subsystems must be coordinated [15,16].

In the context of scientific research, it is also necessary to model and simulate complex energy systems to improve their operating parameters. As the complexity increases, expertise from multiple disciplines must be combined. This paper proposes a hierarchical control architecture that facilitates a simple and flexible application across MEDs. It combines a bottom-up and top-down approach, transferring operational objectives from the upper to the lower levels and vice versa. This enables scientists and engineers to work on the same project using their preferred software, leading to efficient implementation and integration and a scalable and modular aggregation of a multitude of MEDs.

The following sections of the paper are structured as follows: Section 2 discusses the characteristics of the current developments and research results in hierarchical control architectures for MEDs. The different hierarchy levels of the control architecture are described in Section 3. Section 4 shows the conceptual application of the control architecture to an industrial research platform. Finally, Section 5 provides a conclusion and future extensions of this work.

2. Control Architectures in Literature

Coordinated the multi-energy carrier systems (MESs) offer specific opportunities to improve energy efficiency and enhance energy supply flexibility. However, operating an integrated energy system, considering all the interdependencies between the different energy supply networks, also presents various challenges in terms of modeling and planning the control architecture [17,18]. Recently, researchers have shown significant interest in optimizing the operation of MESs. The proposed control architectures vary based on energy consumption and time scale [19]. Typically, the hierarchical control architectures are developed based on a two- or three-level control architecture, depending on the system's complexity.

The two-level control architecture controls multiple-energy carriers by dividing the control tasks into two distinct levels: main or supervisory control level and a primary or unit control level [18,20,21]. Each level has specific responsibilities in managing and optimizing the usage of the energy carriers in the system. The main control is responsible for setting the overall objectives and constraints for the system, such as energy demand and cost. The main control considers the specific requirements of the system and the constraints of the energy carriers to determine the optimal energy demand. The primary control coordinates the operation of the different energy carriers to meet the energy demand set by the main control. It translates the objectives and constraints into specific control actions for individual energy carrier devices. This control architecture has been successfully applied in several studies, some of which are briefly addressed in the following.

The authors in [21] introduce a control strategy for the operation of an autonomous distributed generation system with multiple energy sources, storage devices, and wind energy based on a two-level hierarchical control architecture. The main control manages the entire system, distinguishing control actions for the electrical and heat systems, while the primary control embedded in each component ensures fast and accurate control of individual components to maintain desired set points. The results for a residential district application demonstrate stable and efficient performance of the control strategy in a 24-hour simulation. Leading to achieving the balance between demand and supply for both electricity and heat systems. The authors suggest that it can be adapted for different configurations of multiple energy carrier systems, making it a robust and applicable control solution for autonomous distributed generation systems with various energy sources.

In [18], the author designed a two-level control architecture for the application in systems with multiple-energy carriers. Here, the unit control is a local control system installed in each controllable unit, operating independently but receiving signals from the main control. Whereas the main controller oversees the entire system, monitoring parameters, allocating generation power, optimizing the use of multiple energy sources, and distributing the load among the controllable units. The control architecture was tested at the DENlab, a renewable energy laboratory located at the Power Systems Group of Delft University of Technology, on an off-grid energy system configuration, considering electricity and gas as input and electricity and heat as output. The results of the study demonstrate that the multi-carrier hierarchical control architecture is robust and stable under normal operating conditions. The control strategy successfully handles perturbations and load changes in the system, keeping main control parameters within defined boundary conditions.

The authors of [20] presented a hierarchical control architecture for a hybrid energy system built in Lambton College, Sarnia, Canada. The two-level control architecture consists of a supervisory level with long-term resource planning (hours) and a low-level control reacting to rapid dynamic system changes (seconds) for dynamic real-time optimization and ensuring that each unit operates at its set point determined by the supervisory level. The different time scales of the higher- and low-level control are buffered by a battery, serving as a dynamic energy storage. Simulation results of case studies based on average weather data for a 24-hour period in the month of June in the Ontario region and a typical load demand of the hybrid system show effective energy management with hydrogen and battery storage systems. The authors suggest that the strategy can be adapted for other standalone energy systems with multiple units, offering flexibility in integrating operational, economic, and safety objectives.

In more recent studies, a hierarchical control architecture for MES involving three levels of control have been proposed. In [22], a hierarchical control architecture for multi-source multi-product microgrids is presented. The system includes a supervisory control layer, an optimizing control layer, and an execution control layer. The proposed control architecture coordinates thermal, gas, and electrical systems and incorporates static energy hub models and dynamic characteristics of the microgrid components. Numerical studies demonstrate that the proposed system enables economically efficient operation of multi-source multi-product microgrids. The interactions among thermal, gas, and electrical systems are effectively managed, resulting in cost savings and sustainable operation. The authors suggest that developed control architecture can be implemented for microgrids with various energy sources without the need for a completely new energy management system.

The authors of [23] propose a hierarchical control architecture for multi-energy system that is divided into three levels: superior control, intermediate control and subordinate control. The superior control level serves as the management platform. It is mainly responsible for monitoring operation parameters and analyzing the centralized control strategy of the system. The intermediate control level schedules operation strategies for each subsystem, ensuring flexible and optimal scheduling within the complex energy system. It determines the cooling, heating, and power supply required by each subsystem based on forecasts, maintaining energy supply balance. The subordinate control manages local equipment operations, start-stop, temperature, and flow controls. Based on the simulation results the authors come to the conclusion that this hierarchical approach effectively considers all factors and optimizes the system control at different levels, resulting in a more efficient multi-energy system operation.

Both presented forms of control architecture offer a clear division of control tasks, facilitating the control and optimization of the system. As each level is responsible for specific functions, new elements or energy sources can be integrated without fundamental changes to the existing control architecture. The three-level approach provides a more holistic and efficient approach to managing the complex interactions and dynamic requirements of multiple energy sources. A two-stage system may lack the level of detail and flexibility required to effectively manage the complexity of a larger multi-energy system. Without the intermediate level to provide fine-tuned control, a two-level system may struggle to address the complexity of a larger multi-energy system and manage the specific needs of the various energy carriers and of their interactions. The examples of three-level control architectures presented in literature are limited in scope, as they have been developed for specific applications. The objective of the work at hand is to develop a standardized control architecture based on a three-level system. This contributes towards the applicability of the architecture for different systems and aims to maximize adaptability and extendibility after initial implementation.

3. The Proposed Control Architecture

The proposed architecture consists of three hierarchy levels: the system, the subsystem, and the device levels (Figure 1). Each level can comprise one or more operation models that form the basis for implementing the use cases into operation targets. The presented concept combines a bottom-up and top-down approach, where the data flow is bidirectional, with the purpose depending on the direction.

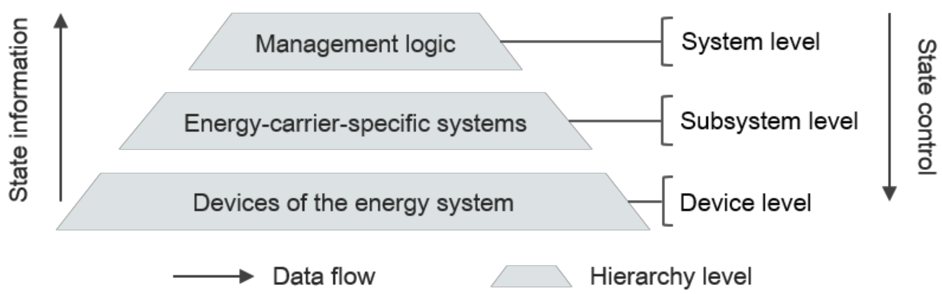


Figure 1: Hierarchy levels of the proposed control architecture.

The hierarchy levels of the control architecture serve the purpose of clearly structured distribution of function and applicability to different energy system compositions. In the following, the framework and tasks of the hierarchy levels are specified, summarized in Table 1.

The *system level* contains the management logic of the energy system. Here, use cases, e.g., market price-dependent choice of energy carriers and hydrogen production from renewable generation, are implemented through operation targets, and the allowed state changes are determined dependent on system constraints. Its task is to coordinate the overall energy system by evaluating the input from the subsystem level regarding required changes in the operational state and the input from use cases regarding the targeted operation to determine necessary adjustments.

The *subsystem level* consists of energy carrier-specific systems. Their task is the supervision of the operation point of each involved device. Here, the individual operating points are aggregated into the overall operating state of the energy carrier's respective subsystem. A continuous comparison between the targeted and the current operational state is carried out. This level optimizes the system efficiency and ensures the security of the energy supply.

The *device level* contains all devices of the examined energy system. Its task is to facilitate information exchange between the devices and the overlying subsystem level, ensuring the execution of targeted operations. From the control architecture viewpoint, these devices are black boxes connected to the subsystem level through an input and an output. The devices themselves are then operated decentral according to the parameters of their respective operation model, which also ensures the operational safety of the devices. This enables easy integration of various devices with minimal limitations to the underlying model of the respective device.

Table 1: Framework and tasks of the proposed control architecture hierarchy levels.

Hierarchy level	Framework	Task
System	Overlying management logic	Specify the operation targets and determine allowed operational state changes based on system constraints.
Subsystem	Energy carrier-specific systems	Supervise the operational point of devices and form an overall energy carrier-specific operating state.
Device	System devices (black boxes)	Enable device integration and ensure the execution of targeted operations.

The management logic at the system level evaluates the requested adjustment to the operating state of the originating energy carrier-specific subsystem and the resulting changes in other subsystems according to the implemented system constraints. If the requested state change of one subsystem is determined to result in a constrained operational state of another, the management logic calculates compensational operating states across all involved energy carrier-specific systems. After each newly determined compensational adjustment, the management logic again assesses whether or not the adjustment results in a constrained operating state for any of the involved energy carrier-specific systems. The concluded operational states are then generated as output and passed on to the subsystem level. In the case of user instructions in the form of use cases, the management logic follows the identical logical path for implementation. For the management logic, a distinction regarding the origin of input is not necessary, as the intention behind the input is always an adjustment of the operational states. The described process of input evaluation prevents undesired or critical operation states across the energy system and is generically depicted in Figure 2.

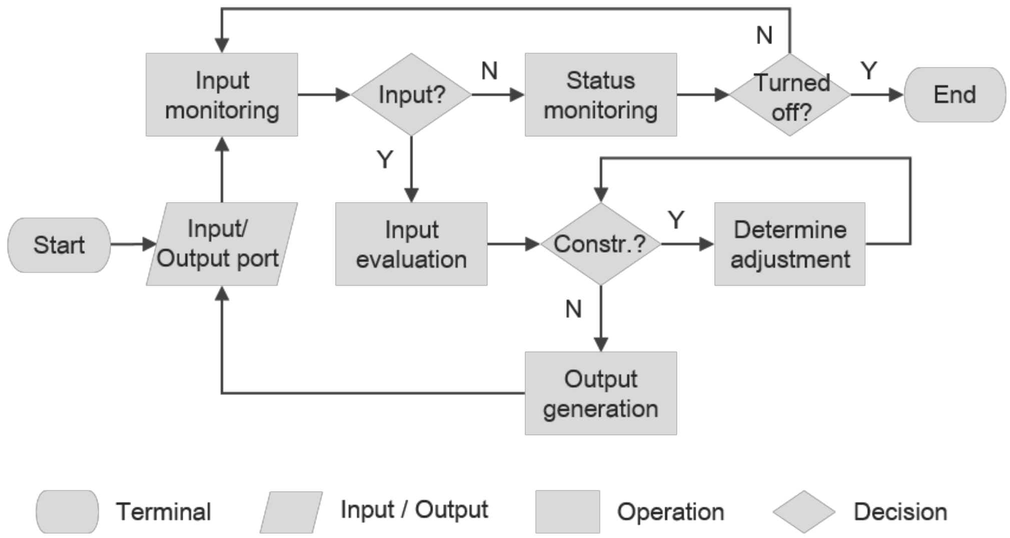


Figure 2: Generic depiction of the management logic at the system level.

The subsystem level is an information carrier between the system and device levels. After the concluded adjustment to the operational state is communicated, the subsystem level passes the resulting operating point adjustments to the device level as input. Here, the black box approach allows the input to be of the same form independent of the addressed device. Thus, the system architecture communicates solely through operating states, the only differentiation being informational and requested ones flowing upwards and directive ones downwards. This allows for easy application of the architecture to various energy carriers and devices and simplifies the integration of differing software used for modeling. This also contributes to the control complexity's scalability by unifying the data flow content between all architecture levels, independent of the energy carrier.

4. Application to the Industrial Research Platform WAVE-H2

The system architecture concept was applied to the hydrogen industrial research platform (WAVE-H2) [24]. The platform is now under construction and will be operated on an industrial scale. The ideal hydrogen value chain for different industrial applications can be tested by using different technologies. The platform offers a hydrogen-based innovation stage for a wide range of industrial applications, further driving the decentralized decarbonization of the industrial sector. The platform consists of a multitude of devices working with different energy carriers. The photovoltaic modules for on-site renewable energy generation and a battery energy storage system for buffer storage are the only devices that are exclusive to a single energy carrier system. Following devices are incorporated regarding the use of multiple energy carriers: a combined heat and power plant capable of running on a mixture of natural gas and hydrogen, two electrolyzers for hydrogen production, one a proton exchange membrane (PEM) electrolyzer and the other an alkaline electrolyzer, a PEM fuel cell, and a heat pump. Subsequently, the platform has three energy carrier systems, hydrogen, electrical and thermal. Apart from the photovoltaic modules and the battery energy storage system, the devices are at least part of two energy carrier systems. The proposed control architecture was used to model the complex interdependencies of the platform's energy system. Figure 3 depicts these interrelationships by mapping the devices' input and output sides to the control architectures' overlying levels.

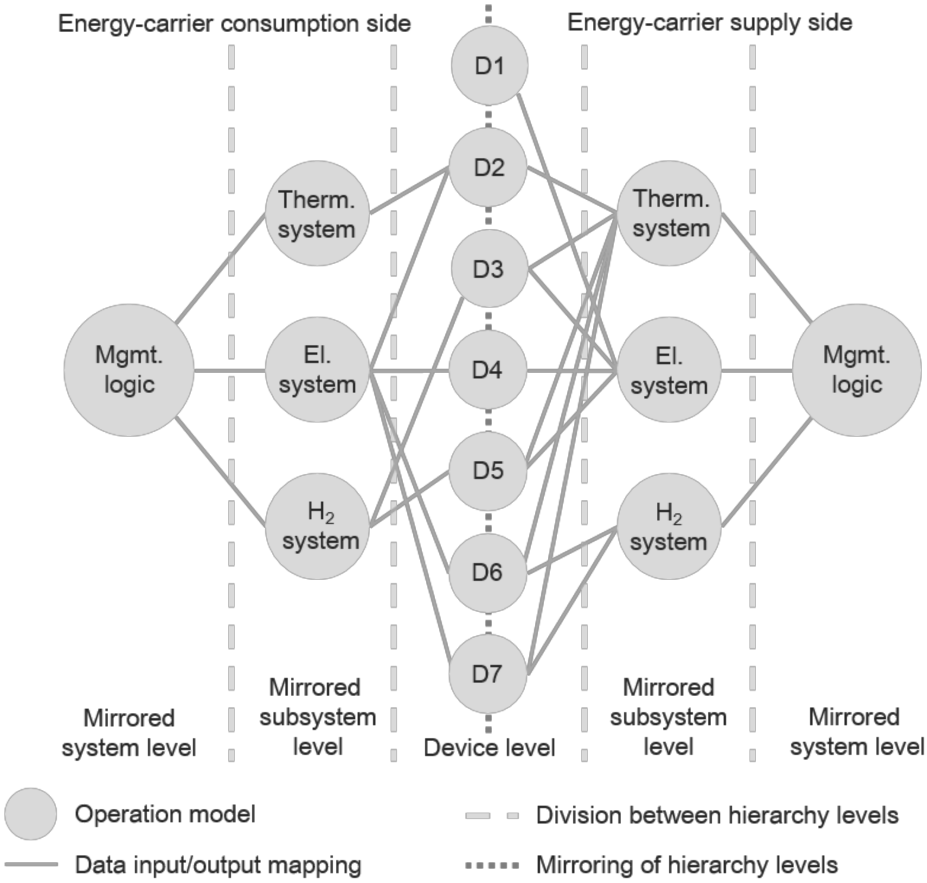


Figure 3: Map of input/output interrelationships between hierarchy levels of the control architecture, depicted by mirroring the architecture according to the device consumption and supply sides.

At the system level, the management logic has been adapted to the constraints of the respective energy carrier systems, e.g., given the research purpose of the platform, it must only act as a consumer of the connected energy grids. Thus, real-world circumstances are depicted, through which the reasonability of operation targets is evaluated before they are acted upon. The three energy carrier systems were integrated at the subsystem level and linked to their respective devices (D1 to D7) at the device level. Table 2 describes the resulting structure of the platform's control architecture and the linking of the hierarchy levels through the input and output parameters. Figure 3 depicts these interrelationships by mapping the devices' input and output sides to the control architectures' overlying levels.

Table 2: Operation models of the industrial research platform and their input and output parameters.

Hierarchy level	Framework	Purpose of Input/ Output
System	Management (Mgmt.) logic	Adjustment requirement/ Operation state adjustment
Subsystem	Thermal (Therm.) system, Electrical (El.) system, Hydrogen (H_2) system	Devices operating point and adjustment/ System operation state and adjustment requirement
Device	Photovoltaic modules (D1), Heat pump (D2), Combined heat and power plant (D3), Battery energy storage system (D4), PEM fuel cell (D5), PEM electrolyzer (D6) and Alkaline electrolyzer (D7)	Adjustment of operating point/ Current operating point

One of the main objectives of such projects as WAVE-H2 is to provide expansion opportunities, ensuring that the work remains adaptable and can grow as new ideas and technologies emerge, which is essential to the long-term success of any scientific endeavor. This paper also encourages and facilitates the development and mapping of a digital twin of the industrial research platform it was applied to. It simulates the physical system and can model, analyze, and optimize its performance. As a result, researchers can gain valuable insights into the systems' behavior and identify areas for improvement, such as enhancing the overall system efficiency, improving the integration of several of multiple-energy carrier devices (MEDs), ensuring interoperability between different MEDs, and promoting the use of low or zero-carbon energy carriers to achieve decarbonization goals.

5. Conclusion

Today, energy systems are expected to include multiple-energy carriers, such as hydrogen, natural gas, and heat, rather than being dominated by a single-energy carrier, like electricity. With an increasing number of energy carriers in one energy system, multiple-energy carrier devices (MEDs) are also becoming the standard. Managing the resulting interdependencies between MEDs and their respective energy carrier systems is challenging. The proposed control architecture addresses this need and provides adaptability by establishing a three-level hierarchical control architecture with unified data content regarding the inputs and outputs.

The hierarchy levels of the control architecture fulfill specific but not application-bound tasks. Firstly, the system level specifies the operation targets and determines allowed operational state changes based on system constraints. Secondly, the subsystem level supervises the operational points of devices and forms an overall energy carrier-specific operating state. Conclusively, the device level enables device integration and ensures the execution of targeted operations. The data flow between the hierarchy levels only contains the operational state information, informing the overlying level and instructing the level below. This allows system devices to be integrated and exchanged with relatively low effort.

Accordingly, the main contribution of this research can be considered as follows:

- Proposal of an appropriate control architecture designed for facilitated applicability to complex energy systems with MEDs.
- Simplified expandability of a multi-energy carrier system (MES) due to the flexibility of the proposed architecture.
- Facilitated development and mapping of a digital twin of a MES.

The next step in this research is the advancement of the digital twin, which implements the proposed system architecture by integrating operation models regarding the subsystem and device level. Subsequently, the aim is to optimize the operation through the proposed architecture. Therefore, a mathematical description of dependencies between the inputs and outputs can be defined mathematically, e.g., by a coupling matrix to minimize a resulting objective function oblique to the optimization objective of the system. Regarding the complexity of interrelationships between energy carrier systems, optimization is required to address multi-objective problems. For this purpose, typical use cases, e.g., peak shaving and consumption-dependent generation, must be defined and tested in combination. Thereafter, it is necessary to analyse the digital twins operational behaviour in comparison to their real-life counterparts before realizing it as the energy management system for the industrial research platform.

Acknowledgement

The authors gratefully acknowledge financial support by the German Federal Ministry of Education and Research (BMBF) via grant number 03SF0667 (project: WAVE-H2) and for making this research possible.

References

[1] Hemmati, M., Mohammadi-Ivatloo, B., Ghasemzadeh, S., Reihani, E., 2018. Risk-based optimal scheduling of reconfigurable smart renewable energy based microgrids. International Journal of Electrical Power & Energy Systems 101, 415–428.

[2] Mancarella, P., 2014. MES (multi-energy systems): An overview of concepts and evaluation models. Energy 65, 1–17.

[3] Wang, X., Liu, Y., Liu, C., Liu, J., 2020. Coordinating energy management for multiple energy hubs: From a transaction perspective. International Journal of Electrical Power & Energy Systems 121, 106060.

[4] Fabrizio, E., Corrado, V., Filippi, M., 2010. A model to design and optimize multi-energy systems in buildings at the design concept stage. Renewable Energy 35 (3), 644–655.

[5] Geidl, M., Koeppel, G., Favre-Perrod, P., Klöckl, B., Andersson, G., Fröhlich, K., 2007. The Energy Hub: A powerful concept for future energy systems. Third Annual Carnegie Mellon Conference on the Electricity Industry 2007.

[6] Alam, M.S., Arefifar, S.A., 2019. Energy Management in Power Distribution Systems: Review, Classification, Limitations and Challenges. IEEE Access 7, 92979–93001.

[7] Fiorini, L., Aiello, M., 2019. Energy management for user's thermal and power needs: A survey. Energy Reports 5, 1048–1076.

[8] Mohammadi, M., Noorollahi, Y., Mohammadi-ivatloo, B., Yousefi, H., 2017. Energy hub: From a model to a concept – A review. Renewable and Sustainable Energy Reviews 80, 1512–1527.

[9] Tabar, V.S., Jirdehi, M.A., Hemmati, R., 2017. Energy management in microgrid based on the multi objective stochastic programming incorporating portable renewable energy resource as demand response option. Energy 118, 827–839.

[10] Olivares, D.E., Canizares, C.A., Kazerani, M., 2011. A centralized optimal energy management system for microgrids, in: 2011 IEEE Power and Energy Society General Meeting. 2011 IEEE Power & Energy Society General Meeting, San Diego, CA. 24.07.2011 - 29.07.2011. IEEE, pp. 1–6.

[11] Olivares, D.E., Canizares, C.A., Kazerani, M., 2014. A Centralized Energy Management System for Isolated Microgrids. IEEE Trans. Smart Grid 5 (4), 1864–1875.

[12] Bahrami, S., Toulabi, M., Ranjbar, S., Moeini-Aghtaie, M., Ranjbar, A.M., 2018. A Decentralized Energy Management Framework for Energy Hubs in Dynamic Pricing Markets. IEEE Trans. Smart Grid 9 (6), 6780–6792.

[13] Yin, H., Zhao, C., Ma, C., 2018. Decentralized Real-Time Energy Management for a Reconfigurable Multiple-Source Energy System. IEEE Trans. Ind. Inf. 14 (9), 4128–4137.

[14] Zhao, P., Suryanarayanan, S., Simoes, M.G., 2013. An Energy Management System for Building Structures Using a Multi-Agent Decision-Making Control Methodology. IEEE Trans. on Ind. Applicat. 49 (1), 322–330.

[15] Marín, L.G., Sumner, M., Muñoz-Carpintero, D., Köbrich, D., Pholboon, S., Sáez, D., Núñez, A., 2019. Hierarchical Energy Management System for Microgrid Operation Based on Robust Model Predictive Control. Energies 12 (23), 4453.

[16] Skarvelis-Kazakos, S., Papadopoulos, P., Grau Unda, I., Gorman, T., Belaidi, A., Zigan, S., 2016. Multiple energy carrier optimisation with intelligent agents. Applied Energy 167, 323–335.

[17] Bhattarai, B.P., Levesque, M., Bak-Jensen, B., Pillai, J.R., Maier, M., Tipper, D., Myers, K.S., 2017. Design and Cosimulation of Hierarchical Architecture for Demand Response Control and Coordination. IEEE Trans. Ind. Inf. 13 (4), 1806–1816.

[18] Ramirez Elizondo, L.M., 2013. Optimal Usage of Multiple Energy Carriers in Residential Systems: Unit Scheduling and Power Control. Dissertation, Delf, Netherlands, 205 pp.

[19] Roy S. Smith, Varsha Behrunani, John Lygeros, 2023. Control of Multicarrier Energy Systems from Buildings to Networks. Annual Review of Control, Robotics, and Autonomous Systems.

[20] Trifkovic, M., Marvin, W.A., Daoutidis, P., Sheikhzadeh, M., 2014. Dynamic real-time optimization and control of a hybrid energy system. AIChE J. 60 (7), 2546–2556.

[21] Velez, V., Ramirez-Elizondo, L., Paap, G.C., 2011. Control strategy for an autonomous energy system with electricity and heat flows, in: 2011 16th International Conference on Intelligent System Applications to Power Systems. 2011 16th International Conference on Intelligent System Applications to Power Systems (ISAP), Hersonissos, Greece. 9/25/2011 - 9/28/2011. IEEE, Place of publication not identified, pp. 1–6.

[22] Xu, X., Jia, H., Wang, D., Yu, D.C., Chiang, H.-D., 2015. Hierarchical energy management system for multi-source multi-product microgrids. Renewable Energy 78, 621–630.

[23] Li, J., Xu, W., Zhang, X., Feng, X., Chen, Z., Qiao, B., Xue, H., 2022. Control method of multi-energy system based on layered control architecture. Energy and Buildings 261, 111963.

[24] University of Stuttgart, 2021. WAVE-H2 – Wasserstoff für mehr Industrieanwendungen. University of Stuttgart. https://www.uni-stuttgart.de/en/university/news/all/WAVE-H2--Wasserstoff-fuer-mehr-Industrieanwendungen/. Accessed 8 July 2023.

Biography

Kerim Torolsan (*1992) has been working as a research associate of the Institute for Energy Efficiency in Production (EEP) at the University of Stuttgart since 2022. M. Sc. Kerim Torolsan completed his studies in the field of sustainable electrical energy supply at the University of Stuttgart in 2022 and has a B. Sc. in the field of renewable energies. His research focus is on energy management for industrial energy systems.

Mirja Mannigel (*1993) has been working as a research associate at the Institute for Energy Efficiency in Production (EEP) at the University of Stuttgart since 2022. M. Sc. Mirja Mannigel graduated in 2021 with a degree in mechanical engineering in the field of energy and process engineering at the University of Duisburg-Essen. Her research focus is on industrial hydrogen systems and energy storage.

Janosch Hecker (*1992) has been working as a research associate at the Institute for Energy Efficiency in Production (EEP) at the University of Stuttgart since 2022. M. Sc. Janosch Hecker graduated in 2020 with a degree in mechatronics engineering at the Reutlingen University. His research focus is on electrical microgrids and energy storages for resource-efficient industrial production.

Alexander Sauer (*1976) has been director of the Institute for Energy Efficiency in Production (EEP) at the University of Stuttgart since 2015 and director of the Institute for Manufacturing Engineering and Automation (IPA) at Fraunhofer since 2020. Prof. Dr.-Ing. Alexander Sauer has established the energy efficiency index of the industry, is head of the Ultra-efficiency Factory and spokesperson for the Kopernikus-Project SynErgie.

5th Conference on Production Systems and Logistics

Overview and Roadmap of Hydrogen Utilization in Industry

Laura Jung[1,2], Verena Lampret[1,2], Alexander Sauer[1,2]
[1]Institute for Energy Efficiency in Production EEP, Stuttgart, Germany
[2]Fraunhofer Institute for Manufacturing Engineering and Automation IPA, Stuttgart, Germany

Abstract

Hydrogen has emerged as a promising solution for achieving a sustainable economy in various industrial sectors. This paper provides an overview of the use of hydrogen in various industrial applications, including energy and heat supply in industrial processes, raw material utilization, and transport. The benefits and role of hydrogen in industrial defossilization are discussed, highlighting its potential to reduce greenhouse gas emissions from energy-intensive industries. The storage properties of hydrogen offer a solution to decouple the availability of renewable energy from its generation time and to increase energy flexibility. In addition, the paper examines the strategic aspects of hydrogen deployment in Germany, such as policy considerations, the economic viability of hydrogen technologies, external influences such as imports, and the current technical challenges associated with its widespread adoption. Considering these aspects, an overview and a roadmap for the integration of hydrogen in industrial sectors are presented, and recommendations for a successful transition to hydrogen are given.

Keywords

Roadmap; Hydrogen; Industry; Energy Supply; Decarbonization

1. Motivation

In the Paris Climate Agreement, 195 countries agreed in 2015 to reduce their climate-damaging emissions to prevent climate change and limit global temperatures [1]. To achieve this goal, 27 of the EU Member States signed the European Green Deal. Thus, the European Union aims to become carbon neutral by 2045 [2]. As an initial measure, greenhouse gas emissions should be reduced by at least 65 % until 2030 compared to 1990. In a further step, emissions should continue to fall, aiming to achieve an 88 % reduction by 2040 [3]. In Germany, greenhouse gas emissions have been continuously reduced over the past years. In 2022, they accounted for about 746 million tons of CO_2-equivalent (Mt CO_2e), which represents a reduction of 40 % compared to the 1990 levels. The main source of emission corresponded to CO_2 from fossil fuel combustion, which accounts for 84 % of total greenhouse gas emissions [4].

In order to achieve climate neutrality in an industrialized nation such as Germany, the reduction of CO_2 emissions must be continuously pushed. In 2022, the industrial sector was responsible for emitting around 164 Mt CO_2e. This sector is Germany's second largest source of greenhouse gas emissions after the energy supply sector, accounting for 22 % of total emissions. To achieve the 2030 targets, the industrial sector must reduce its emissions by about 70 Mt CO_2e [5]. For this reason, the motivation to use hydrogen as an alternative energy source is significant. It could be used to defossilize industrial processes and generate energy or heat, as these processes often rely on fossil fuels combustion. This article provides insight into the role of hydrogen and its potential use in the industrial sector as an alternative energy carrier to reduce emissions. It also examines its future prospects.

DOI: https://doi.org/10.15488/15284
ISSN: 2701-6277

2. Industrial Hydrogen Utilization

2.1 Green Hydrogen as an Alternative Energy Carrier

Hydrogen, chemically H_2, and in Latin hydrogenium, translates "water maker". This underlines hydrogen's crucial role in water formation, which was demonstrated by the scientist Antoine Laurent de Lavoisier in 1785 [6]. Hydrogen is the most abundant element in the universe. On Earth, however, it is usually found with other elements, such as oxygen or carbon. To obtain H_2 in its pure form, it must be separated from the other elements. There are various methods to produce hydrogen, each labeled by a color scheme: black from coal gasification, brown from lignite gasification, grey from gas steam reforming, blue if carbon capture storage or utilization (CCS or CCU) follows the steam reforming and turquoise from methane pyrolysis. Hydrogen is only classified as green and, therefore, climate-neutral if the electricity used for the electrolysis comes from 100 % renewable sources, such as solar or wind power [7,8].

Green hydrogen can be used as an alternative energy carrier to reduce the industry's dependence on fossil fuels. It is therefore considered a key element in the energy transition and climate protection in Germany's industrial sector [9]. Green hydrogen is CO_2 emission-free and can be used in a wide range of industrial applications. It plays an important role in defossilizing industrial processes that cannot be electrified. In addition, hydrogen is a long-term energy storage medium to store the excess energy from renewable sources effectively. The production and storage of green hydrogen are important due to the high variability of energy production from solar and wind sources. It provides a valuable and effective solution during periods of high energy supply and low demand, as it can decouple the availability of renewable energy sources from the time of their generation due to weather conditions. The efficiency and use of renewable power plants can be fully exploited, as the plants do not need to be shut down when energy demand is low. In addition, energy flexibility is addressed to support the expansion of renewables into the industrial energy system. Hydrogen offers the advantage of excellent transportability and storability, as it can be compressed and stored in both gaseous and liquid form. It could be transported through a gas network and used as a fuel at refueling stations [10]. Finally, it allows for energy security since geopolitical developments often affect both the availability and price of fossil fuels [10,7,6].

Given the limited availability and higher costs associated with hydrogen production, it is important to prioritize direct electrification over hydrogen technologies to accelerate the defossilization process of the industrial energy system. Hydrogen should be used primarily in cases where direct electrification is not viable, such as aviation, heavy-duty transport, international shipping, and specific industrial applications. Hydrogen can also be an optimal choice, where a flexible energy system is required.

2.2 Current and Potential Use of Hydrogen in Industrial Applications

At present, hydrogen has significant industrial applications, particularly in the chemical industry and refineries (as shown in Figure 1). This is predominantly grey hydrogen produced by steam reforming of natural gas. However this chapter aims to explore the prospects for green hydrogen and its many potential future applications.

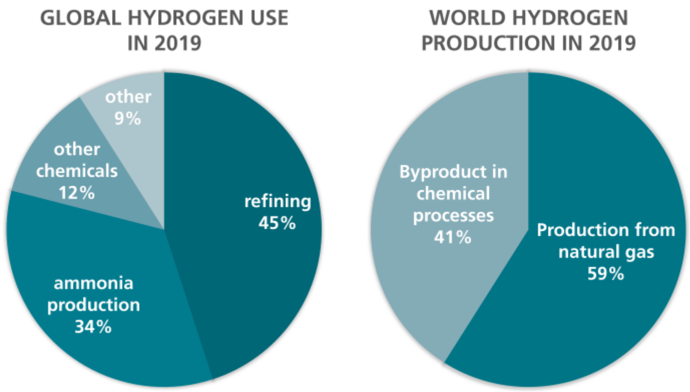


Figure 1: Global hydrogen usage by sectors in 2019, according to [11]

2.2.1 Hydrogen in Industrial Energy Production

Combined heat and power (CHP) plants and fuel cells provide energy-efficient conversion of hydrogen into electrical energy. For industrial applications, fuel cells can be used as decentralized power generators to produce the plant's energy requirements. By utilizing waste heat, plant efficiency can be increased while generating heat for industrial processes. Considering different manufacturers, fuel cells and CHP units offer an overall efficiency of over 80 % for the simultaneous production of heat and electricity [12–18]. The electrical efficiency of fuel cells is 1-2 % higher than that of CHP units [19–22]. The focus of fuel cells is usually on electricity generation. For CHP units, a distinction can be made between the mode of operation: heat and/or electricity-driven. The heat-driven mode is usually predominant [23]. Start-up time and dynamic operation are also important characteristics that should be considered. CHP and polymer electrolyte fuel cells (PEMFC) have a short start-up time compared to phosphoric acid fuel cells (PAFC), molten carbonate fuel cells (MCFC), and solid oxide fuel cells (SOFC). Dynamic operation and emergency power capability are only possible with CHP and PEMFC [24].

2.2.2 Hydrogen in Industrial Heat Production

In the industrial sector, process heat production accounts for about 67 % of final energy consumption. In addition, about 6.5 % of energy is used for heating buildings and producing hot water [25]. Industrial heat demand below 100 °C represents only 8.8 % of the total heat demand. If hot water and space heating are included, this percentage rises to 21 % [26]. Processes involving temperatures above 100 °C include the metal industry, with its melting and casting processes, and glass production, which requires high temperatures for the melting process. Paper manufacturing is also associated with cooking and drying processes. In food processing, high temperatures are used for sterilizing, cooking and drying products.

Temperatures below 100 °C can be covered by waste heat from a CHP or a low-temperature fuel cell. Fuel cells can be used in different temperature ranges. They are divided into low, medium, and high-temperature fuel cells. The electrical efficiency of a fuel cell is higher than its thermal efficiency. However, waste heat is available at different temperature levels. The polymer electrolyte fuel cell (PEMFC) and the alkaline fuel cell (AFC) are low-temperature fuel cells operating at up to 120 °C. The medium-temperature fuel cell includes the phosphoric acid fuel cell (PAFC), which operates at temperatures up to 220 °C [24].

For high-temperature applications, the molten carbonate fuel cell (MOFC) and the solid oxide fuel cell (SOFC) can operate at temperatures up to 450 °C – 1,000 °C [24]. Furthermore, the hydrogen combustion can be adapted to existing burner technology for natural gas and its associated systems. Due to hydrogen's different calorific values and combustion characteristics compared to natural gas, burner adaptation is required to maintain consistent product quality or process heat supply [6]. Several applications are currently under development, such as crucible furnaces for melting aluminum materials, which allow using pure hydrogen for combustion [27]. The most energy-intensive process in cement production is clinker production, which requires high temperatures. Hydrogen is emerging as a viable alternative, providing an opportunity to reduce emissions during the heating phase [28]. Hydrogen is also emerging as a clean-burning fuel alternative in the glass manufacturing and pulp and paper industries, offering the potential to reduce emissions in key high-temperature processes. Additionally, thermal oil systems can use hydrogen combustion to heat the thermal oil. Thermal oil is a pressureless heat transfer medium and can be used in various processes with temperatures of up to 350 °C. Another option for direct steam generation is the oxyfuel process, which is currently under development. Here pure oxygen is used for combustion to avoid the formation of NO_x. The combustion of pure hydrogen and pure oxygen produces water, which can be used as direct process steam after combustion [6].

2.2.3 Hydrogen as a Raw Material for Industrial Processes

Green hydrogen reduces CO_2 emissions in industrial processes where grey hydrogen is used as a raw material for the production of various materials. Here are a few examples of industrial applications:

- **In steel production,** green hydrogen can be used as a reducing agent in the Blast Furnace (BF) instead of carbon to reduce CO_2 emissions in the extraction of iron ore for the production of raw steel. In the BF/Basic Oxygen Furnace (BOF) process, hydrogen and combustion air reduce iron ore in the blast furnace (BF). The resulting liquid iron is then transferred to the converter (BOF) for further processing into raw steel. Initial trials have confirmed the promising direct use of hydrogen, and a second experimental phase is investigating the impact of hydrogen technology on the metallurgical processes in the blast furnace [29]. Another promising approach to steelmaking is the Direct Reduction/Electric Arc Furnace (DR/EAF) process. In this method, iron ore is reduced using hydrogen in a direct reduction (DR) plant, and the obtained iron is then introduced into the electric arc furnace (EAF). These plants are typically fuelled by natural gas, allowing the possibility of transformation to hydrogen. The direct reduction process exhibits the highest potential for emission reduction, and its application has already been successfully demonstrated in the small-scale innovation project µDRAL [6,30].
- **In the chemical industry**, hydrogen is used to produce basic chemicals such as ammonia and methanol. Ammonia, composed of nitrogen (N) and hydrogen (H), finds application in fertilizer production, as a refrigerant in cooling systems, and in the production of various chemical compounds. Methanol, produced from carbon monoxide (CO), carbon dioxide (CO_2), and hydrogen (H), serves as a feedstock for the synthesis of many chemical compounds, including plastics, solvents, and pharmaceuticals [31]. Currently, grey hydrogen derived from natural gas reforming is predominantly used. The chemical sector accounts for about half of the annual hydrogen demand and offers significant potential for emission reductions through substitution. As certain chemical processes rely on CO_2 from steam reforming, the substitution of this process with alternative carbon sources is being investigated. The Carbon2Chem project investigates the utilization of process gases, such as blast furnace gases from steel production, as carbon sources and feedstocks for basic chemicals [32].
- **In refineries,** hydrogen is used for fuel desulfurization and hydrocracking, breaking down heavy crude oil fractions to produce high-value products. Refineries are currently the most significant users of hydrogen. These processes use both grey hydrogen from natural gas reforming and on-site generated hydrogen from refinery operations [31].

2.2.4 Hydrogen in Industrial Transport for a Sustainable Mobility

Hydrogen in fuel cell vehicles offers an environmentally friendly solution for reducing emissions in freight transport. Whether for heavy-duty and long-haul vehicles or within logistics centers, particularly for forklift trucks, hydrogen as an energy carrier offers a sustainable alternative.

2.3 Key Factors for the Use of Hydrogen in Industry

Investments must be carefully balanced, considering both economic viability and sustainability. In addition, certain technologies need to reach certain development milestones (TRL levels) to become cost-effective for industrial implementation. In addition, policy choices, such as investment strategies and international cooperation, will play a key role in shaping their progress.

2.3.1 Political Goals for a Sustainable Transition

Europe's hydrogen strategy is ambitious: By 2050, the percentage of renewable hydrogen in the European energy mix should increase to 13-14 %. In the first phase, from 2020 to 2024, electrolyzers with a total capacity of 6 GW are planned. By 2030, the capacity is expected to reach 40 GW to promote the use of green hydrogen in the energy system. The aim is to make green hydrogen competitive with other production methods by 2030 and to support an energy system based on renewable sources. In the final phase, from 2030 to 2050, renewable hydrogen technologies should be ready for large-scale deployment across all sectors [33].

In Germany, the National Hydrogen Strategy (Nationale Wasserstoffstrategie NWS) 2020 has been adopted to accelerate the use of this climate-friendly alternative. The strategy includes establishing local production facilities, developing hydrogen technologies, expanding the hydrogen infrastructure and cooperating with international partners for imports. In this way, the market for a green hydrogen economy will be gradually prepared. By 2030 electrolyzers with 10 GW of capacity will be installed [34].

The National Hydrogen Strategy Review in July 2023, expands on the 2020 strategy with the goal of adapting the delivery of safe, sustainable, and climate-neutral hydrogen. By 2030, the new Hydrogen Strategy aims to lay the foundations for a sustainable future by ensuring an abundant supply of hydrogen, building a robust infrastructure, promoting its integration into the industrial, energy and heating sectors, and creating the optimal framework to facilitate these transitions. By 2027/2028, Germany plans to have an initial hydrogen network in place. It will consist of 1,800 km of upgraded and new hydrogen pipelines. In parallel, a "European Hydrogen Backbone" of about 4,500 km across Europe will be developed. The aim is to have a network by 2030 that directly connects all major hydrogen production, import and storage hubs with primary consumers. In 2030, hydrogen and its derivatives are expected to have widespread use in industrial applications, heavy-duty vehicles, and air and maritime shipping. In the electricity sector, hydrogen will increase energy security by means of flexible gas power plants (H_2-ready). Conditions for its use in centralized and decentralized heating systems are being developed. Germany aims to lead hydrogen technologies by 2030, with companies covering the entire value chain from electrolyzers to fuel cells [35].

2.3.2 Marketability and Economic Viability

To compete with other energy sources and achieve a breakthrough, green hydrogen’s price must be reduced further. At present, the cost of producing hydrogen is very high. Figure 2 shows the current cost of hydrogen for different production methods. Technologies for green hydrogen production need to be further developed, and the cost of fossil fuels must increase, for example, through a carbon pricing mechanism, to make green hydrogen more competitive [36]. Revenues from carbon pricing could support investment in renewable hydrogen. In 2022, the price of a CO_2 allowance in the EU Emissions Trading Scheme (EU-ETS) will average around €81/tCO_2 [37]. In 2021, the National Emission Trading Scheme (nEHS) will start selling allowances at a fixed price of €25/tCO_2. By 2026, the price will be set at €55-65/tCO_2 [38]. The National Hydrogen Strategy estimates investment expenditure for hydrogen development at least €10 billion [34]. For Europe, the investment is estimated at €180-470 billion [33].

Additionally, the development of production routes is essential. Due to continuous technological advances, the cost of electrolyzers has already fallen by 60 % compared to previous years. Improved efficiencies and economies of scale are expected to further reduce the price by 2030 [33,7]. The average capital expenses (CapEx) for electrolyzers currently are €800/kW. It is expected to fall to around €650/kW just before 2030 and to below €500/kW after 2030 [39]. The expansion of renewable energy sources will also lead to a reduction in electricity costs, which will have a positive impact on operating costs.

Figure 2 presents the projections for hydrogen production costs according to [40]. Two trends are shown for green hydrogen. Assuming a constant natural gas price and a carbon price of €100/ton, a conservative trend emerges in which green hydrogen is slightly more expensive than grey or blue hydrogen by 2050. The second trend assumes a rapid development of electrolyzers. In this scenario, green hydrogen could become cost-competitive before 2050.

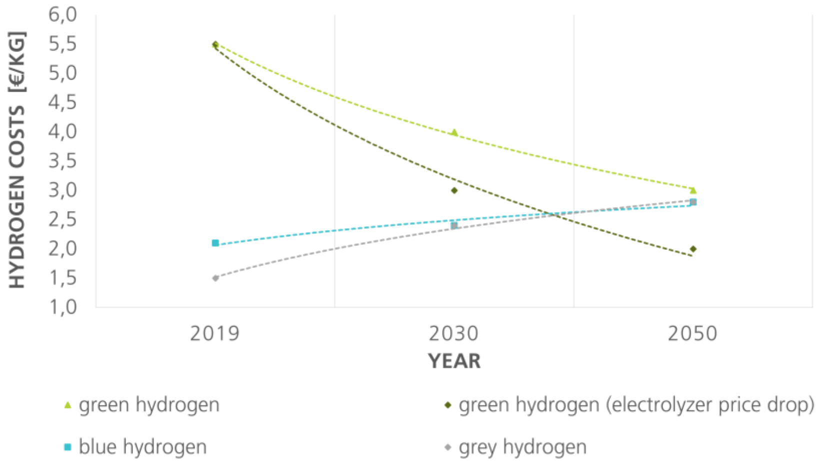


Figure 2: Hydrogen costs [€/kg] according to [40]

2.3.3 Technical Hurdles and Challenges of Hydrogen's Technologies

It takes about 9 kg of water to produce 1 kg of hydrogen. In addition, about 50-55 kWh of electrical energy is required. [41]. Seawater is abundant but must be desalinated before it can be used in processes such as PEM electrolyzers. New insights into hydrogen production from raw seawater by electrolysis have been successfully tested and are under development [42]. Other approaches to hydrogen production are also being explored, such as the use of biomass. In particular, the study of purple bacteria derived from fruit and dairy waste opens up promising avenues for hydrogen production [43].

Another critical issue is the availability of key materials essential for implementing a hydrogen economy. The hydrogen sector requires materials such as aluminum, copper, nickel, and zinc for developing renewable energy sources, and platinum and iridium for advancing electrolyzer technologies. However, the increasing scale of demand in the coming years may pose challenges in sourcing these materials, potentially leading to shortages or higher prices. It is projected that platinum demand for hydrogen production could exceed current production levels by more than a third by the 2030s, while iridium demand for PEM electrolyzers could increase by more than 160 % over current production levels by 2040. Given this increased demand for critical materials, the importance of recycling, improving efficiency, and extending the life of these technologies must be assessed to achieve a sustainable hydrogen economy [44].

Another technical barrier is the transport of hydrogen in the existing gas network. A hydrogen blend of up to 20 vol-% has already been achieved. Further development of up to 30 vol-% is expected [45]. Higher blends bring uncertainties about material degradation of the pipeline steel and pipeline components such as compressors, valves, or pressure-reducing stations. The handling of gas leaks is also much more delicate. Finally, end-user equipment would also need to be adapted to this blend, as the different calorific and density properties may affect the end-use application [46]. Hydrogen blending in pipelines reduces energy transmission efficiency due to its lower volumetric energy density than natural gas, requiring higher operating pressures to maintain constant transmission capacity. However, this poses challenges for steel materials. In addition, exceeding the maximum velocity can cause damage or erosion to the pipeline walls, leading to wall leaks or other problems [47].

2.3.4 External Influences on Hydrogen's Economy Development

Renewable energy sources, such as solar and wind, have lower operating costs than conventional fossil fuels once the equipment is amortized. Countries with abundant solar or wind resources can direct their economic growth towards renewable energy [7]. The European Hydrogen Strategy foresees partnerships with neighboring countries and regions, especially in North Africa [33].

2.4 Development of a Hydrogen Roadmap for Industrial Energy Supply

Based on the issues discussed in the previous chapters, a comprehensive hydrogen roadmap for the industry is proposed. This roadmap outlines the short-, medium-, and long-term goals that must be achieved to facilitate a successful transition to a hydrogen-based energy system.

The transition to renewable energy sources for industrial power supply in industry is increasing. However, renewable energy fluctuations require a flexible energy demand and storage in industries, which could be achieved through the integration of hydrogen. The results of Stuttgart University's Energy Efficiency Index survey from 2021 show that over 60 % of the companies have integrated or are integrating renewable energy within the company. In addition, more than 30 % of the companies have or plan energy storage solutions. According to the survey, the use of hydrogen in industry is currently very low at 8 %. However, about 58 % of the companies surveyed are currently investigating the use of hydrogen or have plans to investigate [48]. As renewable energy is expected to continue to grow, the industry has identified the potential of hydrogen for energy storage or as an alternative fuel and is exploring its implementation.

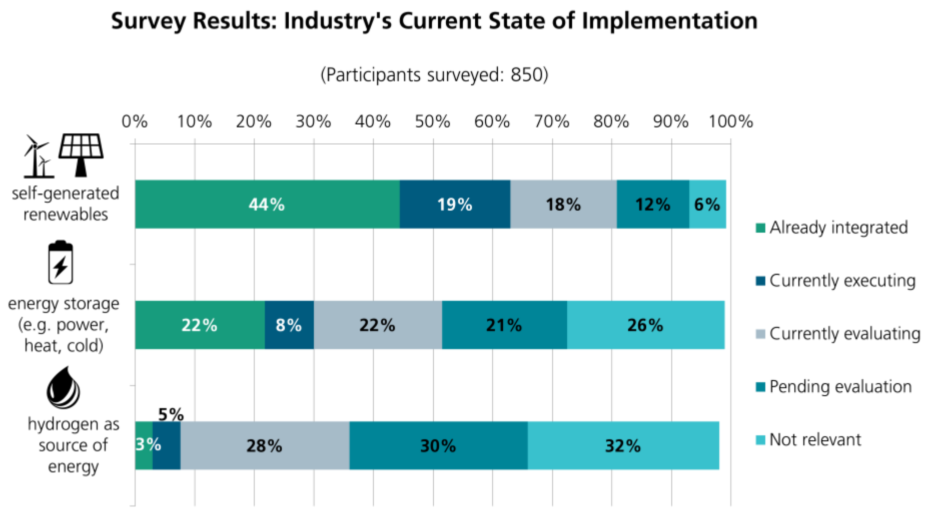


Figure 3: Survey Results: Industry's Current State of Implementation [48]

In the short and medium term, the use of H_2 blending in natural gas can be a solution to reduce CO_2 emissions for the industrial energy supply using the existing technologies. The availability of hydrogen-ready technologies allows a switch in operation without additional plant modifications. Some CHP engine manufacturers, allowing a blending percentage in the existing plant of up to 40 %, are following this approach [49]. As described in the previous chapters, it is expected that the high prices of hydrogen and electrolyzers will decrease while the import of hydrogen increase, so that in the long term hydrogen can be used economically as an energy source in industry. In addition, the development and ongoing research in hydrogen technologies will enable a long-term breakthrough in the industry.

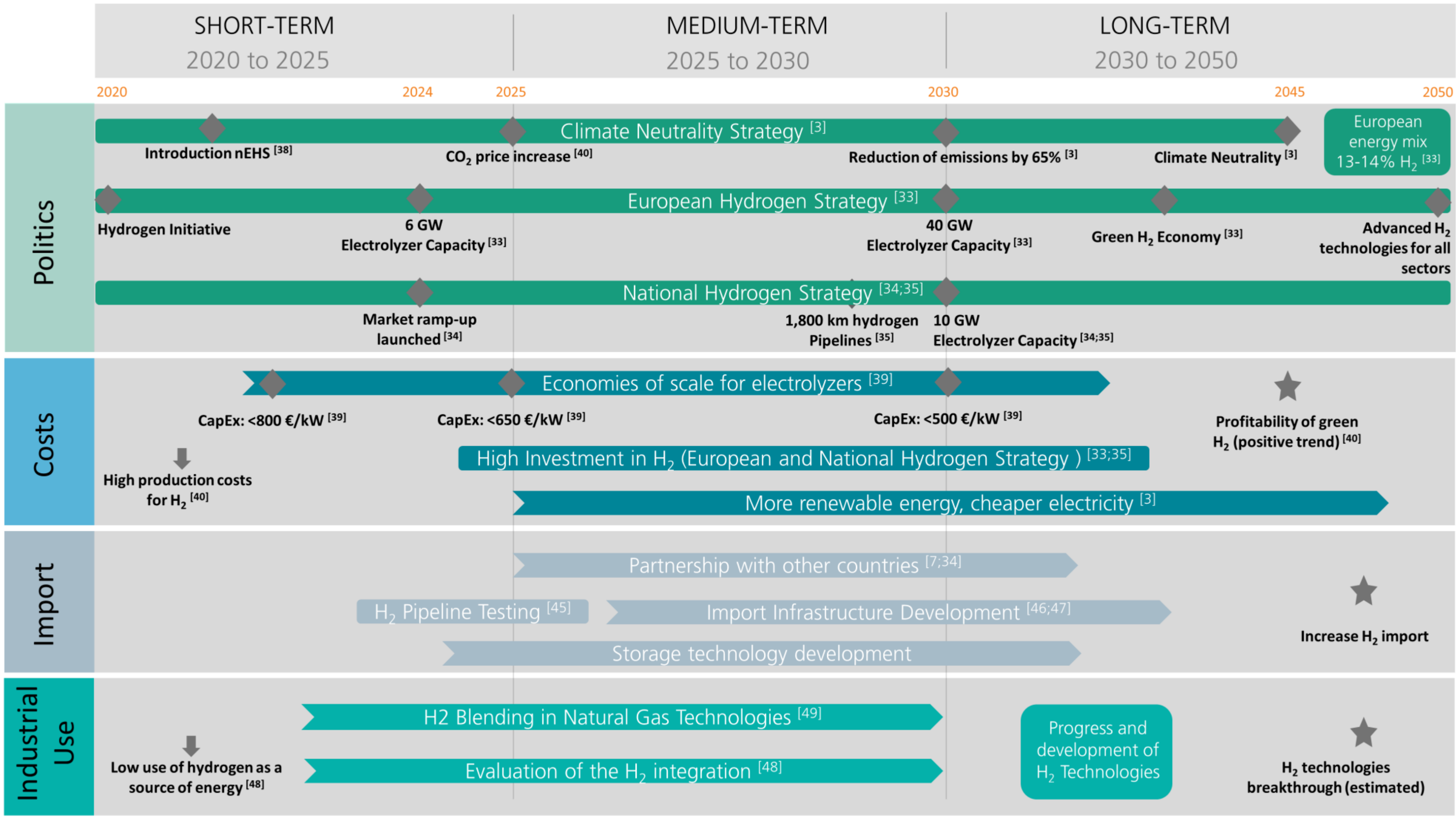


Figure 4: Hydrogen Roadmap

3. Summary and Outlook

This paper provides an overview of the potential development of green hydrogen technologies in industrial applications focussing on their use in achieving climate neutrality goals. The analysis considers political and economic developments as well as technical barriers associated with hydrogen production and use. The results suggest that significant hydrogen economy development can be expected after 2045. This projection is based on several factors, including expected cost reductions for hydrogen, the availability of abundant renewable energy sources, and advances in related technologies and infrastructure. Looking forward, the outlook for green hydrogen technologies appears promising. With projected cost reductions and advances in renewable energy sources, hydrogen is expected to become a viable and competitive option for various industrial applications. In addition, the continued development of technologies and infrastructure will further increase the adoption and implementation of hydrogen-based solutions. This transformation holds great potential for reducing carbon emissions and promoting sustainable industrial practices.

3.1.1 The Vision of an Industrial Research Platform: WAVE-H2

To achieve climate neutrality and advance the technological development of hydrogen technologies on an industrial scale, the Federal Ministry of Education and Research (Bundesministerium für Bildung und Forschung BMBF) is funding the establishment of a "Versatile, Energy-Flexible, and interconnected H_2 Industrial Research Platform (WAVE-H2)". The University of Stuttgart will establish a dynamic hydrogen infrastructure by 2025. The aim is to investigate the optimal and flexible path for hydrogen in terms of production, distribution, storage, and consumption in industrial energy and heat supply, considering different technologies [50].

Nomenclature

CapEx	Capital Expenditures
CHP	Combined Heat and Power
FC	Fuel Cell
MCFC	Molten Carbonate Fuel Cell
PAFC	Phosphoric Acid Fuel Cell
PEMFC	Polymer Electrolyte Membrane Fuel Cells
SOFC	Solid Oxide Fuel Cell

References

[1] Bundesministerium für wirtschaftliche Zusammenarbeit und Entwicklung, 2023. Klimaabkommen von Paris. https://www.bmz.de/de/service/lexikon/klimaabkommen-von-paris-14602. Accessed 19 April 2023.

[2] Europäische Kommission, 2023. Europäischer Grüner Deal. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_de. Accessed 19 April 2023.

[3] Die Bundesregierung, 2023. Klimaschutzgesetz und Klimaschutzprogramm. https://www.bundesregierung.de/breg-de/aktuelles/klimaschutzgesetz-2197410. Accessed 23 June 2023.

[4] Umweltbundesamt, 2023. Treibhausgas-Emissionen in Deutschland. https://www.umweltbundesamt.de/daten/klima/treibhausgas-emissionen-in-deutschland#treibhausgas-emissionen-nach-kategorien. Accessed 19 April 2023.

[5] Umweltbundesamt, 2023. Emissionsübersichten nach Sektoren des Bundesklimaschutzgesetzes: 1990 - 2022. http://www.umweltbundesamt.de/emissionen. Accessed 19 April 2023.

[6] Neugebauer, R. (Ed.), 2022. Wasserstofftechnologien, 1. Aufl. 2022 ed. Springer, Berlin, Heidelberg, 483 pp.

[7] Linnemann, M., Peltzer, J., 2022. Wasserstoffwirtschaft kompakt: Klimaschutz, Regulatorik und Perspektiven für die Energiewirtschaft. Springer Vieweg, Wiesbaden, 252 pp.

[8] Pauline Horng, M.K., 2020. Wasserstoff - Farbenlehre: Rechtwissenschaftliche und rechtspolitische Kurzstudie. Institut für Klimaschutz, Energie und Mobilität IKEM. https://www.ikem.de/wp-content/uploads/2021/03/IKEM_Kurzstudie_Wasserstoff_Farbenlehre.pdf. Accessed 28 February 2023.

[9] Bundesministerium für Wirtschaft und Klimaschutz, BMWK, 2023. Wasserstoff: Schlüsselelement für die Energiewende. BMWI. https://www.bmwk.de/Redaktion/DE/Dossier/wasserstoff.html. Accessed 8 May 2023.

[10] Emde, A., 2023. Techno-ökonomische Bewertung von energieträgerübergreifenden hybriden Energiespeichern.

[11] Statista, 2020. Wasserstoff: Produktion und Verwendung weltweit 2019. Statista. https://de.statista.com/statistik/daten/studie/1195241/umfrage/produktion-und-verwendung-von-wasserstoff-weltweit/. Accessed 2 June 2023.

[12] 2G Energy, 2023. Effizienz in Reinkultur: Für maximalen Ertrag durch zuverlässige Höchstleistung – der agenitor von 2G. https://2-g.com/de/produkte/agenitor. Accessed 30 June 2023.

[13] Atwany, H., Al-Abdullah, A., Orhan, M.F., 2022. Performance analysis of a molten carbonate fuel cell. Journal Energy Systems (13).

[14] Doosan Fuel Cell Co, 2023. PureCell® Model 400 Hydrogen: Technology & Products. https://www.doosanfuelcell.com/en/prod/prod-0102/. Accessed 30 June 2023.

[15] Fuji Electric Global, 2023. Fuel Cells: Specifications. https://www.fujielectric.com/products/fuelcell/spec.html. Accessed 30 June 2023.

[16] Innio Jenbacher GmbH, 2023. Technische Daten des Wasserstoffmotors. https://www.jenbacher.com/de/energieloesungen/energietraeger/wasserstoff/technische-details. Accessed 30 June 2023.

[17] Panasonic Corporation, 2021. Panasonic Launches 5 kW Type Pure Hydrogen Fuel Cell Generator. Press Release. https://news.panasonic.com/global/press/en211001-4. Accessed 30 June 2023.

[18] Toshiba Energy Systems & Solutions, 2023. Use Hydrogen: Products and technical services. https://www.global.toshiba/ww/products-solutions/hydrogen/products-technical-services/fuel-cell.html. Accessed 30 June 2023.

[19] Bloom Energy, 2022. Hydrogen Fuel Cell. https://www.bloomenergy.com/wp-content/uploads/hydrogen-data-sheet.pdf. Accessed 30 June 2023.

[20] Energy Gov, 2023. Comparison of Fuel Cell Technologies. https://www.energy.gov/eere/fuelcells/comparison-fuel-cell-technologies. Accessed 30 June 2023.

[21] M. Hasegawa, Y.H., 2023. Development of the FP-100i Phosphoric Acid Fuel Cell. Fuji Electric Review. https://felib.fujielectric.co.jp/docfetch2/CustomContentBrowse.aspx?dataid=68603492&version=0&site=america&lang=en. Accessed 30 June 2023.

[22] NOW GmbH, 2014. Integration von Wind-Wasserstoff-Systemen in das Energiesystem: Abschlussbericht, 250 pp. https://www.planet-energie.de/de/media/Abschlussbericht_Integration_von_Wind_Wasserstoff_Systemen_in_das_Energiesystem.pdf. Accessed 30 June 2023.

[23] ASUE Arbeitsgemeinschaft für sparsamen und umweltfreundlichen Energieverbrauch, 2010. BHKW-Grundlagen. https://asue.de/sites/default/files/asue/themen/blockheizkraftwerke/2010/broschueren/06_06_10_bhkw-grundlagen-2010.pdf. Accessed 30 June 2023.

[24] Kurzweil, P., 2016. Brennstoffzellentechnik: Grundlagen, Materialien, Anwendungen, Gaserzeugung, 3., überarbeitete und aktualisierte Auflage ed. Springer Vieweg, Wiesbaden, 260 pp.

[25] BMWK - Bundesministerium für Wirtschaft und Klimaschutz, 2022. Gesamtausgabe der Energiedaten - Datensammlung des BMWK: Zahlen und Fakten: Energiedaten. BMWI. https://www.bmwk.de/Redaktion/DE/Artikel/Energie/energiedaten-gesamtausgabe.html. Accessed 1 June 2023.

[26] Universität Kassel, 2011. Das Potential solarer Prozesswärme in Deutschland. https://www.uni-kassel.de/maschinenbau/institute/thermische-energietechnik/fachgebiete/solar-und-anlagentechnik/downloads. Accessed 1 June 2023.

[27] PINTER GUSS GmbH, 2023. H2-NextMelt - PINTER GUSS: Qualifizierung von Wasserstoff-Technologien zum Schmelzen von Aluminium. https://www.pinterguss.de/forschung-entwicklung/h2-nextmelt.html. Accessed 1 June 2023.

[28] Juangsa, F.B., Cezeliano, A.S., Darmanto, P.S., Aziz, M., 2022. Thermodynamic analysis of hydrogen utilization as alternative fuel in cement production. South African Journal of Chemical Engineering 42, 23–31.

[29] thyssenkrupp Steel, 2023. Wasserstoffeinsatz im Hochofen: thyssenkrupp Steel schließt erste Versuchsphase erfolgreich ab. Press Release. https://www.thyssenkrupp-steel.com/de/newsroom/pressemitteilungen/thyssenkrupp-steel-schliesst-erste-versuchsphase-erfolgreich-ab.html. Accessed 2 June 2023.

[30] SALCOS®, 2023. µDRAL: Hydrogen Direct Reduction. Salzgitter AG. https://salcos.salzgitter-ag.com/de/mydral.html. Accessed 2 June 2023.

[31] Stiller, C., 2014. Nutzung von konventionellem und grünem Wasserstoff in der chemischen Industrie, in: Töpler, J., Lehmann, J. (Eds.), Wasserstoff und Brennstoffzelle: Technologien und Marktperspektiven. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 175–188.

[32] Fraunhofer-Institut für Umwelt-, Sicherheits- und Energietechnik UMSICHT, 2020. Verbundprojekt Carbon2Chem®. Fraunhofer UMSICHT. https://www.umsicht.fraunhofer.de/de/forschungslinien/kohlenstoffkreislauf.html. Accessed 2 June 2023.

[33] Europäische Kommission, 2020. Eine Wasserstoffstrategie für ein klimaneutrales Europa. https://eur-lex.europa.eu/legal-content/DE/TXT/PDF/?uri=CELEX:52020DC0301. Accessed 2 June 2023.

[34] Bundesministerium für Wirtschaft und Energie (BMWi), 2020. Nationale Wasserstoffstrategie. https://www.bmbf.de/bmbf/shareddocs/downloads/files/die-nationale-wasserstoffstrategie.pdf?__blob=publicationFile&v=2. Accessed 5 June 2023.

[35] Bundesministerium für Wirtschaft und Klimaschutz (BMWK), 2023. Fortschreibung der Nationalen Wasserstoffstrategie (Berlin).

[36] Steffen Joest, Maximilian Fichtner, Martin Wietschel, 2009. Studie zur Frage: Woher kommt der Wasserstoff in Deutschland bis 2050: m Auftrag des Bundesministeriums für Verkehr, Bau und Stadtentwicklung (BMVBS) und in Abstimmung mit der Nationalen Organisation Wasserstoff- und Brennstoffzellentechnologie (NOW)., Berlin, 62 pp. https://epub.wupperinst.org/frontdoor/deliver/index/docId/5183/file/5183_GermanHy.pdf. Accessed 28 February 2023.

[37] Statista, 2022. CO2-Emissionen in Deutschland. https://de.statista.com/statistik/studie/id/6920/dokument/co2-emissionen-in-deutschland/. Accessed 5 June 2023.

[38] Umweltbundesamt, 2023. Nationalen Emissionshandel verstehen. https://www.dehst.de/DE/Nationaler-Emissionshandel/nEHS-verstehen/nehs-verstehen_node.html. Accessed 5 June 2023.

[39] Fraunhofer-Institut für System- und Innovationsforschung ISI, Karlsruhe, Fraunhofer-Institut für Solare Energiesysteme ISE, Freiburg, 2019. Eine Wasserstoff-Roadmap für Deutschland. Fraunhofer. https://www.martin-stuempfig.de/fileadmin/assets/Redaktion/PDFS/Downloads/Energie/Wasserstoff/19-10_Fraunhofer_Wasserstoff-Roadmap_fuer_Deutschland.pdf. Accessed 28 February 2023.

[40] Deutscher Bundestag, 3. April, 2020. Wasserstoff: Produktionskosten nach Typ bis 2050. https://de.statista.com/statistik/daten/studie/1195863/umfrage/produktionskosten-von-wasserstoff-nach-wasserstofftyp-in-deutschland/. Accessed 7 June 2023.

[41] Staiger, R., Tanţău, A.D., 2020. Geschäftsmodellkonzepte mit grünem Wasserstoff: Wirtschaftliche und ökologische Auswirkungen für H2 als nachhaltiger Energieträger. Springer Gabler, Wiesbaden, 323 pp.

[42] Schwarz, M., 06.2023. Entsalzung überflüssig: Forscher gewinnen Wasserstoff aus Meerwasser - H2-news.eu.

[43] Forschung Kompakt, 2022. Grüner Wasserstoff aus Pflanzenresten. Press Release. Fraunhofer-Gesellschaft. https://www.fraunhofer.de/de/presse/presseinformationen/2022/juli-2022/gruener-wasserstoff-aus-pflanzenresten.html. Accessed 7 June 2023.

[44] Hydrogen Council, 2022. Sufficiency, sustainability, and circularity of critical materials for clean hydrogen. https://hydrogencouncil.com/wp-content/uploads/2022/12/WB-Hydrogen-Report-2022.pdf. Accessed 5 July 2023.

[45] DVGW Deutscher Verein des Gas- und Wasserfaches e. V., 2021. Erstmals 20 Prozent Wasserstoff im deutschen Gasnetz: Innovationsprojekt von E.ON, Avacon und DVGW startet mit Wasserstoffbeimischungen.

[46] Fraunhofer Institute for Energy Economics and Energy System Technology, 2022. Limitations of hydrogen blending in the European gas grid: A study on the use, limitations and cost of hydrogen blending in the European gas grid at the transport and distribution level. https://www.iee.fraunhofer.de/content/dam/iee/energiesystemtechnik/en/documents/Studies-Reports/FINAL_FraunhoferIEE_ShortStudy_H2_Blending_EU_ECF_Jan22.pdf. Accessed 5 July 2023.

[47] Kevin Topolski, Evan P. Reznicek, Burcin Cakir Erdener, Chris W. San Marchi, Joseph A. Ronevich, Lisa Fring, Kevin Simmons, Omar Jose Guerra Fernandez, Bri-Mathias Hodge, and Mark Chung, 2023. Hydrogen Blending into Natural Gas Pipeline Infrastructure: Review of the State of Technology.

[48] Universität Stuttgart, 2022. Energieeffizienz-Index Sommer 2022. Institut für Energieeffizienz in der Produktion EEP, 2 pp. https://www.eep.uni-stuttgart.de/dokumente/EEI-Sommer-2022/PM_Energieeffizienz-Index_Sommer_2022_final.pdf. Accessed 19 July 2023.

[49] 2G Energy Inc, 2021. Hydrogen CHP: The future has begun, 4 pp. https://2-g.com/downloads/de/Pressespiegel/alt/hydrogen.pdf. Accessed 19 July 2023.

[50] Universität Stuttgart, 2021. WAVE-H2 – Wasserstoff für mehr Industrieanwendungen: Über 30 Millionen Euro für eine neue Forschungsplattform an der Universität Stuttgart. Universität Stuttgart. https://www.uni-stuttgart.de/universitaet/aktuelles/meldungen/WAVE-H2--Wasserstoff-fuer-mehr-Industrieanwendungen/. Accessed 7 June 2023.

Biography

Laura Jung, M. Sc.,(*1993) is a researcher at the Institute for Energy Efficiency in Production at the University of Stuttgart and the Fraunhofer Institute Institute for Manufacturing Engineering and Automation IPA. Her focus is the research of energy concepts based on renewable energy.

Verena Lampret, M. Sc.,(*1995) is a researcher at the Institute for Energy Efficiency in Production at the University of Stuttgart and the Fraunhofer Institute for Manufacturing Engineering and Automation IPA. Her focus is the research of hydrogen-powered CHP units.

Prof. Dr.-Ing. Dipl.-Kfm. Alexander Sauer (*1976) is 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.

CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
CPSL 2023-2

5th Conference on Production Systems and Logistics

Hype Cycle Assessment Of Emerging Technologies For Battery Production

Achim Kampker[1], Heiner Heimes[1], Benjamin Dorn[1], Daniel Neb[1],
Henning Clever[1], Jennifer Machura[1]
[1]*Chair for Production Engineering of E-Mobility Components, RWTH Aachen University, Aachen, Germany*

Abstract

The demand for battery-powered electric vehicles is growing rapidly as more and more OEMs are shifting their strategy towards an all-electric vehicle fleet. The lithium-ion battery cell is considered as the core component in terms of performance, range and price of electric vehicles. Since the development of the functional principle of the lithium-ion battery, both the product and the associated production technology have evolved significantly. OEMs, start-ups, equipment suppliers and other players in the automotive industry are investing heavily in research and development of various technologies to improve both the battery as a product and its production. An essential aspect is to enable sustainable battery production. While breakthroughs in battery technology are regularly announced, the actual merits of the technologies and the potential remain uncertain until commercial deployment. The aim of this paper is to systematically identify upcoming breakthroughs and announced innovations to provide an overview of promising battery technologies that companies should focus on to enable the planning of resilient and sustainable production systems. Hence, a hype cycle assessment following Gartner was adopted as the underlying approach to evaluate battery technologies for deployment in electromobility and mass production. First, various technologies, innovations, research activities and announcements in the field of battery technologies were screened, recorded and classified in order to obtain an overview of the current state of developments on both product and production levels. This includes an overview of innovations in battery design and configuration as well as process technologies and production systems. Subsequently, these technologies are evaluated according to predefined evaluation criteria in order to enable a systematic classification of the individual technologies in the hype cycle. The result is a consolidated overview of emerging battery technologies for sustainable battery production and a display for further recommendations for relevant companies and stakeholders.

Keywords

Hype Cycle; Technology Assessment; Lithium-Ion Battery; Battery Production

1. Introduction

In order to become independent of fossil fuels and minimize greenhouse gas emissions, a change in mobility is essential. A major step in this sector is electrification, thus increasing the importance of batteries as one of the key drivers. [1,2] Because of their excellent properties for use as a rechargeable energy storage system, lithium-ion batteries (LIBs) have established themselves in various applications from consumer electronics up to stationary storage systems. Especially in the automotive industry, batteries gained significant importance as a key technology for electric vehicles (EV). Due to the current pace of automotive

DOI: https://doi.org/10.15488/15290
ISSN: 2701-6277

electrification, the global demand for lithium-ion batteries is projected to surpass over 3,970 GWh in 2030. [3]

Lithium-ion batteries have become the focus of research in recent years. New battery concepts and material combinations are being researched and developed to meet current demands and to drive further developments. Also, the production of battery cells requires improvement through innovation. Recent studies shown that the production of 1 Wh of storage capacity requires a cumulative energy demand of 328 Wh [4]. Since the battery cell production is very energy and time consuming, resulting in high manufacturing costs, innovative approaches towards a greener cell production must be advanced. [5,6].

Breakthroughs for product and process innovations in the field of battery technology are regularly presented in scientific journals and announced by companies. However, the progress and significance of these research activities and developments of various innovations cannot always be concluded from the quantity of announcements. Therefore, new technologies and innovations need to be systematically identified and assessed from the multitude of announcements. Hence, an approach for the evaluation of technologies needs to be explored to provide an aggregate and generalized overview of emerging battery technologies and to derive a long-term strategy regarding future activities and developments for various stakeholders. In this paper, a variety of product and process innovations in battery technology were identified, analysed according to the hype cycle and classified in a priority matrix. Subsequently, an aggregated overview of emerging battery technologies was created to enable a long-term orientation.

2. Fundamentals on lithium-ion technology

Current advancements and technological trends are based on the ongoing market drivers and requirements for the lithium-ion battery. Some of the key market drivers and requirements are energy density, power density, safety, life cycle behaviour, product quality, life-time, product safety, cost and expenditure, and sustainability. However, it is not yet possible to maximize all these properties with a single cell chemistry or design. Therefore, during system development, the appropriate cells and their properties must be carefully selected and designed depending on the application. [7,8]

The energy density is decisive for EVs, as it determines the range to a large extent. [9] A high power density enables fast charging capabilities of the battery or fast acceleration of an EV. [10] The lifetime is determined by the electrochemical processes within a cell that lead to the decrease of cell capacity and performance. Regardless of the battery, a distinction is made between two forms: calendrical and cyclical life. [11] For EVs, battery cells are generally required to have a service life of more than 10 years [7]. Safety-critical situations can arise when external influences such as high temperatures or mechanical impacts occur [7]. In particular, the cost factor is constantly improved to reduce the costs of battery systems, as it is responsible for up to 33 % of the total cost of an EV. [12] Lithium-ion batteries have emerged as a key technology and currently strongly dominate the market as they meet and satisfy most requirements and market drivers for EVs to a high degree.

2.1 Basic structure and cell formats of LIBs

A LIB in its basic form is composed of the following main components: two electrodes (anode and cathode), a separator and the liquid electrolyte. The anode typically consists of a copper foil coated with graphite. The cathode typically is composed of aluminium foil coated with a lithium-containing compound as an active material. The separator is a porous membrane, that electrically isolates the two electrodes, yet allows ions to pass through. The electrolyte consists of an ionic conducting salt and serves as a transport medium for the ions between the two electrodes. [13] The term lithium-ion battery covers various chemistries and material combinations [14]. While carbon composites such as graphite are usually used as the active material for the anode, different cathode lithium-containing materials can be seen. [15,16]

There are currently three battery cell formats used for mass application in EVs: Pouch, cylindrical and prismatic cells [17]. The various battery cell formats use the same general structure as described previously. They mainly differ in the design and manufacture of the inner cell composite and thus in the outer shape. Depending on the application, different battery cell formats can be beneficial. In general, the production and application experience are most profound with cylindrical cells, as they have been commercially used in many consumer applications since 1991. Higher energy and packing densities can be achieved with pouch cells. However, they are more susceptible to deformation as they only consist of a thin pouch foil as a cell casing. The prismatic cell combines properties of both cell types and offers high packing densities on module level with higher bending stiffness. [18] For use in EVs, the single battery cells are assembled to a module. The module consists of the cell stack, a wiring harness, the module housing and the bracing. Afterwards, the modules are integrated into a battery system, that typically consists of several modules, the electrical and thermal management system as well as the casing and external interfaces. [7,19]

2.2 Production process for LIB manufacturing

The production of battery cells can be divided into three main segments starting with the electrode manufacturing, followed by cell assembly and lastly cell finishing. Figure 1 shows a schematic overview of the production processes of the three battery cell formats: pouch, cylindric and prismatic cells.

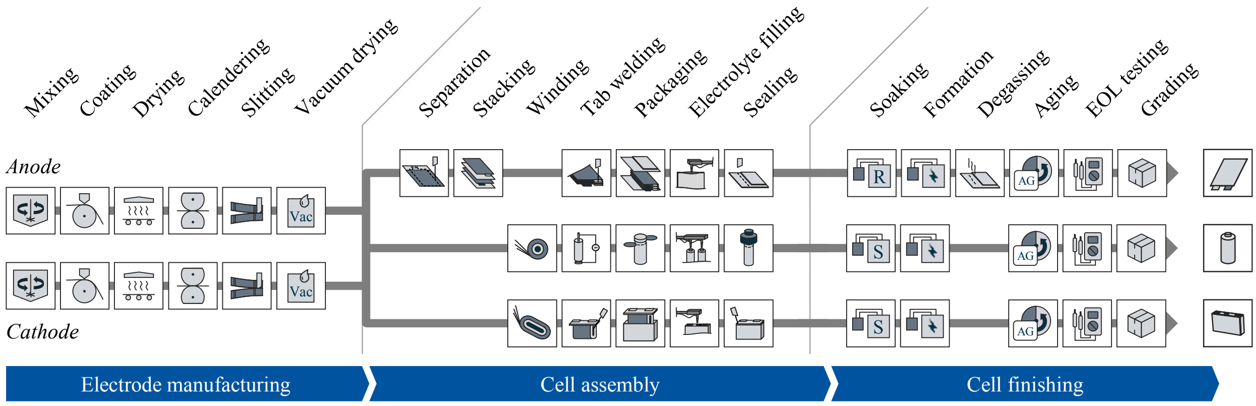


Figure 1: Overview of the general process chains for manufacturing of different lithium-ion battery cell formats

In electrode manufacturing, material-specific anodes and cathodes are produced using two separate lines. First, the active materials are mixed into a slurry. Afterwards the slurry is coated onto a thin metal foil and dried. After two roll-to-roll processes, calendaring and slitting, the finished electrode is vacuum dried and transported to the next production section. In cell assembly, the used process technology and sequence are strongly influenced by the cell format. First, alternating layers of anode, separator and cathode are assembled to form the inner electrode-separator composite (jelly-roll or stack). After the packaging and electrolyte filling, the cell housing is sealed und the cell is fully assembled. In cell finishing, the battery cell is charged for the first time to establish the final electrochemical properties of the cell. Starting with soaking of the electrolyte, the formation is done by controlled charging and discharging cycles. During this process, gases can occur which must be evacuated. After a monitored storage (aging), the end-of-line (EOL) testing is conducted and the cells get graded according to their quality. The process flow in cell finishing is almost identical for the cell formats, but the equipment may differ in its technical realization. [19,20]

2.3 Innovation and emerging battery technologies

Innovations are an essential factor for long-term success and capability to compete globally. Innovations can be described as "the development and implementation of an innovative idea that generates tangible added value" [21]. In this context, the pursuit of technological progress and the object of innovation can have very different characteristics, ranging from products and production processes to services and organizations. Next to focused advancement of certain technologies, entire industries can be influenced by overall market trends such as ‘Internet of Things’ or the discovery of new material applications. [21]

In this paper, the focus is on product and process innovations in battery technology. When referring to advancements, innovations and emerging technologies in this paper, the established state of the art of LIB and the previously described prevalent process chain and technologies for battery cell production form the basis.

Product innovations generally describe new or improved products by technically enhancing an existing product, adding a new product feature to the existing portfolio or creating a completely novel product line. Typically, product innovations follow an external perspective by focusing on the customer or the application of the product, whereas process innovations often pursue an internal perspective by focusing on the processes and operations. Process innovations result from novel combinations of manufacturing techniques and aim at more efficient, reliable and economical as well as high-quality and green production by implementing certain improvements (e.g. tools, controls, sensors). [21,22,23] Product and process innovations are often linked, as new processes are needed to produce innovative products or new product opportunities are created through innovative processes. The introduction of different types of innovations can lead to different competitive advantages. [21,22]

Breakthroughs in a variety of different battery technologies are announced regularly. Numerous battery chemistries and designs have been researched and demonstrated in laboratory or prototype applications. Major advances in cell chemistry and material composition for battery applications typically aim to increase key properties such as energy and power density. But various innovations and technologies are also emerging in the context of production. There are many critical process steps along the entire process chain that are decisive for the quality of the battery cell. Also, since the production of battery cells is time and energy consuming, energy-efficient and accelerated processes are essential, among other aspects, to reduce battery costs and increase productivity.

3. Method and approach

The field of battery research has been explored intensively for years, and various technologies are advancing rapidly. In this dynamic environment, a frequent overview of upcoming technologies is essential for industry and research. Literature is filled with various battery roadmaps, reviews and assessments of current and future battery manufacturing [24,25,26,27]. Yet, these assessments are focused on single approaches regarding a certain technology or its implementation (e.g. dry coating) or they compare a few technologies regarding one specific topic (e.g. battery materials). There was no paper found that provides a holistic overview for strategic development of the multitude of battery technologies in the future.

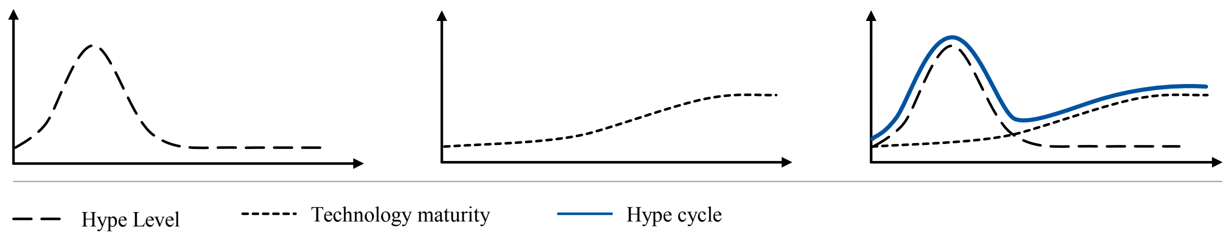


Figure 2: Hype cycle by combining hype level and technology maturity [28]

In 1995 Gartner Inc. introduced the Gartner Hype Cycle which is intended to be a graphical representation of the hype (expectation) of a technology over time. As similar patterns of hype and disillusionment can be applied to various concepts and technologies, an assessment approach based on Gartner's Hype Cycle was used in this paper to evaluate product and process battery technologies. The hype cycle is an accumulation of two effects: The hype level and the technology maturity (Figure 2). The graph reflects the nature of enthusiasm as the technology develops. Gartner has normalized the vertical scale as the expectations for each technology may vary based on its importance to industry and society. Thus, all individual hype curves fit into one hype cycle. The time is plotted on the horizontal axis and divided into five stages. Every technology will proceed through each stage, but each at its own pace. Some technologies might be in a particular phase for a short time, while others might persist for a longer period to reach mainstream adoption. [28,29]

3.1 Criteria for the hype cycle assessment

As Gartner's initial analysis of the hype cycle is mainly focused on information technologies, the assessment categories and their criteria had to be modified in order to adapt them for battery products and processes. The goal of the assessment is to identify the current hype of a technology and to evaluate the technological maturity, the time to market, and the overall potential. Therefore, the hype cycle assessment was conducted based on these four categories.

Hype level is based on the phases of the Gartner Hype Cycle and comprises five levels. As the interest in an innovation grows, so do the expectations until the pinnacle of expectation is reached. [30] The respective hype level of a technology is determined based on a consensus assessment of the maturity level and the frequency of reports and announcements.

Readiness level describes the maturity of a technology, a design or a process. The maturity was classified according to the readiness levels. The technology readiness level (TRL) was introduced by NASA to support the "tracking [of] technologies in development and their transition into production" [31]. The manufacturing readiness level (MRL) refers to development activities "when a (manufacturing) technology or process is matured and transitioned to a system" [31]. TRL and MRL share a similar numbering system by using a common metric and vocabulary for assessing readiness and technology risk described in detail in [31].

Potential describes the expected benefit of a technology. Each type of technology was evaluated and measured against defined reference points (e.g. product quality, cost reduction, energy consumption). In each case, the potential refers to a fully mature technology and not to the current development status. For the identified technologies, the current state of the art for LIB and cell production was used as a reference.

Time-to-market describes the duration until the technology will enter the market and will be commercially available. Since maturity is not related to market availability, it is also possible that a technology is on the market and at the same time is not yet fully mature. The final assessment regarding time to market were made based on various announcements, which have been reviewed and affirmed regarding their plausibility.

3.2 Approach for technology research and scouting

The scouting and evaluation of emerging innovations in the field of battery technology was conducted in four steps: initial scouting, information gathering, technology evaluation and final aggregation. This approach enabled to systematically translate the wide range of innovations, announcements and activities into a final selection of technologies. The goal was to identify various product and process technologies in the battery industry.

The technology research was conducted based on a scouting in various sources, including scientific journals and databases (IEEE Xplore, Web of Science, MDPI, Elsevier, etc.), as well as public presentations and proceedings of conferences (Future Battery Forum, The Battery Show, AABC, etc.). Additionally, news sites (battery-news.de, electrive.net, etc.) were reviewed, along with expert panels (e.g. the Battery Brunch), battery roadmaps (e.g. VDMA, Fraunhofer), as well as press articles and events like the Tesla Battery Day and Volkswagen Power Day. Patents were searched using search terms such as "battery," "lithium-ion battery," "battery cell production," and "battery production". This comprehensive approach ensured that emerging battery technologies were identified, enabling a systematic selection of promising technologies across a wide range of sources. The search was conducted between October 2021 and December 2022. An iterative screening process was used to determine whether the technology was state of the art or a novel approach.

After the preliminary scouting a total of 65 technologies have been listed. An initial assessment of the technology's utility was also conducted. Since some development activities are aimed at a similar or the same technology, a few innovations have been combined in this case (e.g. optimized NMC compositions such as NMC-955 or NMx), leaving a total of 54 technologies. During the technology evaluation, further research was conducted to obtain sufficient data for a valid assessment. Expert interviews were added to challenge or expand upon the available information for certain technologies, if needed. The technology research was concluded with a set of 39 technologies for both product and process innovation.

4. Results

The following section presents the results of the hype cycle assessment for battery technologies and derives a priority matrix based on potential benefits.

4.1 Hype cycle for emerging battery technologies

The battery hype cycle for emerging battery technologies is shown in Figure 3. The technologies are divided into product and process innovations. Due to the tremendous efforts in various research areas, the overview is a snapshot in time, in which certain innovations may progress faster than others.

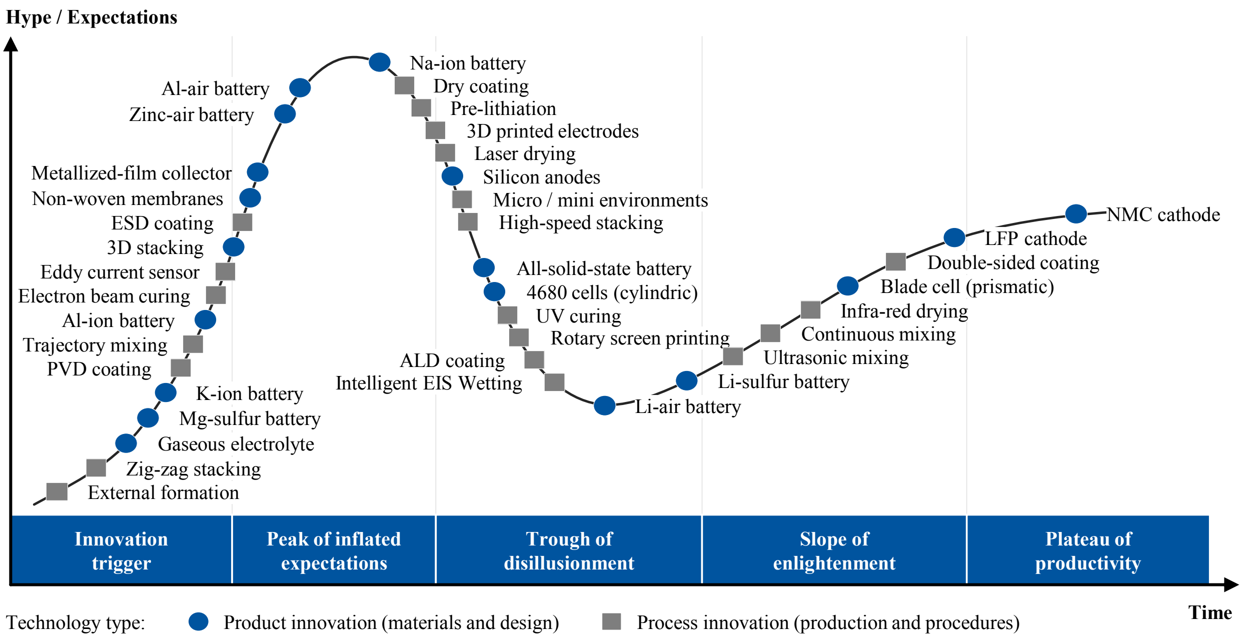


Figure 3: Battery hype cycle for emerging battery product and production process technologies (as of 2023)

Product innovation: A total of 17 technologies at battery product level have been considered. A majority of the emerging product technologies focus on innovations in material pairing and combinations for the battery cell active material. Lithium-based materials such as LFP but also lithium-sulphur or lithium-air batteries are beyond the hype and advancing in their development. Currently, sodium-ion, aluminium-air, zinc-air and aluminium-ion batteries are experiencing a major hype. However, high expectations are also being placed on novel material combinations such as potassium-ion or magnesium-sulphur batteries. Other product innovations focus on novel product designs such as large-format cells, e.g. prismatic blade cells or cylindric 4680 cells. On the other hand, individual key components of the battery cell are being further advanced, e.g. non-woven membranes or metallized plastic foil current conductors for increased intrinsic safety of the battery cell.

Process innovation: In total, 22 technologies have been considered in the context of production. Noticeably, many of the process innovations focus on advancing single aspects or steps of the current LIB manufacturing processes rather than overall production. One focus area is the reduction of energy costs, e.g. through improved drying technologies such as infra-red drying, UV curing, laser drying or controlling the process atmosphere in energy-efficient mini-environments. Besides, various coating processes are investigated which would render the drying process obsolete, e.g. ALD coating, ESD coating or 3D printed electrodes. Dry coating is receiving a particularly large amount of attention. In addition, some other process steps are optimized by innovations regarding their process quality and efficiency, such as continuous mixing, high-speed stacking or intelligent EIS wetting. Others focus on improving product quality, for example eddy current sensors for inline quality inspection of the active material slurry or pre-lithiation for increased cell capacity.

The selected technologies show the broad spectrum of current research activities. In this context, it is important to emphasize that the battery hype cycle does not claim to be exhaustive, but rather provides a representative overview of current developments and innovations and must be updated and aligned on a regular basis for further evaluation.

4.2 Priority matrix for strategic technology selection

The priority matrix contains additional information about the potential or benefits of an innovation or technology. It is a tool for presenting innovation opportunities and covers all the technologies presented in the hype cycle. Unlike the hype cycle, the priority matrix does not focus on the hype or attention a technology gets, but on its prospective benefits. However, its value is in providing decision support on which technologies a company should focus on or invest in. Therefore, the rating of the potential is sorted into four categories: transformative, high, moderate, and low. This is then combined with the expected time to market. In Figure 4, the derived priority matrix from the battery hype cycle is shown.

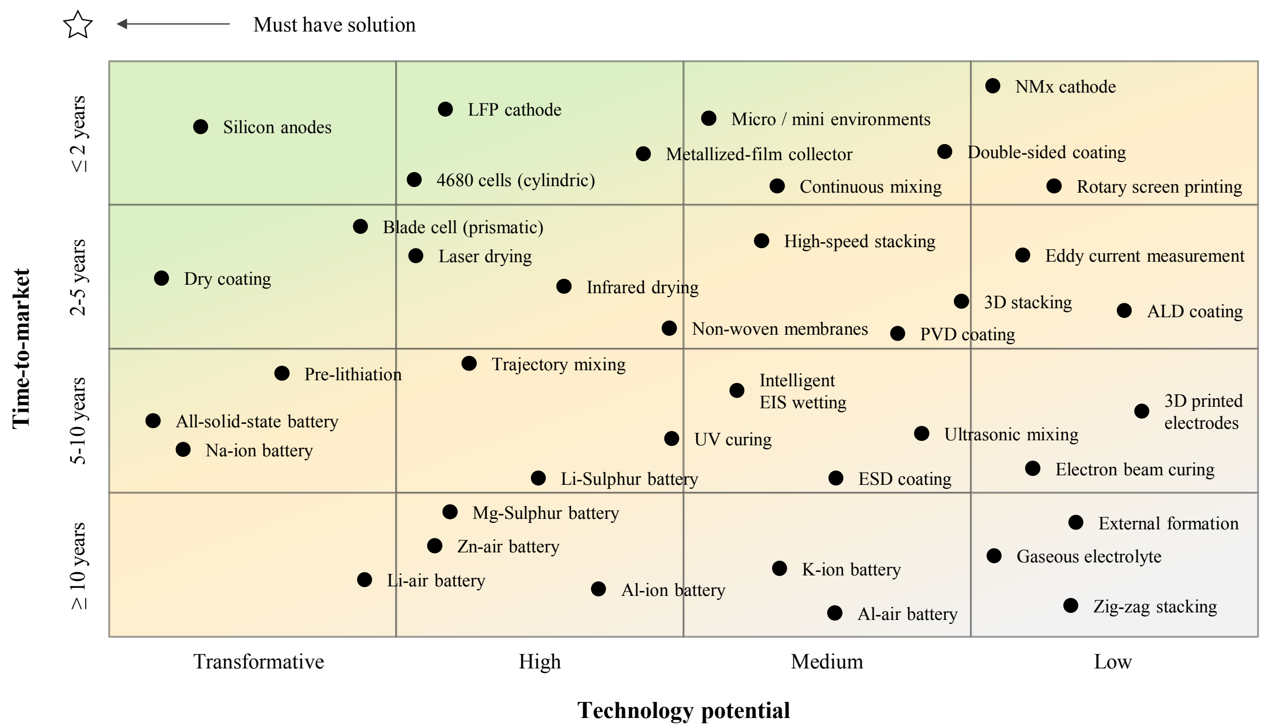


Figure 4: Priority matrix for emerging battery technologies

In the technology assessment, seven technologies were identified that are expected to fundamentally transform the current market for automotive battery technologies. On the product level, transformative innovations include silicon anodes, as they will increasingly displace graphite in particular as an active material for anodes from the market in the upcoming years. Apart from this, current trends already show that large-format cells are more and more prominent and especially blade cells (prismatic) are prone to enable the cell-to-pack approach. Furthermore, novel material compositions are becoming increasingly important, with sodium-ion (more abundant and less expensive) and all-solid-state (high energy density and more stable) batteries. However, their full market maturity is not expected for another 5 to 10 years. In the manufacturing context, dry coating and pre-lithiation are seen as transformative, as their market introduction may enable new processes and procedures for all battery material technologies, which will lead to major changes in the dynamics of battery production. [32] Other innovations expected to reach full market maturity, particularly in the next 2 years, include large-format 4680 cells (cylindrical), the widespread introduction of LFP cathodes to take NMC shares, and the introduction of mini-environments, continuous mixing and simultaneous double-sided coating. As for 4680 cells first announcements about mass production were made and terminated for a time within the next two years, also emphasizing silicon anodes as they are both a transformative and an upcoming technology [34,33].

The priority matrix shows that technologies located in the upper left corner are particularly relevant and directly seeking involvement in these technologies should be explored. The technologies which can be found in the lower right corner are recommended to be observed or invested in with caution as these technologies show a relatively low benefit on the battery industry and won't reach the plateau of productivity within the next 10 years.

4.3 Discussion

In comparison to other reviews dealing with the assessment of battery technologies, this paper addresses a holistic overview of innovations in the context of battery application in EVs and its manufacturing in mass production. This hype cycle can provide an initial basic strategic orientation for a broad number of stakeholders. For specific industries or companies, however, the hype cycle assessment should be focused to address specific areas. Pantoja et al. [26] for example compare different materials for alternative battery technologies and conclude with two material hype cycles for promising anode and cathode materials. The same approach and level of detail might be useful, for example, for a focus in the area of mechanical and plant engineering (e.g. application of laser technologies in battery production), and must therefore be specified depending on the industry and use-case of the hype cycle.

The sentiment of publications can generally not be measured but it plays a significant role in the positioning of a technology. Especially publication with a negative sentiment can cause a decrease in the hype and a tendency for the technology to enter the trough of disillusionment. Thus, the publication number is no longer sufficient to give an accurate picture. Since the assessment is based on public literature and announcements, a dark figure of missing information has to be considered. This include unrestricted and global access to intellectual property and research results, as well as the industrial research and development activities of individual companies that keep their results under lock and key until final application.

5. Conclusion

In this paper, emerging technologies for battery production have been evaluated using a hype cycle assessment regarding the expectations and maturity of various technologies. The assessment provides an overview of where a technology is in its development lifecycle and helps identifying promising technologies. Yet, a hype cycle is only representing a snapshot at a particular point in time. The hype cycle derived in this paper includes a total of 39 product and process technologies. The priority matrix shows, the classification of technologies according to their respective benefits and time-to-market. Nonetheless, the assessment shows to be useful for identifying potential opportunities and challenges related to the adoption of new technologies in the battery manufacturing industry and helps companies make informed decisions about which technologies to invest in and how to position themselves in the market. Further research is necessary to identify and setup a systematic approach on how to face individual technical challenges for the strategically selected emerging technologies that must be overcome and how they can be commercialized.

Acknowledgements

This work is part of the project “FoFeBat2” and has received funding from the German Federal Ministry of Education and Research (BMBF) under the funding code 03XP0323A. The authors are responsible for the content of this publication. Corresponding authors are Henning Clever and Jennifer Machura.

Appendix

Table 1 shows the assessment of the selected emerging battery technologies based on the defined assessment criteria. Please note that this overview indicates the status as of mid-2023. New findings due to vast market dynamics and current technology developments require a regular review and update of this list.

Table 1: Assessment of emerging battery technologies

#	Battery technology	Hype cycle	Readiness	Potential	Time-to-m.
1	4680 cells (cylindric)	Trough of disillusion	TRL 7-8	High	≤ 2 years
2	3D printed electrodes	Trough of disillusion	TRL 5-6	Low	5-10 years
3	3D stacking	Innovation trigger	TRL 3-4	Medium	2-5 years
4	All-solid-state batteries	Trough of disillusion	TRL 5-6	Transform.	5-10 years
5	ALD coating	Trough of disillusion	TRL 3-4	Low	2-5 years
6	Al-air battery	Peak of expectations	TRL 3-4	Medium	≥ 10 years
7	Al-ion battery	Innovation trigger	TRL 5-6	High	≥ 10 years
8	Blade cell (prismatic)	Slope of enlightenment	TRL 9	Transform.	2-5 years
9	Continuous mixing	Slope of enlightenment	TRL 7-8	Medium	≤ 2 years
10	Double-sided coating (simult.)	Slope of enlightenment	TRL 9	Medium	≤ 2 years
11	Dry coating	Peak of expectations	TRL 5-6	Transform.	2-5 years
12	Eddy current measurement	Innovation trigger	TRL 3-4	Low	2-5 years
13	Electron beam curing	Innovation trigger	TRL 5-6	Low	5-10 years
14	ESD coating	Peak of expectations	TRL 3-4	Medium	5-10 years
15	External formation	Innovation trigger	TRL 1-2	Low	≥ 10 years
16	Gaseous electrolyte	Innovation trigger	TRL 3-4	Low	≥ 10 years
17	High-speed stacking	Trough of disillusion	TRL 3-4	Medium	2-5 years
18	Infrared drying	Slope of enlightenment	TRL 9	High	2-5 years
19	Intelligent EIS wetting	Trough of disillusion	TRL 3-4	Medium	5-10 years
20	K-ion battery	Innovation trigger	TRL 3-4	Medium	≥ 10 years
21	Laser drying	Peak of expectations	TRL 3-4	High	2-5 years
22	LFP cathode (Li-ion)	Slope of enlightenment	TRL 9	High	≤ 2 years
23	Li-air battery	Trough of disillusion	TRL 3-4	Transform.	≥ 10 years
24	Li-sulphur battery	Trough of disillusion	TRL 3-4	High	5-10 years
25	Metallized-film collector	Peak of expectations	TRL 7-8	High	≤ 2 years
26	Mg-sulphur battery	Innovation trigger	TRL 3-4	High	≥ 10 years
27	Mini-environments	Trough of disillusion	TRL 7-8	Medium	≤ 2 years
28	Na-ion battery	Peak of expectations	TRL 7-8	Transform.	5-10 years
29	NMC cathode (Li-ion)	Plateau of productivity	TRL 9	Low	≤ 2 years
30	Non-woven membranes	Peak of expectations	TRL 5-6	High	2-5 years
31	Pre-lithiation	Peak of expectations	TRL 7-8	Transform.	5-10 years
32	PVD coating	Innovation trigger	TRL 3-4	Medium	2-5 years
33	Rotary screen printing	Trough of disillusion	TRL 9	Low	≤ 2 years
34	Silicon anodes	Trough of disillusion	TRL 9	Transform.	≤ 2 years
35	Trajectory mixing	Innovation trigger	TRL 5-6	High	5-10 years
36	Ultrasonic mixing	Slope of enlightenment	TRL 3-4	Medium	5-10 years

37	UV curing	Trough of disillusion	TRL 7-8	High	5-10 years
38	Zig-zag stacking	Innovation trigger	TRL 3-4	Low	≥ 10 years
39	Zn-air battery	Peak of expectations	TRL 5-6	High	≥ 10 years

References

[1] Lazkano, I., Nøstbakken, L., Pelli, M., 2017. From fossil fuels to renewables: The role of electricity storage. European Economic Review 99 (1), 113–129.

[2] Yong, J.Y., Ramachandaramurthy, V.K., Tan, K.M., Mithulananthan, N., 2015. A review on the state-of-the-art technologies of electric vehicle, its impacts and prospects. Renewable and Sustainable Energy Reviews 49 (4), 365–385.

[3] Bernhart, W., 2022. Battery Monitor 2022: Technology And Sustainability In The Battery Market. https://www.rolandberger.com/en/I-nsights/Publications/Battery-Monitor-2022-Technology-and-sustainabili-ty-in-the-battery-market.html. Accessed 19 December 2022.

[4] Peters, J.F., Baumann, M., Zimmermann, B., Braun, J., Weil, M., 2017. The environmental impact of Li-Ion batteries and the role of key parameters – A review. Renewable and Sustainable Energy Reviews 67 (7490), 491–506.

[5] Bockey, G., Kampker, A., Dorn, B., Offermanns, C., Wennemar, S., Clever, H., Sasse, K., Vienenkötter, J., Locke, M., Soldan, N., Kisseler, N., Cacciotti, P., 2022. Battery Atlas 2022: Shaping the European Lithium-Ion Battery Industry, 1. Auflage ed. PEM der RWTH Aachen University, Aachen, 20 pp.

[6] Michaelis, S., 2016. Roadmap Batterie-Produktionsmittel 2030, Update 2016 ed. VDMA Batterieproduktion, Frankfurt am Main, 76 Seiten.

[7] Heimes, H.H., Kampker, A., Haunreiter, A., Davids, H., Klohs, D., 2020. Product-requirement-model to approach the identification of uncertainties in battery systems development. Int J Interact Des Manuf 14 (3), 911–922.

[8] Thielmann, A., Isenmann, R., Wietschel, M., 2010. Technologie-Roadmap Lithium-Ionen-Batterien 2030, 1. Aufl., Stand: Juni 2010 ed. Fraunhofer ISI, Karlsruhe, 22 S.

[9] Schmaltz, T., Wicke, T., Weymann, L., Voß, P., Neef, C., Thielmann, A., 2022. Solid-State Battery Roadmap 2035+.

[10] Dorrmann, L., Sann-Ferro, K., Heininger, P., Mähliß, J.D., 2021. Compendium: Li-ion batteries: Principles, characteristics, laws and standards. VDE Verband der Elektrotechnik Elektronik Informations-technik e. V, Frankfurt am Main, 30 pp.

[11] Vetter, J., Novák, P., Wagner, M.R., Veit, C., Möller, K.-C., Besenhard, J.O., Winter, M., Wohlfahrt-Mehrens, M., Vogler, C., Hammouche, A., 2005. Ageing mechanisms in lithium-ion batteries. Journal of Power Sources 147 (1-2), 269–281.

[12] 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.

[13] Vuorilehto, K., 2013. Materialien und Funktion, in: Korthauer, R. (Ed.), Handbuch Lithium-Ionen-Batterien, vol. 414. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 21–29.

[14] Leuthner, S., 2013. Übersicht zu Lithium-Ionen-Batterien, in: Korthauer, R. (Ed.), Handbuch Lithium-Ionen-Batterien. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 13–19.

[15] Ding, Y., Cano, Z.P., Yu, A., Lu, J., Chen, Z., 2019. Automotive Li-Ion Batteries: Current Status and Future Perspectives. Electrochem. Energ. Rev. 2 (1), 1–28.

[16] Miao, Y., Hynan, P., Jouanne, A. von, Yokochi, A., 2019. Current Li-Ion Battery Technologies in Electric Vehicles and Opportunities for Advancements. Energies 12 (6), 1074.

[17] Tschöke, H., 2015. Die Elektrifizierung des Antriebsstrangs. Springer Fachmedien Wiesbaden, Wiesbaden.

[18] Röth, T., Kampker, A., Reisgen, U., Hameyer, K., Doncker, R.W. de, Stolze, T., Vetter, A., Hagedorn, J., Sauer, D.U., Müller, D., 2013. Entwicklung von elektrofahrzeugspezifischen Systemen, in: Kampker, A., Vallée, D., Schnettler, A. (Eds.), Elektromobilität, vol. 13. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 235–334.

[19] Pettinger, K.-H., Kampker, A., Hohenthanner, C.-R., Deutskens, C., Heimes, H., Vom Hemdt, A., 2018. Lithium-ion cell and battery production processes, in: Korthauer, R. (Ed.), Lithium-Ion Batteries: Basics and Applications, vol. 196. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 211–226.

[20] 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.

[21] Jäcklin, B., 2021. Führung und Innovation. Springer Fachmedien Wiesbaden, Wiesbaden.

[22] Dietrich, J.R., Meitinger, T.H., 2021. Innovationsmanagement, in: Dietrich, J.R., Meitinger, T.H. (Eds.), Erfinderhandbuch. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 27–35.

[23] Schawel, C., Billing, F., 2018. Innovationsmanagement, in: Schawel, C., Billing, F. (Eds.), Top 100 Management Tools. Springer Fachmedien Wiesbaden, Wiesbaden, pp. 161–162.

[24] Degen, F., Kratzig, O., 2022. Future in Battery Production: An Extensive Benchmarking of Novel Production Technologies as Guidance for Decision Making in Engineering. IEEE Trans. Eng. Manage., 1–19.

[25] Liu, Y., Zhang, R., Wang, J., Wang, Y., 2021. Current and future lithium-ion battery manufacturing. iScience 24 (4), 102332.

[26] Ma, J., Li, Y., Grundish, N.S., Goodenough, J.B., Chen, Y., Guo, L., Peng, Z., Qi, X., Yang, F., Qie, L., Wang, C.-A., Huang, B., Huang, Z., Chen, L., Su, D., Wang, G., Peng, X., Chen, Z., Yang, J., He, S., Zhang, X., Yu, H., Fu, C., Jiang, M., Deng, W., Sun, C.-F., Pan, Q., Tang, Y., Li, X., Ji, X., Wan, F., Niu, Z., Lian, F., Wang, C., Wallace, G.G., Fan, M., Meng, Q., Xin, S., Guo, Y.-G., Wan, L.-J., 2021. The 2021 battery technology roadmap. J. Phys. D: Appl. Phys. 54 (18), 183001.

[27] Pantoja, W., Perez-Taborda, J.A., Avila, A., 2022. Tug-of-War in the Selection of Materials for Battery Technologies. Batteries 8 (9), 105.

[28] Blosch, M., Fenn, J., 2018. Understanding Gartner's Hype Cycles. https://www.gartner.com/en/documents/3887-767

[29] Strawn, G., 2021. Open Science and the Hype Cycle. Data Intelligence 3 (1), 88–94.

[30] Dedehayir, O., Steinert, M., 2016. The hype cycle model: A review and future directions. Technological Forecasting and Social Change 108 (5), 28–41.

[31] OSD Manufacturing Technology Program, 2018. Manufacturing Readiness Level (MRL) Deskbook: Version 2018. http://www.dodmrl.co-m/MRL_Deskbook_2018.pdf.

[32] Bryntesen, S.N., Strømman, A.H., Tolstorebrov, I., Shearing, P.R., Lamb, J.J., Stokke Burheim, O., 2021. Opportunities for the State-of-the-Art Production of LIB Electrodes—A Review. Energies 14 (5), 1406.

[33] Crider, J., 2022. Panasonic Now Mass-Producing Tesla 4680 Batteries. https://cleantechnica.com/2022/06/03/panasonic-now-mass-producing-tesla-4680-batteries/.

[34] Randall, C., 2022. Panasonic to launch 4680 battery cell production next year. https://www.electrive.com/2022/01/24/panasonic-to-launch-4680-battery-cell-production-next-year/

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 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. From March 2019 to 2023, he was PEM's Executive Chief Engineer before being appointed Professor.

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.

Daniel Neb (*1992) is research associate at the Chair of Production Engineering of E-Mobility Components (PEM) at the RWTH Aachen University and group lead for the research group Battery Production Management since 2023. He studied mechanical engineering specializing in automotive engineering 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 and group lead for the research group Battery Production Management from 2021 to 2023. He studied mechanical engineering specializing in production engineering at the RWTH Aachen University.

Jennifer Machura (*1996) has been a master student at the Chair of Production Engineering of E-Mobility Components (PEM) at the RWTH Aachen University and has specialized in battery technologies. She studied business administration and electrical engineering at the RWTH Aachen University.

5th Conference on Production Systems and Logistics

Transforming AC-Powered Production Machines For Operation In DC Microgrids: From Methodology To Realization

Dietmar Hölderle[1,2], Janosch Hecker[1,2] Alexander Sauer[1,2]

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

Abstract

Manufacturing processes play a major role in the emission of greenhouse gases. To achieve the international goal of climate neutrality, it is necessary to decrease the amount of energy consumed by factories and their production machines. A promising approach is to improve grid efficiency and reduce voltage converter losses by using DC microgrids (DC-MGs). Furthermore, DC-MGs have proven suitable for an efficient integration of renewable energy producers and prosumers with energy recuperation capabilities.

To establish DC-MGs successfully in production environments, it is necessary to provide solutions for DC-MG integration of AC-powered machines. This paper describes how to enable production machines originally designed for AC-grid use to be operated on industrial DC-MGs. The article focuses on a methodology for AC-DC transformation of machines, including definition of specifications, system analysis, and redesign. The methodology is described using the example of an injection-moulding machine. Finally, the results of the transformation process are evaluated.

Keywords

DC Microgrid; Production Machines; AC-DC Transformation; Industrial Microgrids; Transformation Methodology

1. Introduction

Recent research activities on direct current microgrids (DC-MGs) have revealed the great potential of this technology regarding multiple criteria such as energy efficiency [1], resource efficiency [2], grid stability supply reliability [3], and energy flexibility.

Climate change is one of humanity's biggest challenges within the next decades. To achieve international climate targets, more sustainable technologies for decreasing energy consumption and its resulting carbon footprint are needed. The industrial sector is still one of the biggest final energy consumers in the European Union with 25.6 % of the total consumption, amounting to approximately 10.2 Terajoules in 2021 [4]. Using more energy-efficient production machines and more efficient energy grids can contribute a lot to reducing the emission of the greenhouse gas carbon dioxide, which results from fossil power generation.

DC-MGs have attracted attention as a means to make industrial electricity supply more efficient. More electrical high-power devices are now DC-powered, such as servo drives or battery electric vehicle (BEV) chargers. Many devices use DC parts, such as intermediate circuits or consist semiconductors, which are DC systems by design. Consequently, it takes many conversion steps to integrate such consumers into a standard alternating current (AC) grid. Integrating DC consumers directly into DC grids, makes many parts such as

DOI: https://doi.org/10.15488/15296
ISSN: 2701-6277

converters and filters and their resulting energy losses superfluous. With fewer losses, less electric power is necessary, while fewer heat losses lead to a reduction in cooling devices.

Most modern lighting systems in factories use light-emitting diodes (LED), which are DC-powered due to integrated AC-DC converters. Here, using lamps with DC-DC converters instead could save between 3 % and 5 % of energy [5]. The energy reduction in data centres can be even higher when using DC grids, with savings between 7 % and 28 % [6].

Apart from efficiency improvement, another convincing argument for DC-MGs is their ability to recuperate power. Dynamic processes such as robot handling can recuperate kinetic energy. Usually, the energy released during braking is fed back into the DC link of the machine and transformed into heat by a braking resistor [7]. Dynamic robot processes are able to feed back 5 % to 20 % [8] of energy depending on the moving profile.

Additionally, the importance of integrating decentralized electrical power generation into factory grids, such as photovoltaic (PV) plants, is increasing. By directly integrating PV panels into DC-MGs, a reduction of conversion losses of up to 8 % is possible [9].

As AC-specific constraints, such as the transmission of reactive power or frequency stabilisation become superfluous. However, there are many issues to face before being able to establish DC-MGs in great variety. One are the missing DC-powered production machines on the market. Only few equipment manufacturers respond to the current technological change. As the production machine market is not yet ready, it is necessary to refurbish AC production machines for DC grids. This article offers a methodology for transforming AC-powered consumers for use in DC-MGs. The methodology does not claim to make machines more efficient but enabling the dissemination of DC Microgrids as a more efficient grid technology.

2. Methodology for the AC-DC transformation of a production machine

Key components, such as DC-DC converters, safety breakers, and ultra-fast fuses for use in DC-MGs, have already been developed. DC-powered production machines are not yet available in sufficient numbers, but are needed to establish DC-MGs in factory environments. One approach is to retrofit existing equipment, most of them three-phase AC-powered. The presented methodology was developed to facilitate the integration of standard AC machines for use in DC-MGs. Its properties are described in the system design of the research project *DC-Industrie2* [10].

First, the requirements are defined before the transformation methodology is implemented. Second, the methodology is described theoretically and applied on an injection moulding machine. Finally, the methodology for AC-DC transformation is validated on a real-life injection-moulding machine.

2.1 Requirements of the transformation methodology

Defining the requirements of the DC transformation methodology (DC-TM) requires taking a closer look at the factory environment. The properties of AC and DC grids mirror the constraints of the start and the target state of the transformation of production machines. In addition, human aspects such as worker qualification should not be neglected. The requirements of the DC-TM are defined as follows:

1. The methodology needs to be valid for every kind of AC-powered production equipment.
2. The methodology needs to be valid for integrating a machine into a DC-MG, specified by the DC-Industrie2 system concept.
3. The methodology needs to reduce the complexity of the transformation by dividing the process into several manageable steps.
4. Every step of the methodology has defined input and output parameters.

5. The methodology needs to deliver an outcome that any electrically qualified team member can put into practice.

As the following points are not relevant to the machine's functionality, they should not be kept in mind as hard requirements but only criteria of optimization.

To better manage the transformation process, the DC-TM should result in minimally invasive modifications on the target machine. This means the machine should maintain the same physical size, and the most important parts should not be modified.

Moreover, machine-specific control software is usually protected against operator modifications to avoid changes to functionality or making safety adjustments. When replacing actuators or control elements, it should be kept in mind that closed-loop control behaviour can change without the option of adjusting control parameters in the software.

2.2 Requirements for result achievement

To ensure that a machine's transformation leads to the desired result, the requirements for validating the DC-TM need to be defined.

1. The method must not lead to any changes in the grid topology or grid behaviour
2. There must not be any safety problems with the machine after transformation
3. The production performance of the machine must not be influenced negatively

A main target for applying DC-MGs is to raise energy efficiency compared to standard electric grids in production environments. Since the redesign of an existing machine may reveal more design constraints than developing from scratch, a transformed machine probably is not an ideal solution in terms of energy efficiency. Nevertheless, the methodology should result in the same or even in improved energy efficiency.

2.3 First stage: Definition of specifications

Based on the defined requirements, a suitable DC-TM can be developed. A methodology for transforming production machines was described by Knapp [11] as a procedure model based on the systems engineering approach. The approach offers a methodology composed of a block diagram describing specific activities in the transformation process. Each block is organised into the four superior stages of dimensioning, state analysis, procurement, and results. The sub-stages of this process provide an overview of and orientation in the transformation process, including recommended actions and the specific input parameters that are needed. After working out each stage, the kind of an output parameter is defined for continuing. Knapp formulates the procedure of his methodology in a very general way to suit any type of machine. The machine's functionality is not of any relevance. He also mentions the possibility of non-feasibility in particular cases. The methodology focuses on electric drives, closed-loop control, and electro-mechanic energy converters. Supply systems, cables, energy storages, and filters are not taken into account [11]. To allow for its claim to general validity, the procedure does not go into detail at some points. In consequence, users have to select their own methods adapted to the specific case to reach the next step.

The transformation methodology (DC-TM) in this article takes up and advances the approach of Knapp. The general procedure of the expanded DC-TM was presented in [12]. This article presents the DC-TM in greater detail, and evaluates it on an exemplary transformation of an injection-moulding machine.

Generally, the DC-TM is structured into the three major stages of specification, system analysis, and implementation (Figure 1). The three stages must be carried out one after the other. The output of every stage forms the input parameters for the next stage.

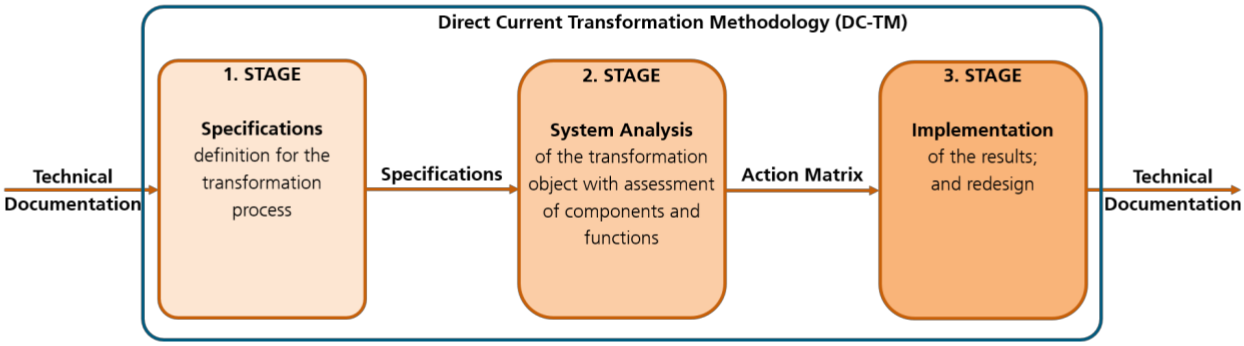


Figure 1: Overview of the three stages of the DC-TM

The specification stage is meant to provide a set of basic conditions for redesigning the machine. The system analysis stage proposes a decision algorithm to assess the machine properties, based on the defined requirements. The output is an action matrix with defined action propositions. At the implementation stage, the propositions are turned into practice by keeping, replacing, adding, or deleting specific components and their resulting functions. The technical documentation records the changes to the machine design.

When defining the specifications, the considered production ecosystem is divided into three major consideration units (Figure 2). The unit members are allocated with regard to system boundaries and flux variables that need to be considered during the transformation process.

The first unit defines the production environment of the machine. This unit can be divided into two sub-units. The first one is the physical environment of the machine. Its conditions can be defined through parameters such as space limitations, temperature limits, dust, explosion hazard, or requirements for the operators. Most of them are not further considered as the conditions do not change neither for AC- nor DC-powered machines. However, they need to be considered in redesigning or in designing specific machine parts from scratch. The second sub-unit defines the attributes more essential for energy supply.

The sub-unit focuses on the replacement of AC-supply by DC-supply, i.e., it points out the constraints linked to the electrical grid properties. In some cases, multiple energy supplies with combined or hybrid grid forms are possible. Some transformation methodologies aim at a step-by-step transformation, where consumers can have multiple power supplies [13]. Usually, the aim is to replace the previous electrical energy supply with pure DC-supply. For some cases, transforming the machine to run on hybrid energy supply may be more economical. Such optimizations can take place in the third phase of the DC-TM.

The second unit deals with the output environment, comprising the process, the production technology, and the machine's output. This unit is not to be modified in any case, as the output product or the production process parameters must not be changed. Therefore, it is recommended to consider the two parts together and to take heed of any possible changes to the product resulting from the machine's transformation process.

The third consideration unit is the most relevant one for transformation and is defined as the transformation object. Its system boundaries are limited by the machine-inherent energy transition components. The input and output parameters greatly influence the execution of the transformation. One of the difficulties in the DC-TM is to define the interfaces between units two and three. The part mostly affected by transformation lies within the transformation unit and will be dealt with in detail at the system analysis stage of the DC-TM.

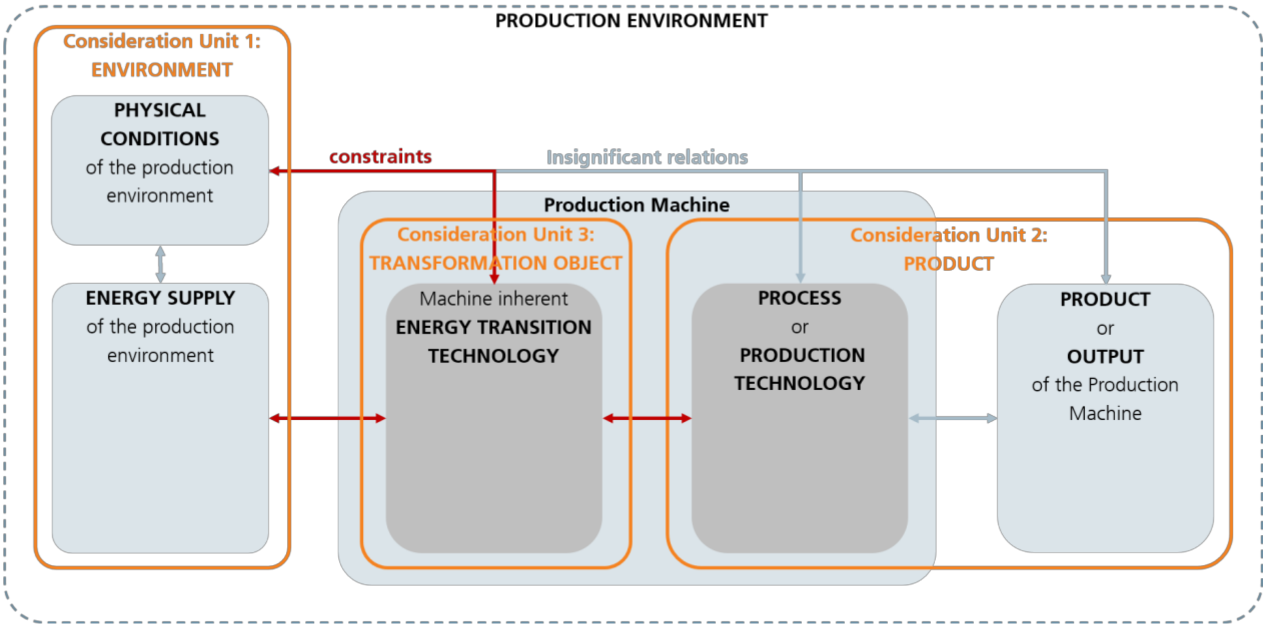


Figure 2: Extracting relevant system boundaries (orange) and constraints (red) for transforming production machines by defining three consideration units.

Applying the consideration unit model on the injection-moulding machine leads to grid- and the machine-inherent specifications, which are the constraints for the transformation process. Environmental specifications can be neglected due to marginal changes.

2.3.1 Grid-inherent specifications

Grid-inherent specifications are linked to the energy supply of the production environment. Originally, energy was supplied by a three-phase AC grid with amplitudes of 230 V and fuses for maximum currents of 16 A.

The specifications of the DC-MG are defined by the system design of the research project *DC-Industrie* [10]. The most significant attribute is the voltage band, which can vary within the nominal operation band of 620 V and 750 V. The grid has two phases, DC+ and DC- and a protective conductor. In line with safety aspects, faster fuses are necessary than in AC grids.

2.3.2 Machine-inherent specifications

Every component needs to be suitable for use with a maximum voltage level of more than 800 V in error cases. Special attention needs to be paid to clearance and creepage distances. Furthermore, the safety standard for operators and machines must be the same as in AC-grid use. Short circuit protection and voltage separation have to be guaranteed.

2.4 Second stage: System analysis of the transformation object

At the end of the first phase/stage, after defining the requirements of the system, the system analysis of the machine can take place in three steps. First, the transformation object is analysed at component level. Second, the component diagram is transferred to functional group level. Third, the components are evaluated according to relevance and their functional suitability for DC grids, based on a decision tree. The results are compiled in an action matrix.

2.4.1 Analysis at component level

Based on the technical documentation, the energy transition technology of the machine is analysed and visualized in a component diagram (Figure 3Figure 3: The flux variables illustrate the impact of the components on the electrical signal, where U_i is a voltage signal, I_i a current signal and f_i a frequency signal. The index stands for changes in the signal characteristics. Left side: Component diagram of the energy transition unit of an injection-moulding machine. Right side: Function diagram of the energy transition unit of an injection-moulding machine.).

Every box represents the component of a component in during the period of energy. The index of flux variables clarifies the changes to the electrical input generated by a particular component.

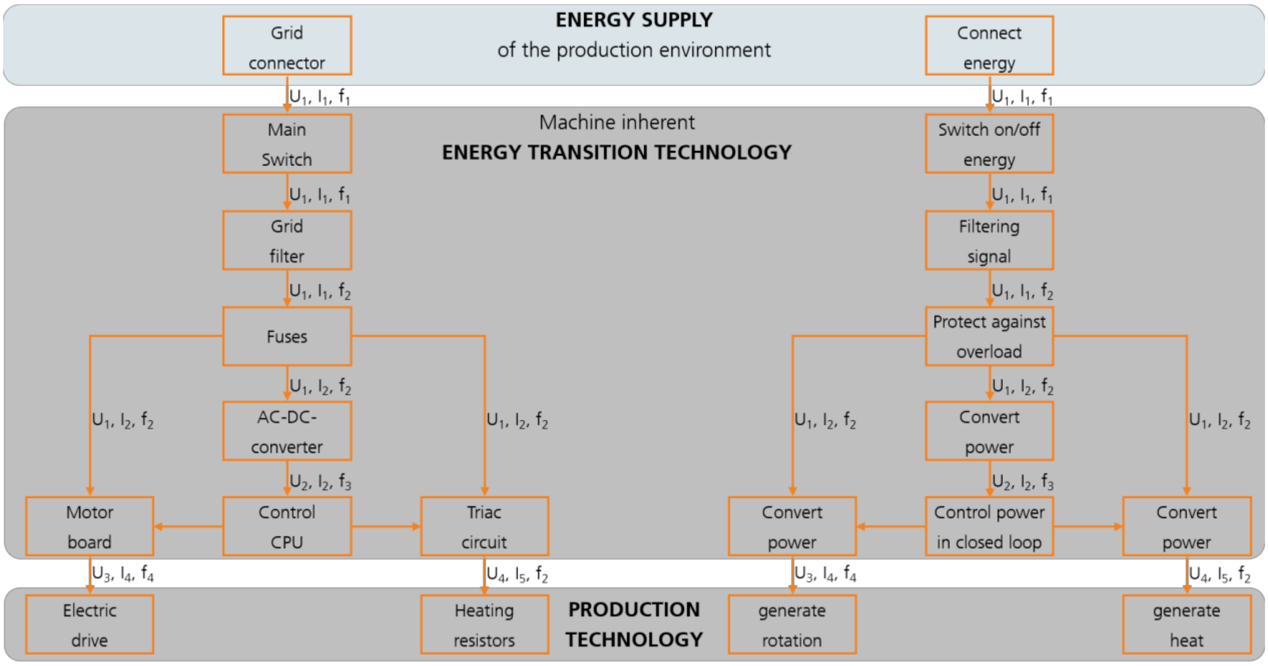


Figure 3: The flux variables illustrate the impact of the components on the electrical signal, where U_i is a voltage signal, I_i a current signal and f_i a frequency signal. The index stands for changes in the signal characteristics. Left side: Component diagram of the energy transition unit of an injection-moulding machine. Right side: Function diagram of the energy transition unit of an injection-moulding machine.

2.4.2 Transformation from component model to functional model

The component diagram is transferred to a functional diagram (Figure 3: Right side). The composition of the components as to their particular functions helps to get a more detailed view of the system.

Sometimes it can be reasonable to regroup similar functions into one functional block. The visualized functional relation is the basis for the DC suitability evaluation.

2.4.3 Assessment of components and functional groups

The components and their functions are listed in a table (Table 1). A decision tree is used for evaluating DC-grid suitability of each component and its function, illustrated in Figure 4. Executing the decision tree with every component leads to the four different actions of maintaining, replacing, deleting, or adding further components. The results are marked in the action matrix.

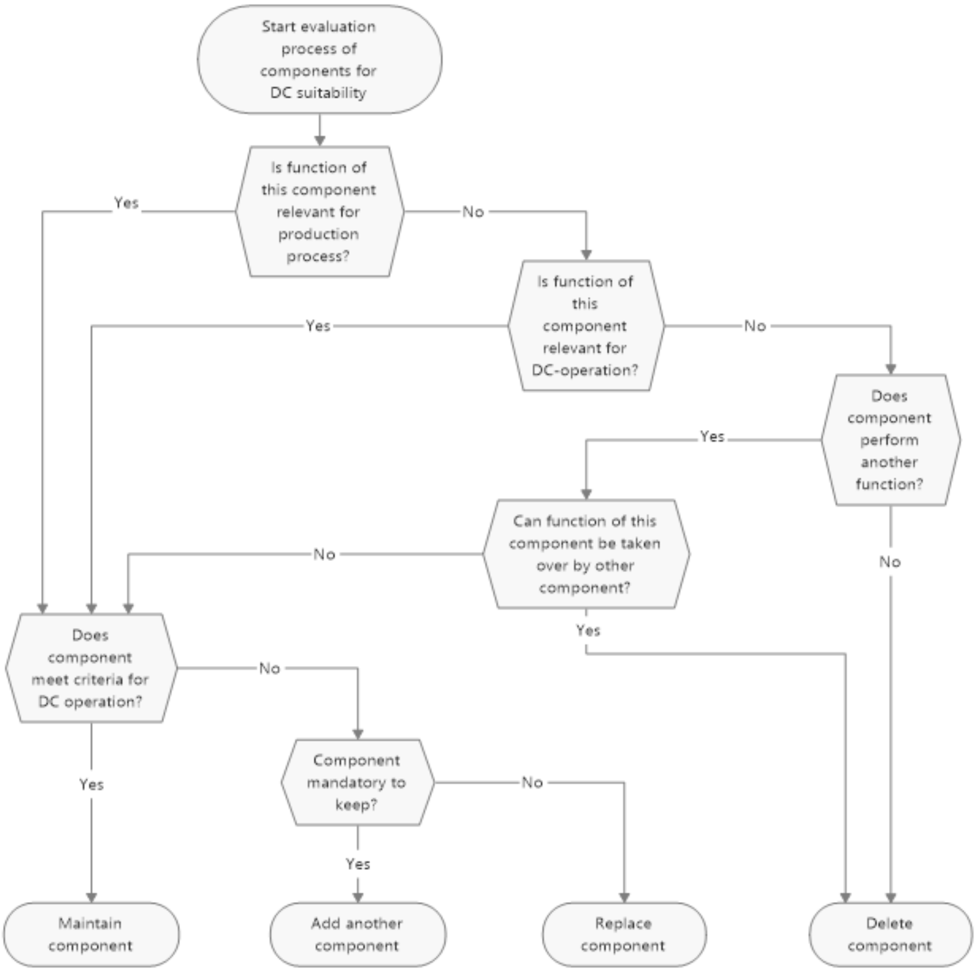


Figure 4: Decision tree for evaluating the DC suitability of AC components.

The user needs to determine the data on which each decision is based, according to the defined constraints. The decision algorithm is adapted to the specific case of electric transformation from AC to DC. For other use cases, the decision tree needs to be modified.

Table 1: Action matrix for reengineering exemplified by an injection-moulding machine

COMPONENT	FUNCTION	DECISION			
		Maintain component	Replace component	Add further component	Delete component
Grid connector	Connect energy supply		X		
Main switch	Switch on/off		X		
Grid filter	Eliminate frequencies				X
Fuses	Avoiding overload		X		
AC-DC Converter	Convert power		X		
Control CPU	Control power	X			
DC-DC Converter	Convert power			X	
Triac Circuit	Convert power		X		
Motor driver	Convert power	X			

Once the action matrix has evaluated the action for every component, the system analysis phase ends.

2.5 Third stage: Implementation and redesign

In the last phase of the DC-TM, the results of the previous phases are implemented and transferred to the machine's technical documentation. The implementation stage can be compared to the standard model care process, the difference in this case being that the machine is already on site. The redesign process requires to be done iteratively as described in the standard literature for development methodologies, e.g., [14–16]. . Therefore, this stage is not described in detail.

The transformation of the injection-moulding machine led to several minor and major changes in the machine design. Minor changes, such as replacement of plugs, fuses, or connection cables, are not described in detail. Noteworthy adjustments were made to the power electronics of the heating resistors. Originally, they were controlled by triacs, which are AC-specific components. A specifically designed electronic board with IGBTs (insulated gate bipolar transistors) replaced the triac circuits. Optical couplers assured necessary galvanic isolations. An advantage of this design is that it requires no adaptations in the control software.

Minor changes were made to the motor board of the hydraulic pump. The AC-DC converter was replaced by a DC-DC converter to reduce the input voltage to a suitable motor voltage of 300 V. A great advantage being the fact that the motor did not require any further modifications.

3. Results

The example of the injection-moulding machine illustrates the successful transformation of a production machine by the DC-TM. All requirements were fulfilled at the end of the transformation process. The machine's operation did not bring about any noticeable changes with regard to safety aspects, machine performance, or influences on the DC grid.

Functional proof was provided by applying the DC-TM to the production machine under consideration. The requirements for the methodology were defined in section 2.1. The first requirement mentioned above is that the DC-TM is to be valid for any kind of AC-powered production machine. This requirement is partially fulfilled by applying the DC-TM to one type of production machine. For complete validity, the DC-TM needs to be applied to further machine types. Requirements two to five were accomplished without restrictions.

4. Conclusion

The transformation of AC-supplied machines for operation with DC enables the establishment of DC-MGs. The DC-TM is a suitable to support the transformation process and leads through the different stages of definition of specifications, analysis of the production machine, and hardware redesign. An algorithm for evaluating DC suitability of components concerned is provided in form of a decision tree. The results are presented in a compact action matrix as a guideline for redesigning the machine.

In the future, the DC-TM should be applied to different types of production machines. Additionally, several aspects of the methodology need to be further specified. Furthermore, the DC-TM can be abstracted to become a universally valid methodology for redesigning field machines. A detailed classification in the field of development methodologies is pending. The energy efficiency before and after the transformation process can be evaluated. Probably, design guidelines for cost-effective and energy-efficient redesign could be added to the DC-TM.

References

[1] Kuhlmann, T., Zeiser, R., 2022. Wie effizient sind gleichspannungsversorgte Maschinen?: Methode zur Identifikation des Energieeffizienzpotenzials durch Umrüstung von Wechselspannung (AC) auf Gleichspannung (DC). Zeitschrift für wirtschaftlichen Fabrikbetrieb ZWF, Jahrg. 117 12.

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

[3] Laribi, R., Schaab, D., 2019. Nutzenpotenziale von DC-Smart-Grids in der Industrie: Energieeffizienz, Fabrikplanung. VDI Fachmedien GmbH & Co. KG, Düsseldorf. https://elibrary.vdi-verlag.de/10.37544/1436-4980-2019-05-9/nutzenpotenziale-von-dc-smart-grids-in-der-industrie-benefits-of-dc-smart-grids-in-the-industry-jahrgang-109-2019-heft-05?page=1.

[4] Eurostat - Statistics Explained, 2023. Energy statistics - an overview: Final energy consumption by sector, EU, 2021. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_statistics_-_an_overview#Final_energy_consumption. Accessed 14 July 2023.

[5] Gerber, D.L., Vossos, V., Feng, W., Marnay, C., Nordman, B., Brown, R., 2018. A simulation-based efficiency comparison of AC and DC power distribution networks in commercial buildings. Applied Energy 210, 1167–1187.

[6] AlLee, G., Tschudi, W., 2012. Edison Redux: 380 Vdc Brings Reliability and Efficiency to Sustainable Data Centers. IEEE Power and Energy magazine (6).

[7] Borcherding, H., Stammberger, H., 2021. DC-Industrie: Gleichstrom für die nachhaltige Fabrik. DC-Industrie & ZVEI. Gleichstromnetz in der Fabrikautomation. Stand: 11.05.2021. Internet: https://dc-industrie.zvei.org/fileadmin/user_upload/Presse_und_Medien/Publikationen/2020/November/DC-INDUSTRIE-Gleichstrom-fuer-die-nachhaltige-Fabrik-final.pdf. Accessed 7 July 2023.

[8] Rankis, Meike, Senfelds, 2013. Utilization of Regeneration Energy in Industrial Robots System. Power and Electrical Engineering.

[9] Fregosi, Ravula, Brhlik, 2015. A comparative study of DC and AC microgrids in commercial buildings across different climates and operating profiles. IEEE First International Conference on DC Microgrids.

[10] Stammberger, Austermann, Borcherding, 2023. Systemkonzept DC-INDUSTRIE2. ZVEI. https://dc-industrie.zvei.org/publikationen/systemkonzept-fuer-dc-industrie2. Accessed 7 July 2023.

[11] Knapp, J., Righetti, P. de, Schaab, D., 2022. Methodik zur Umrüstung von Produktionsmaschinen. WT WerkstattsTechnik (03).

[12] Hölderle, D., Knapp, J., Sauer, A., 2023. Methode für Analyse, Entwurf und Umrüstung von Maschinen/Methodology for analysis, design and retrofitting of machines operating in an industrial DC network: Transformationsprozess von Produktionsmaschinen in einem industriellen Gleichstrommikronetz. https://elibrary.vdi-verlag.de/10.37544/1436-4980-2023-03-63/methode-fuer-analyse-entwurf-und-umruestung-von-maschinen-methodology-for-analysis-design-and-retrofitting-of-machines-operating-in-an-industrial-dc-network-jahrgang-113-2023-heft-03?page=1. Accessed 12 July 2023.

[13] Timm Kuhlmann, Darian Andreas Schaab, Alexander Sauer, 2020. Unterwegs zur Gleichstromfabrik: der Transformationsprozess im industriellen Stromnetz: Der Wandel vom heutigen AC-Netz zum industriellen DC-Smart-Grid. Zeitschrift für wirtschaftlichen Fabrikbetrieb 115 (11), 769–773.

[14] Bender, B., Gericke, K. (Eds.), 2021. Pahl/Beitz Konstruktionslehre: Methoden und Anwendung erfolgreicher Produktentwicklung, 9. Aufl. 2021 ed. Springer Berlin Heidelberg, Berlin, Heidelberg, 1162 pp.

[15] Krause, W. (Ed.), 2018. Grundlagen der Konstruktion: Elektronik - Elektrotechnik - Feinwerktechnik - Mechatronik; mit 350 Bildern und 67 Tafeln sowie einem Anhang Technisches Zeichnen, 10., aktualisierte Auflage ed. Carl Hanser Verlag, München, 1327 pp.

[16] Lienig, J., Brümmer, H., 2014. Elektronische Gerätetechnik: Grundlagen für das Entwickeln elektronischer Baugruppen und Geräte. Springer Vieweg, Berlin, Heidelberg, 242 pp.

Acknowledgements

The authors gratefully acknowledge financial support by the German Federal Ministry for Economic Affairs and Climate Action (BMWK) via grant numbers 03EI6002L, 03EI6002N and 03EI6002D (project: “DC-INDUSTRIE 2 - Gleichstrom für die Fabrik der Zukunft“).

Biography

Dietmar Hölderle (*1992) studied mechatronics engineering and microsystems technologies at Ilmenau University of Technology in Germany and ENSMM (école nationale supérieure de méchanique et des microtechniques) Besancon in France. Since 2021 he has been a research associate at the University of Stuttgart. His main research focuses on industrial DC microgrids and energy efficiency of production machines.

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.

CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
CPSL 2023-2

5th Conference on Production Systems and Logistics

Methodical Implementation Of Digital Data Consistency In Assembly Lines Of A Learning Factory

Marius Knott[1], Tobias Schmelter[1], Tom Nowak[1], Christopher Prinz[1], Bernd Kuhlenkötter[1]
[1]*Chair of Production Systems/ Ruhr-University Bochum, Bochum, Germany*

Abstract

The possibility of acquiring data in production and manufacturing processes is almost limitless. But especially small and medium-sized enterprises (SMEs) lack the knowledge to successfully integrate digital tools and use real-time production data for critical decision-making. Numerous initiatives already exist to inform and support SMEs in Germany, funded at various levels by municipal, federal, and state entities. These initiatives offer expertise in digitalisation and provide diverse activities to support SMEs across different industrial sectors. To make abstract concepts such as artificial intelligence (AI) or digitalisation more tangible, demonstrations and practical best practice showcases demonstrate methodological approaches for facilitating independent implementation initiatives within SMEs. However, most of these activities primarily showcase rudimentary and isolated technological implementations, with limited integration into the complex environment of a manufacturing company. This paper focuses on a holistic methodical brownfield implementation of a demonstrator for digital data consistency in an assembly line of a learning factory by applying an extended methodology for implementing demonstrators and its validation by industrial participants. It stresses the complexity of production data acquisition in a practical environment and illustrates a best-practice showcase. Key performance indicators are visualized by acquiring, storing, and cross-linking data points. The demonstrator is implemented and evaluated by SMEs' representatives, to show promising potential for sustainable knowledge transfer into the SMEs.

Keywords

digitalisation; industry 4.0; production data acquisition; factory planning; machine learning; learning factories, demonstrator

1. Introduction

Exploiting a company's value creation potential within production sites is paramount in achieving substantial revenues. The utilization of digital tools becomes crucial for the enhancement of lean implementation as well as decisions with great impact, as they provide real-time data for informed decision-making [1]. This data needs to be extracted from machines (machine data) or processes (operating data) at essential information points and serve as data points to establish transparency by key performance indicators (KPIs) [2]. Especially small and medium-sized enterprises (SMEs) often lack such implementations of data usage in their production sites [3]. Consequently, decision-making tends to be delayed or based on inaccurate assumptions due to the absence of transparency in value-creation processes [2]. Existing initiatives of various centres of competence funded on municipal, federal, and state levels already assist SMEs on this matter by informing companies on digitalisation or artificial intelligence (AI) and showcasing best practice use cases to make these topics tangible [4]. Such demonstrations tend to be downscaled or simplified for better understanding and were developed as greenfield implementations [5–7]. Furthermore, existing brownfield concepts often prioritize hardware infrastructure and production processes and do not consider the extension of existing IT infrastructure [8]. The object of research, presented in this paper, is a solution which can be easily transferred to SMEs thus ensuring an applicable transposing of production processes. Following the established learning factory (LF) approach [9], using realistic and industrial-like surroundings for best transfer results, the existing infrastructure of the Learning and Research Factory (LFF) of the Chair of Production Systems (LPS) at the Ruhr-University Bochum [10] was extended. Consequently, a demonstrator for digital data consistency is methodically developed, focusing on assembly lines as an illustrative example. An extension of the existing methodology for a demonstrator's brownfield implementation into an existing environment constitutes the primary emphasis of this paper. The functional implementation of the demonstrator serves as the extended methodology's proof of concept. Validation is then conducted through integration into informational events and subsequent surveys. However, it is important to note that the validation is not part of the methodology itself and paper does not address the comprehensive development of a competency-based LF environment (LFE) for action-oriented learning.

2. Fundamentals

2.1 Learning factories and demonstrators

LFs provide hands-on and experimental training for students and industrial employees. These facilities aim to replicate industrial settings, allowing participants to acquire practical knowledge and skills in a controlled and safe environment. [11] A comprehensive classification morphology has been developed to describe different types of LFs. Initially introduced by TISCH ET AL. [9], this framework has recently been updated and expanded to a total of eight dimensions [12]. Of relevance to this paper and therefore to the implementation of a demonstrator, are the dimensions of process, setting and product, as they describe the environment of a LF. The LFE includes the overall physical or virtual setting that emulates a real industrial or manufacturing workspace. It consists of various workstations, machinery, equipment, and resources that replicate those found in actual industrial settings. This LFE is designed to fulfil the didactical requirements as a secure and controlled space for this purpose. It enables participants to acquire knowledge and skills related to production processes, production management, digitalisation, automation, and related areas [13].

On the one hand, demonstrators are typically characterized as model-scale environments [5] and are interpreted in this paper as components within an existing or future LFE. They serve to represent specific technologies, processes, and best practices, or provide foundational information on various topics [13]. These segregated systems offer participants hands-on experiences and facilitate a deeper understanding of the practical applications of the technologies being showcased. Demonstrators play a crucial role in bridging the gap between theoretical knowledge and practical implementation and are frequently utilized in knowledge transfer initiatives such as the "Mittelstand-Digital Zentren" in Germany [14]. Demonstrators can be categorized as either material or non-material manifestations. Materialistic demonstrators can be either mobile [15,7] or stationary [6,8]. On the other hand, the LFE in the narrow sense encompasses the broader setting that replicates an industrial workspace and provides a comprehensive learning experience with various workstations and resources [16].

2.2 Existing design approaches for demonstrators

Various design approaches have already been established for the development of LFEs. One comprehensive approach, pioneered by Tisch et al. [9] and used most often [17], focuses on creating a LFE that offers direct applications of competencies for extensive learning modules. This approach contains two didactic transformations. The first didactic transformation encompasses organizational requirements and learning objectives, while the subsequent stage involves the configuration and implementation of the didactic and sociotechnical infrastructure. Another approach, which builds upon TISCH ET AL. [9], specifically addresses the development of a mobile demonstrator [7]. Additionally, there is an effort to create a model scale environment tailored to enhance energy efficiency [5] or a demonstrator's framework in cyber-physical production systems [18]. The application of a reference architecture for demonstrators [19] does not match the usage of demonstrators as mentioned above, but the simulation of new cyber-physical systems. Consequently, a gap exists in the existing methodology when it comes to the technical implementation of demonstrators as a preliminary step within an already established hardware and software infrastructure.

2.3 Learning factory evaluation

To ensure the success of a demonstrator and its effectiveness in illustrating specific information to participants, evaluation is essential. When assessing the success of LFs, the Kirkpatrick Model [20] is frequently used already [21]. The Kirkpatrick Model is a widely recognized framework for evaluating the effectiveness and impact of training and development programs. This model provides a systematic approach to evaluating training outcomes across four levels. The first level focuses on participants' immediate reactions to the training program. It measures their satisfaction with the training, their perception of its relevance, and their overall engagement. Feedback is typically gathered through surveys and questionnaires. The second level assesses the extent to which participants have acquired new knowledge, skills, or competencies because of the training. It measures the increase in participants' knowledge and understanding. The third level of evaluation examines the extent to which participants apply the newly acquired knowledge and skills in their workplace. The highest level of evaluation focuses on the overall impact of the training on the organization's outcomes. Considering that demonstrators primarily serve as a form of learning but may not address high-level competencies [13] due to their limited interaction period with participants, this paper focuses its evaluation on the initial reactions and low-level learning outcomes [20]. Specifically, it examines the taxonomy levels of remembering and comprehension [22] in stage two.

3. Methodology

The foundations for the systematic development and implementation of a LFE have already been established [9], and there are already comparable instances of mobile [7] and stationary demonstrations that have built upon this foundation. The subsequent chapter describes the extension of the existing approach, including the necessary adaptations to meet the given specific use case, which entails integrating a demonstrator into the existing hardware and software infrastructure and surroundings within a brownfield LFE. The pre-existing design approach of a first and second didactic transformation is still the macro-structure. However, adjustments to align this approach with the technological focus of the demonstrator are made. Considering the requirements of a practical demonstrator, alongside the extensive implementation within an existing operational infrastructure, more comprehensive guidance is relevant for the conception and execution phases. This can be accomplished by complementing the existing approach with the incorporation of the VDI 5200 [23] guideline for factory planning (see Figure 1).

4. Implementation

4.1 Phase 1 – setting of objectives

The main target groups for the demonstrator primarily comprise representatives from SMEs. Their professional roles include digitalisation officers, process engineers, plant managers, and potentially other positions. The second group consists of multipliers, such as chambers of commerce, associations, and consultants. Each target group has distinct transfer objectives, which are further categorized as primary and secondary objectives (see Table 1). The primary objectives aim to generate participants' interest and foster their understanding of the functionality of live data acquisition, interfaces, and the steps involved in establishing KPIs, using the demonstrator as a best practice example. Moreover, the secondary objectives aim to encourage SMEs to take further steps towards implementing similar digitalisation practices in their production processes.

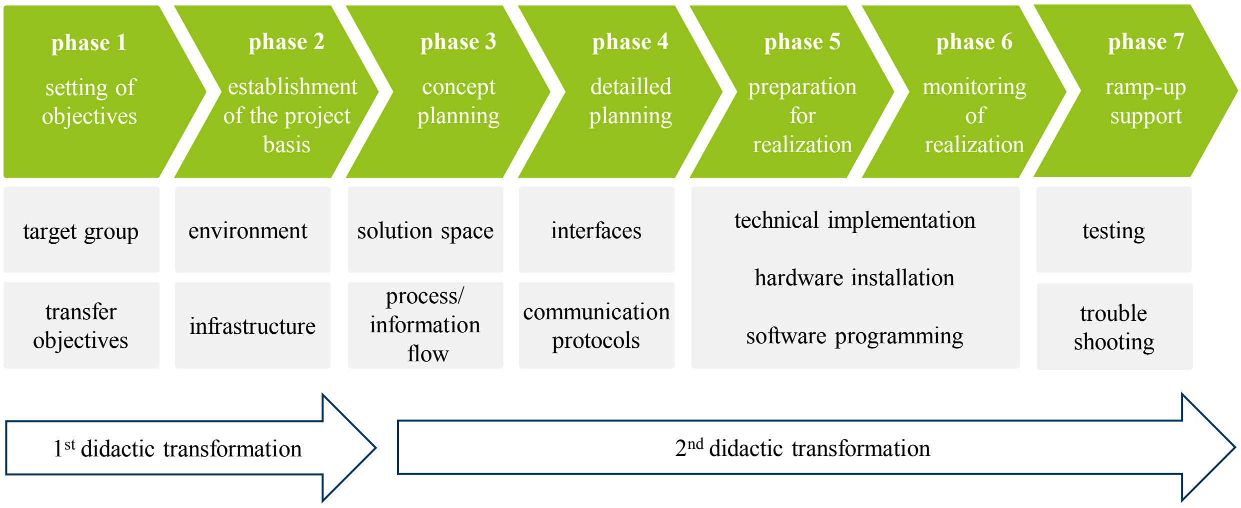


Figure 1: Phase model of a demonstrator's brownfield implementation following TISCH ET AL. [9] and VDI 5200 [23]

It is important to note that other groups, such as students or works councils, are not listed as primary targets, as their specific transfer objectives may differ from those of the primary target groups. The transfer objectives play a crucial role in evaluating the demonstrator later. They were developed in discussions with the target groups and condensed in expert brainstorming sessions.

Table 1: Target groups and transfer objectives of a demonstrator for digital data continuity

target groups	primary transfer objectives	secondary transfer objectives
digitalisation officers, process engineers, plant managers, etc.	• Generating participants' interest in live data-driven KPIs • Understanding the concept and functionality of the demonstrator • Understanding the basic digitalisation phases • Increase in understanding of digital data continuity • Stressing the variousness of interfaces and the system's entities	• Initializing digitalisation efforts by showcasing best practices • Raising awareness of the challenges and complexity of digital data continuity • Supporting SMEs initiatives for digitalisation • Increasing transparency and data-based decision-making in manufacturing SMEs
multipliers, industrial chambers of commerce, associations, etc.	• Showcasing best practice examples for digital data continuity • Train-the-trainer format in digitalisation of production sites	• Creating a presumption of competence to hold joint events • Multiplying gained impressions to manufacturing SMEs

4.2 Phase 2 – establishment of the project basis

To address the transfer objectives, various hardware and software solutions already exist. By integrating the new demonstrator into the existing infrastructure, investments and efforts can be reduced by selecting the most suitable project foundation of already existing hard- and software. Three potential scenarios are considered within the LFF: a hybrid assembly line [24], a terminal strip assembly line with real production orders [25], and the UniLokk bottlecap assembly line [26]. These scenarios are listed and compared, highlighting the pros and cons of each (see Table 2). All the scenarios can equally leverage the established IT infrastructure of the LFF, which encompasses essential components such as a router for the communication standard Open Platform Communications Unified Architecture (OPC UA router), a

Structured Query Language database (SQL database), and a broker of the message protocol Message Queuing Telemetry Transport (MQTT-Broker). Among these options, the UniLokk assembly line presents the most compelling advantages. It mostly captivates with the existing track and trace system, and cognitive worker assistance systems, incorporates AI for object detection and quality management [26], and offers various human-machine interfaces (HMI). These features provide a well-suited project foundation for achieving the desired transfer objectives (see Table 1). The setup consists of three assembly stations (see appendix Figure 3 and Figure 4). The first station serves as a preassembly area where the worker (1) is responsible for glueing tasks. In the subsequent station, worker (2) assembles the pre-assembled component from station one along with the remaining UniLokk components. Following the hardening process, worker (1) transitions in the meantime to station three to conduct quality inspections on an assembled UniLokk before packaging the final UniLokk product and moving back to station one for finishing the preassembly.

Table 2: An overview of the advantages and disadvantages of given assembly line scenarios in the LFF

scenarios	pro scenario	contra scenario
COssembly (hybrid assembly line)	• Already existing digital twin • Machine data of robots available • Production data is available	o Very complex system o Complex start-up procedures for hard- and software o No database connected
terminal strip assembly line	• Manufacturing execution system already integrated • Order production for customers • High amount of production data (also used for research)	o Interference with production results in loss of piece numbers o Interference with production results in falsified research results
UniLokk bottlecap assembly line	• Isolated digital applications already exist (AI object detection, track and trace system) • Versatile product with most frequent use in other transfer events, formats and topics • Various cognitive worker assistance systems exist (pick-to-light system, HMI-based, etc.)	o No database connected o No interfaces or connections to frontends exist o Lean processes via paper

4.3 Phase 3 – concept planning

Enhancing the transparency of the UniLokk assembly line includes gathering target KPIs and extrapolating the general functionalities of the demonstrator. Relevant data points of each assembly station are listed in Figure 3 in the appendix. An overview of the approximate function and information flow is depicted in Figure 2. The flow traverses the primary dimensions, including the human dimension, the human-machine interface, and the cyber-informatic dimension. These flows will be elaborated in greater detail in phase 4.

4.1 Phase 4 – detailed planning

Subsequent planning efforts yield a comprehensive draft outlining the detailed information flow (see appendix, Figure 5). This precise depiction describes the specific dimensions and processes involved in customer interaction and worker assembly. The digital dimensions are derived from the digitalisation phases outlined in the acatech phase model [27], differentiating between data collection, data processing, data provision, data storage, data visualization, and data analysis or prediction. Each station of the UniLokk assembly line is equipped with radio frequency identification (RFID) scanners to facilitate seamless and contactless tracking of the product. The RFID chips' identification number captured by the scanners is processed through their programmable logic controllers (PLCs) and afterwards mapped by the OPC UA router to ensure efficient signal transmission. To showcase the capability of utilizing two frequently used communication standards in production digitalisation, the OPC UA router further processes the signals into the MQTT protocol, which is then published by the MQTT broker. Open-source software, such as node-red,

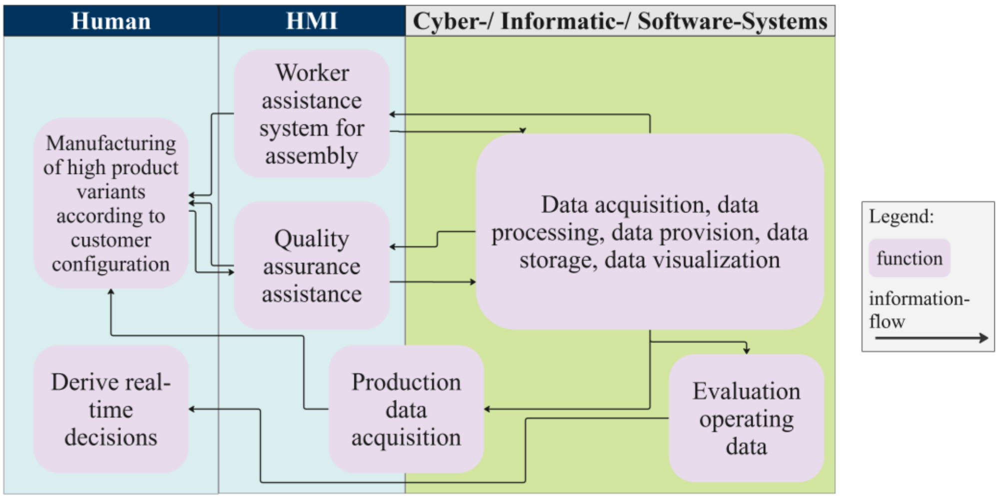


Figure 2: Concept planning of a digital data consistency

incorporates various programs and flows to assimilate the data and write it into the database. Additional node-red flows provide diverse front-end interfaces customized for both workers and plant managers on screens, featuring different KPIs. The application of the YOLOv7 AI algorithm [28] enables object recognition via camera, providing relevant data for comparing the manufactured product with the customer configuration. However, beyond this specific function, no further data analysis or prediction is conducted. It is important to note that the interpretation of the dashboard data by the plant manager or worker is not depicted in Figure 5. Lastly, each RFID chip, which identifies the current product in each station, triggers a pick-to-light flow to guide the worker in picking the appropriate parts.

4.2 Phases 5, 6 and 7 – preparation, monitoring of realization and ramp-up support

The hardware yet to be acquired was obtained through offers and procurement requests. The execution of the project involved a collaborative effort among students undertaking their final theses, research assistants, technical personnel, and academic staff. All persons involved worked together on parallel tasks or coordinated milestones. The collaboration involved interdisciplinary teams composed of students specializing in applied informatics, electronic engineering, automation engineering, and process management. These teams worked together to synchronize their efforts and ensure smooth integration among the various components of the previously described system architecture. A conventional ramp-up process is dispensable due to the non-commercial and non-value-added utilization of the demonstrator's environment. However, despite this fact, a series of stress tests and iterative optimization cycles remain essential even post-realization. The demonstrator's content has been integrated into the operational flow of the pre-existing technology tour. The initial application and evaluation for project assessment are conducted within this phase but will be dealt with in the subsequent chapter.

5. Application and evaluation

5.1 Application of the demonstrator

The proof of concept was assessed during organized events hosted in the LFF. The target audience for these events consisted of employees from SMEs who participated in technology tours offered free of charge as part of externally funded transfer projects [14]. These tours serve as a platform to provide participants with first-hand exposure to state-of-the-art technologies. The insight is facilitated through research cells or demonstrators. During these technology tours at the LFF, participants receive basic knowledge of technologies, as well as principles related to digitalisation, AI, automation, and robotics. To augment the participants' understanding of the digitalisation of production data, the implemented demonstrator for data consistency in assembly lines has been integrated into the tour. This integration allows for a more comprehensive and immersive experience, enhancing the participants' superficial understanding of the subject matter.

Initially, participants were provided with fundamental knowledge about the acatech phase model [27] and its phases related to digitalisation and Industry 4.0. They were immersed in a scenario involving a fictional SME engaged in the production of the UniLokk. The basic assembly process of the product was illustrated across three stations, prompting the participants to contribute their ideas regarding KPIs relevant to the assembly lines through a collaborative brainstorming session. Together, they identified the need for feedback on productivity, efficiency, and transparency. The resulting KPIs aligned with the objectives defined in Chapter 4, including metrics such as the number of units, quality rates, and cycle times. Instead of developing a technological solution concept from scratch, the participants were introduced to the fully implemented demonstrator that served as a best-practice example. Each aspect, system component, and software interface were described to the participants by the event host of the LPS. Following the introduction, the participants were given the opportunity for hands-on experience. They engaged in activities such as entering customer orders, initiating production orders via RFID chips, operating the optical quality control, and submitting quality data through the HMI. Through these interactions, each participant gained insights into the information flow of every actuator and sensor. The hardware components, such as scanners and PLCs, were visually illuminated to indicate the acquisition and transmission of data. The data flows were then visualized within the system's components, including the OPC UA router, MQTT-broker, node-red backend, node-red frontend, and SQL database. Feedback was conveyed through visual changes in various options, such as debugging messages, colour modifications, or the addition of characters.

5.2 Evaluation of the demonstrator

Upon completion of the testing phase, each participant was requested to complete questionnaires as part of the evaluation process for the demonstrator. As the current classification categorizes the event as an informational session, the primary objective is not focused on profound competency development. The questionnaire was developed based on the Kirkpatrick approach [20], only focusing on levels one and two. The main content of the surveys deals with the predefined objectives established before the planning phase. Section one of the survey refers to the participants' subjective assessment of their comprehension of the first level of Kirkpatrick's evaluation framework. The questionnaire specifically asks participants to self-assess their interest in digitalisation within assembly lines, as well as their perception of the complexities surrounding data collection and distribution for visualization purposes. Additionally, it evaluates their reaction to the effectiveness of the demonstrator in clarifying relevant functions, the participants' understanding of data acquisition processes, and their comprehension of the overall system architecture. Section two examines the participants' understanding of the demonstrator's functionality, ranging from Anderson's levels of remembering to comprehension, through a series of targeted questions, like the sequence of the digitalisation phases, the relevance of software interfaces and other aspects of the demonstrator's functionality. In the third section, the success of knowledge transfer is assessed by a request for feedback on the emergence of inspiration. This section primarily focuses on comparing existing aspirations for digitalisation in assembly lines, existing use cases, and participants' interest in commercial or prototypical implementations. It is worth noting that each question allows for abstention, providing participants with the option to decline to respond if desired. Sections one and three consist of scale questions, requiring feedback ranging from 1 (strongly agree) to 5 (strongly disagree), including the option to abstain. Additionally, section four collects data on participants' backgrounds, such as their industry, number of employees, and role within their companies. The survey results are presented in Figure 6 of the appendix. A total of 19 surveys were collected and the survey's questions are numbered in their section. Outliers are indicated by dots on the graph. Three surveys were excluded from the evaluation in section three, as the secondary target group did not possess aspirations for transfer goals due to the absence of manufacturing applications in their companies. These individuals did not abstain from providing feedback, which is why their responses were not considered. Overall, the reactions in section one rank in the higher categories, except for question 1.6. This question served as a negated control question to prevent any potential falsified results and is opposite to that of the other questions. The distribution of correct and incorrect answers in section two also reveals the most correct responses, with approximately 15.8 % abstentions and 26.3 % incorrect answers combined across all four questions. However, the feedback regarding transfer goals demonstrates a wider range of opinions. These numbers do not directly align with the positive feedback received in section one. The discrepancy observed in question 3.2 indicates a lack of knowledge among participants or no applications at all regarding the existence of comparable use cases within their companies.

6. Conclusion and outlook

The primary objective of this paper was to methodically implement a low-threshold demonstrator for digital connectivity and data continuity in assembly lines, laying the groundwork for knowledge transfer to SMEs. Existing approaches fell short of meeting the requirements of industry-oriented integration of demonstrators within the existing infrastructure of the LFF. Consequently, the existing concept was enhanced by incorporating a guideline for factory planning projects. The usage of the demonstrator in information events focused on stimulating digitalisation efforts in SMEs at lower taxonomy levels. The initial proof of concept yielded positive feedback on the demonstrator's set-up and illustration of digitalisation on assembly lines in an existing brownfield IT infrastructure. With most correct answers obtained on the lower levels of taxonomy, the demonstrator successfully meets the established requirements, indicating its promising potential for future application. However, it is important to note that the demonstrator does not fully eliminate all existing barriers inhibiting SMEs on their own comparable projects in their production, as evidenced by the mixed feedback on transfer. This emphasises the current limitations of the demonstrator concept and stresses the necessity for comprehensive competency development within SMEs.

Ongoing evaluation will play a crucial role in further developing the demonstrator and improving the current information format. A new evaluation category could be introduced to assess the industry-like format of the demonstrator and ensure its practical orientation. Additionally, a more detailed information module could equally balance technology and methodology by integrating the guideline for factory planning. Moreover, there is room for enhancing participant involvement. By implementing further didactical and technological improvements, such as incorporating new data points or applying data analytics, new qualification modules can be developed. These modules would focus on the profound application of methods, such as *value stream mapping 4.0 plus* [29] or digital shopfloor management, at higher taxonomy levels and foster competency development in digitalisation. The demonstrator can serve as an appropriate LFE for such advanced modules. Furthermore, the effect of the demonstrator on heterogenous target groups from different SMEs with differing employee numbers, professions and industries still has to be examined as the number of participants is not high enough at this moment.

Acknowledgements

This article has been elaborated during the transfer project "Mittelstand-Digital Zentrum Ländliche Regionen Teilvorhaben: Innovationen und Methoden für Unternehmen" (reference number: 01MF22009B). The project is funded by the German Federal Ministry for the Economy and Climate Protection within the initiative of "Mittelstand-Digital, Mittelstand-Digital Centres" and supervised by the project executing agency German Aerospace Centre (DLR). The authors are responsible for the content of this publication.

Appendix

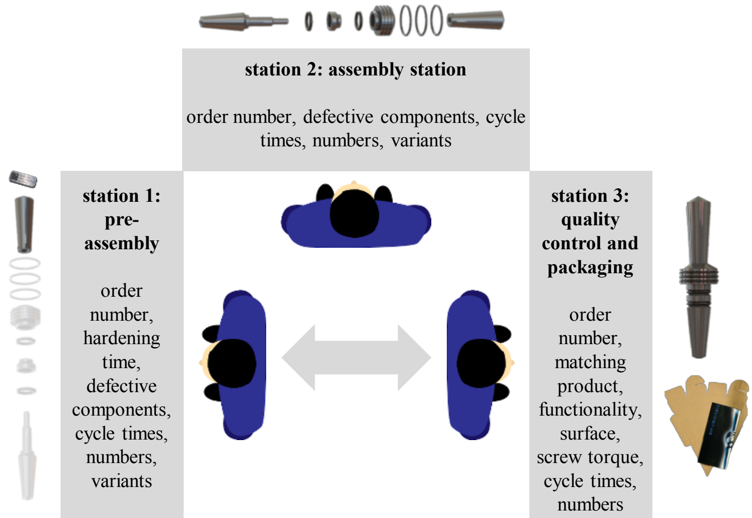


Figure 3: Schematic representation of the UniLokk assembly line

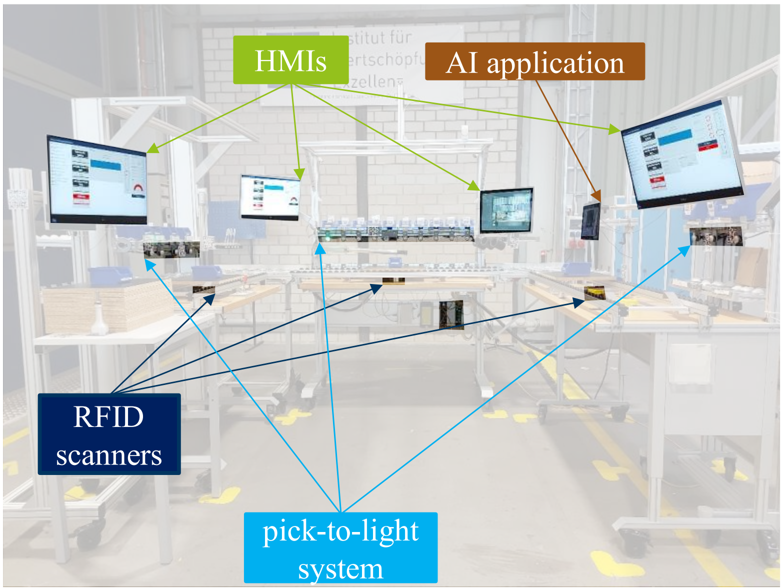


Figure 4: Hardware infrastructure of the UniLokk assembly line with HMIs, pick-to-light system, AI application and RFID scanners

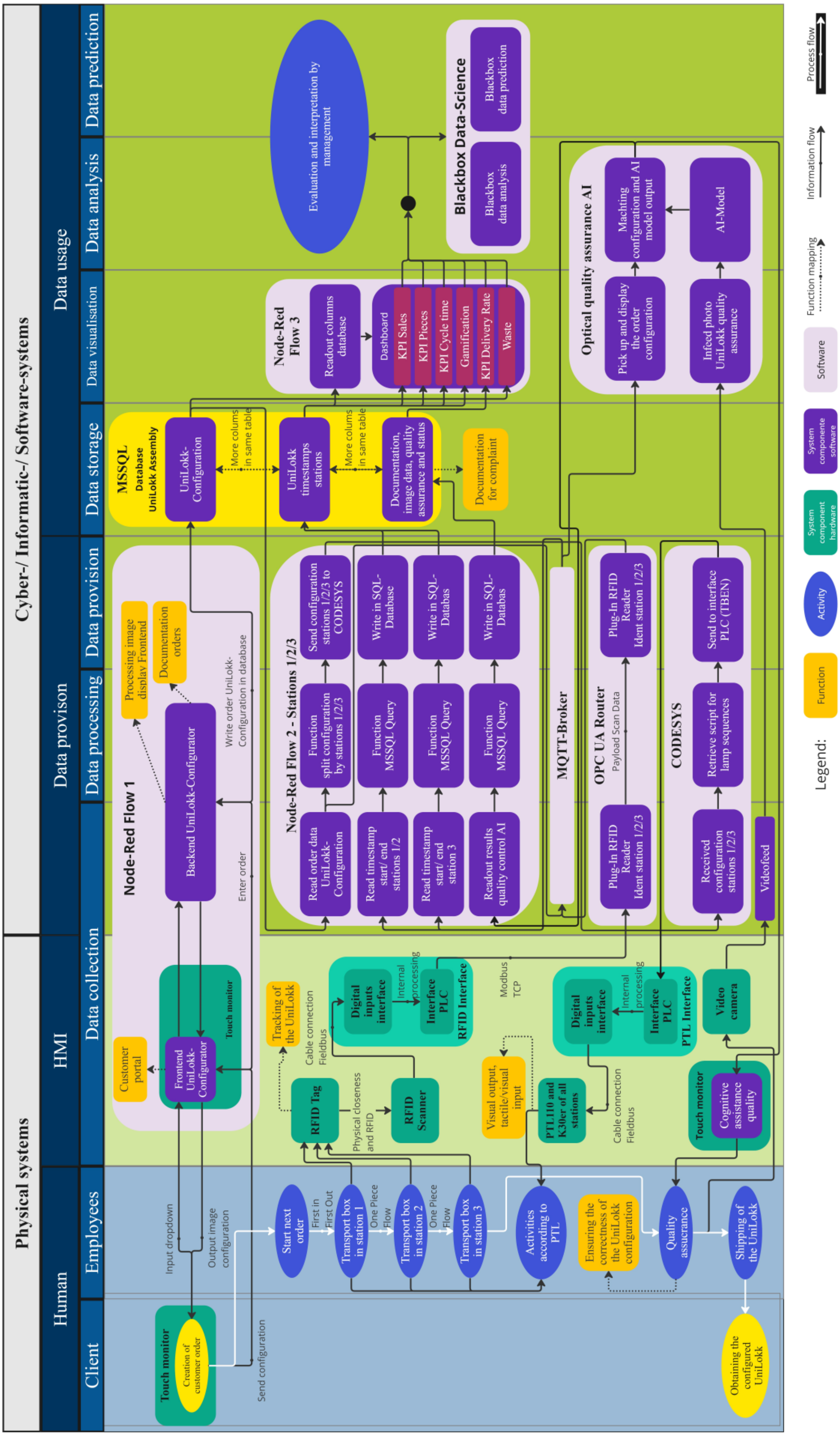


Figure 5: Detailed planning of a digital data consistency

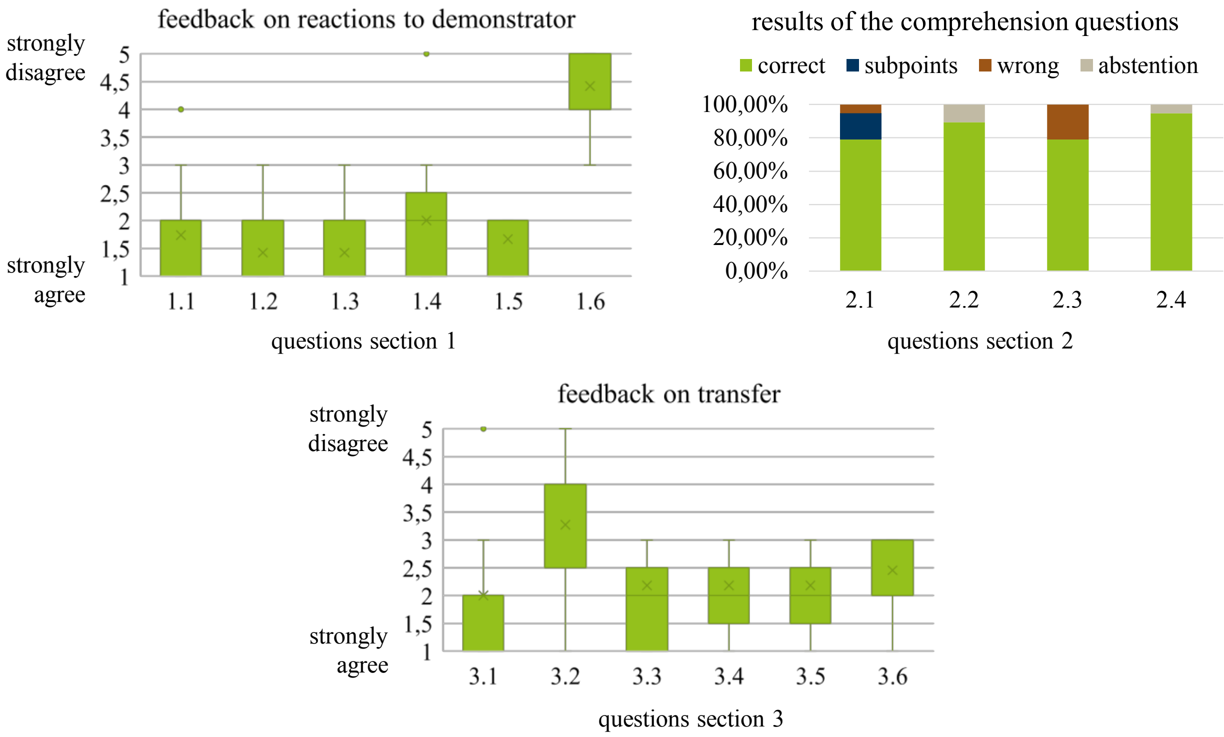


Figure 6: Results of the survey (section 1: n = 19; section 2: n = 19; section 3: n = 16)

References

[1] Bauernhansl, T., Krüger, J., Reinhart, G., Schuh, G., 2016. WGP-Standpunkt Industrie 4.0.

[2] Joppen, R., Enzberg, S. von, Gundlach, J., Kühn, A., Dumitrescu, R., 2019. Key performance indicators in the production of the future. Procedia CIRP 81, 759–764.

[3] Bundesministerium für Wirtschaft und Klimaschutz, 2022. Digitalisierung der Wirtschaft in Deutschland: Digitalisierungsindex 2021.

[4] Mittelstand-Digital Zentrum Ilmenau. Demonstratoren bei Mittelstand-Digital. https://demonstratoren.gfe-net.de/demonstrator. Accessed 11 July 2023.

[5] Alexander Kaluza, M. Juraschek, Benjamin Neef, Reinhard Pittschelllis, G. Posselt, S. Thiede, C. Herrmann, 2015. Designing Learning Environments for Energy Efficiency through Model Scale Production Processes. Procedia CIRP 32, 41–46.

[6] Keaveney, S., Athanasopoulou, L., Siatras, V., Stavropoulos, P., Mourtzis, D., Dowling, D.P., 2021. Development and Implementation of a Digital Manufacturing Demonstrator for Engineering Education. Procedia CIRP 104, 1674–1679.

[7] Weyand, A., Seyfried, S., Gosch, B., Fuhrländer-Völker, D., Panten, N., Abele, E., 2020. Method for transforming energy and production systems into mobile demonstrators. Procedia Manufacturing 45, 134–139.

[8] Louw, L., Walker, M., 2018. Design and implementation of a low-cost RFID track and trace system in a learning factory. Procedia Manufacturing 23, 255–260.

[9] Tisch, M., Hertle, C., Abele, E., Metternich, J., Tenberg, R., 2016. Learning factory design: a competency-oriented approach integrating three design levels. International Journal of Computer Integrated Manufacturing 29 (12), 1355–1375.

[10] Prinz, C., Kreimeier, D., 2019. Best Practice Example 21: LPS Learning Factory at LPS, Ruhr-Universität Bochum, Germany, in: Abele, E., Metternich, J., Tisch, M. (Eds.), Learning Factories. Springer International Publishing, Cham, pp. 412–416.

[11] Cachay, J., Wennemer, J., Abele, E., Tenberg, R., 2012. Study on Action-Oriented Learning with a Learning Factory Approach. Procedia - Social and Behavioral Sciences 55, 1144–1153.
[12] Kreß, A., Hummel, V., Ahmad, R., Hulla, M., Quadrini, W., Callupe, M., Gärtner, Q., Weyand, A., Barth, J., Riemann, T., Fumagalli, L., Ramsauer, C., Metternich, J., 2023. Revision of the Learning Factory Morphology. Proceedings of the 13th Conference on Learning Factories (CLF2023).
[13] Abele, E., Metternich, J., Tisch, M., 2019. Learning Factories. Springer International Publishing, Cham, 474 pp.
[14] Bundesministerium für Wirtschaft und Klimaschutz, 2022. Mittelstand-Digital: Unterstützung bei der digitalen Transformation im Mittelstand.
[15] Marvin Ehrhardt, Jan Felix Niemeyer, Mark Mennenga, Christoph Herrmann. Mobile Teaching & Training Platform to support Sustainability in SMEs.
[16] Abele, E., Metternich, J., Tisch, M., Chryssolouris, G., Sihn, W., ElMaraghy, H., Hummel, V., Ranz, F., 2015. Learning Factories for Research, Education, and Training. Procedia CIRP 32, 1–6.
[17] Kreß, A., Wuchterl, S., Metternich, J., 2021. Design approaches for learning factories - review and evaluation. SSRN Electronic Journal.
[18] Thiede, S., Juraschek, M., Herrmann, C., 2016. Implementing Cyber-physical Production Systems in Learning Factories. Procedia CIRP 54, 7–12.
[19] Oks, S.J., Jalowski, M., Fritzsche, A., Möslein, K.M., 2019. Cyber-physical modeling and simulation: A reference architecture for designing demonstrators for industrial cyber-physical systems. Procedia CIRP 84, 257–264.
[20] Kirckpatrick, J.D., Kayser Kirckpatrick, W., 2016. Kirckpatrick's Four Levels of Training Evaluation. ATD Press, 238 pp.
[21] Tisch, M., Hertle, C., Metternich, J., Abele, E., 2014. Lernerfolgsmessung in Lernfabriken - Kompetenzorientierte Weiterentwicklung praxisnaher Schulungen. Industrial Management 30 (3), 20–24.
[22] Anderson, L.W., Krathwohl, D.R., Airasian, P.W., Cruikshank, K.A., Mayer, R.E., Pintrich, P.R., Raths, J., Wittrock, M.C., 2001. A Taxonomy for Learning, Teaching and Assessing: A Revision of Bloom's Taxonomy of Educational Objectives. Longman, New York.
[23] Verein Deutscher Ingenieure e.V., 00.2011. Factory planning - Planning procedures. Beuth Verlag GmbH, Berlin 03.100.99, 24 pp.
[24] Kulessa, P., Boshoff, M., Kuhlenkötter, B., 2022. Cobot-Technologien in der Montage. Industrial Production Bd 2022, 46–47.
[25] Linsinger, M., Sudhoff, M., Lemmerz, K., Glogowski, P., Kuhlenkötter, B., 2018. Task-based Potential Analysis for Human-Robot Collaboration within Assembly Systems, in: Schüppstuhl, T., Franke, J., Tracht, K. (Eds.), Tagungsband des 3. Kongresses Montage Handhabung Industrieroboter. Springer Vieweg, Berlin, Heidelberg, pp. 1–12.
[26] Oberc, H., Fahle, S., Prinz, C., Kuhlenkötter, B., 2020. A Practical Training Approach in Learning Factories to Make Artificial Intelligence Tangible. Procedia CIRP 93, 467–472.
[27] G. Schuh, R. Anderl, R. Dumitrescu:A. Krüger:M. ten Hompel, 2020. Industrie 4.0 Maturity Index. Die digitale Transformation von Unternehmen gestalten – UPDATE 2020 – (acatech STUDIE). acatech – Deutsche Akademie der Technikwissenschaften.
[28] Wang, C.-Y., Bochkovskiy, A., Liao, H.-Y.M., 2022. YOLOv7: Trainable bag-of-freebies sets new state-of-the-art for real-time object detectors, 15 pp. http://arxiv.org/pdf/2207.02696v1.
[29] Bega, M., Sapel, P., Ercan, F., Schramm, T., Spitz, M., Kuhlenkötter, B., Hopmann, C., 2023. Extension of value stream mapping 4.0 for comprehensive identification of data and information flows within the manufacturing domain. Prod. Eng. Res. Devel.

Biography

Marius Knott (*1993) has been working as a research assistant at the Chair of Production Systems (LPS) at the Ruhr-University Bochum since 2020 in the field of production management. He earned a master's degree in mechanical engineering at the Ruhr-University Bochum. His primary research topic is the development of LFs and assumes the role of coordinator for the LPS' learning and research factory.

Tobias Schmelter (*1996) has been working as a research assistant at the Chair of Production Systems (LPS) at the Ruhr-University Bochum since 2020 in the field of production digitalisation. He earned a master's degree in mechanical engineering at the Ruhr-University Bochum. His main fields of activity are the implementation of AI in SMEs and basic research in the field of shape memory alloys.

Tom Nowak (*1997) has been working as a research assistant at the Chair of Production Systems (LPS) at the Ruhr-University Bochum since 2022 in the field of production digitalisation. He earned a master's degree in mechanical engineering at the Ruhr-University Bochum. His primary research topics are adaptive systems for personalized learning and applied machine learning algorithms with a focus on computer vision.

Christopher Prinz (*1985) studied mechanical engineering at the Ruhr-University Bochum. After receiving his doctorate in 2018 on the topic of knowledge management in production, he was named Academic Advisor at the Chair of Production Systems (LPS). As part of the chair management, he is responsible for the strategic development of the chair and the initiation and control of research projects.

Until 2009 **Bernd Kuhlenkötter** (*1971) was responsible for product management and technology at ABB Robotics Germany. In 2009 Bernd Kuhlenkötter took over the professorship for "Industrial Robotics and Production Automation" at the Technical University of Dortmund. Since 2015 he holds the professorship of the Chair of Production Systems (LPS) at the Ruhr-University Bochum and is managing director of the Institute for the Engineering of Smart-Product Service Systems.

5th Conference on Production Systems and Logistics

Method For Semi-Automated Improvement Of Smart Factories Using Synthetic Data And Cause-Effect-Relationships

Vera Hummel[1,2], Jan Schuhmacher[1]

[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

Abstract

Smart factories, driven by the integration of automation and digital technologies, have revolutionized industrial production by enhancing efficiency, productivity, and flexibility. However, the optimization and continuous improvement of these complex systems present numerous challenges, especially when real-world data collection is time-consuming, expensive, or limited. In this paper, we propose a novel method for semi-automated improvement of smart factories using synthetic data and cause-effect-relations, while incorporating the aspect of self-organization. The method leverages the power of synthetic data generation techniques to create representative datasets that mimic the behaviour of real-world manufacturing systems. These synthetic datasets serve together with the cause-and-effect relationships as a valuable resource for factory optimization, as they enable extensive experimentation and analysis without the constraints of limited or costly real-world data. Furthermore, the method embraces the concept of self-organization within smart factories. By allowing the system to adapt and optimize itself based on feedback from the synthetic data, cause-effect-relationships, the factory can dynamically reconfigure and adjust its processes. To facilitate the improvement process, the method integrates the synthetic data with advanced analytics and machine learning algorithms as well as and the cause-and-effect relationships. This synergy between human expertise and technological advancements represents a compelling path towards a truly optimized smart factory of the future.

Keywords

Smart factories; synthetic data; cause-and-effect relationships; semi-automated improvement; self-organization; data-driven decision-making

1. Introduction

Globalized customer markets require companies to adapt to small production batch sizes and rapidly changing demands. Short innovation, technology, and product life cycles, as well as the need for cost-effective customized products, call for reconfigurable process paths [1], [2]. Smart, self-organized factories offer the potential to achieve flexible and adaptive production processes to solve arising problems in factory environments dealing with dynamic and rapidly changing boundary conditions and increasing complexity [3]. Self-organized factories are capable to perform a target-oriented (re-)structuring of the factory system to adapt to changing conditions without the need for a higher (hierarchical) decision-making level [4], [5]. To carry out these adaptations, autonomously acting system elements in the subsystems (like semi-autonomous working groups in assembly or autonomously mobile workstations) are necessary, which allow a targeted-oriented self-adjustment to enable an adaptation of the subsystem [6], [7]. The concepts of self-organization and autonomous control are closely linked to each other [5]. Self-organization deals with the

DOI: https://doi.org/10.15488/15310
ISSN: 2701-6277
publish-Ing.

autonomous emergence of ordered structures in dynamic, complex systems. It refers to the way in which order emerges from within a system and a system designs processual and systemic structures by itself [5], [8]. Autonomous control describes, in particular, processes of decentralized decision-making in heterarchical structures on the execution level [9], [10].

In a smart factory, interconnected manufacturing processes use data processing for early improvements. The continuous improvement process (CIP) includes problem analysis, solution generation, implementation, and checking, leading to new standards [11]. The philosophy behind CIP is proactive, using employee expertise to prevent problems and achieve significant improvements through continuous small changes over time. The analysis of product, process and factory data of including historical data combining with cause-effect relationships enables the identification of measures to achieve or even exceed defined production target dimensions by a semi-automatic improvement process using the self-organization capabilities.

2. Analysis of the state of science

To set the theoretical base the state of science in the fields of continuous improvement of smart factories, synthetic data generation, data analytics and cause-and-effect relationship analysis is examined.

2.1 Continuous improvement of smart factories

The continuous improvement process (CIP) involves small improvements in small steps and is one of the tools of lean management [12], [13]. In contrast to innovation, which is a top-down approach, CIP involves the employees [12]. In traditional CIP, digital tools assist processes, with improvement measures drawn from human expertise, promoting cross-functional collaboration among employees from various departments.

In the last decade a number of advanced digital technologies known as Industrie 4.0 were developed, which offer new approaches to managing complexity and improving productivity [14]. Integrating digital technologies in Industrie 4.0 with established lean management principles like CIP can optimize processes by enhancing transparency, networking, and automation, offering companies substantial potential. A study by BearingPoint [15] shows that the successful use of Lean Management 4.0 varies greatly depending on the industry. In a study of 50 manufacturing companies, 72% of decision-makers acknowledged the potential of lean management and digitalization for optimizing business processes. However, most companies are still in the early stages of implementing digital technologies within lean management methods [15]. There is also a trend towards developing tools that autonomously perform data analysis without human assistance [16]. Existing approaches (I) use especially human-based knowledge and experience for a manual or semi-automated transfer to new problems or (II) require large amounts of real data for an automated process using advanced analytics or machine learning to identify patterns [17], [18].

2.2 Synthetic data generation

Synthetic data is used when real data is challenging to access, lacks detail or scale, or is incomplete [19]. The three primary categories of synthetic data include dummy data, rule-based generated synthetic data, and synthetic data generated using artificial intelligence [20].

Dummy data, often made with a mock data generator, is randomly generated and lacks the characteristics, relationships, and statistical patterns of the original data, making it unrepresentative of the actual data [20]. Rule-based generated synthetic data, on the other hand, is produced by defining specific rules for data generation, which can be achieved using simulation tools [20], [21]. Within the realm of data farming, simulation methods are utilized to generate and analyse synthetic data to gain targeted insights [22], [23]. Rule-based synthetic data generation relies on precisely defining all features, relationships, and statistical patterns, with the quality of the generated data depending on the accuracy of the predefined rules, making it valuable when real data is unavailable [20]. Using artificial intelligence algorithms, synthetic data can be generated by training an AI model with real data to learn its features, relationships, and statistical patterns, and then the model creates entirely new data points that mimic the characteristics of the original dataset [20].

2.3 Data analytics

Data analytics is the scientific process of mathematically and logically transforming historical data into insights to explain the past and to achieve better future decision-making [24], [25]. With increasing maturity of analytical skills, descriptive (*What happened?*), diagnostic (*Why did it happen?*), predictive (*What will happen (with which probability)?*) and prescriptive analytics (*How can we make it happen?*) are distinguished, which all build on each other [24], [25], [26]. The starting point for analysis is set by the descriptive analytics by analysing what has happened based on statistics and instruments such as tables and charts organizing, summarizing and visualizing data [24], [27]. After descriptive analytics, diagnostic analytics is used to uncover patterns, root causes, and connections among attributes. It employs data-driven machine-learning algorithms like k-means clustering [24]. Diagnostic analytics analyses attribute correlations and interactions, such as process errors' influences and root causes of process time delays. In the predictive analytics step, methods and models are utilized to forecast errors and disruptions based on identified patterns within the dataset [24], [25]. In the final step of prescriptive analytics, simulation and optimization approaches are employed to positively impact the future by making targeted decisions, such as optimizing assembly processes to prevent errors like incorrectly mounted or forgotten components.

2.4 Cause-and-effect relationships (CER)

This work utilizes cause-and-effect relationships to identify interrelationships in a product lifecycle and improve production semi-automatically. These relationships indicate connections between variables, where changes in one variable cause changes in others, and genuine connections, rather than just close links, must be ensured during the identification process [24]. One process that builds on cause-and-effect relationships is quality problem-solving (QPS), which is used in the manufacturing industry. This process consists of problem definition, problem analysis, cause identification, solution generation and selection, and solution implementation and testing [28]. The data that exists in a QPS system includes the problem, the causes, different types of solutions and a solution evaluation. If the problems and causes are represented graphically, the result is a bipartite graph [29].

3. Research Method

The procedure of this work is based on Österle's Design Science Research [30] with a focus on a practice-oriented research approach. The work begins with an analysis phase using mixed literature analysis, including snowballing, to establish theoretical foundations, analyse and evaluate literature aspects, and identify CER in a product lifecycle along with relevant data types. In the draft phase, the method is created based on the part solutions, generating synthetical data, CERs, data streams and fundamentals from literature as well as research already carried out. The verification was done against the requirements based on use case 1 for the suitability of the synthetically generated data. The validation to prove the achievement of the goal for application of the developed method was partly done by the use case 2 for a smart product and production.

4. Development of the method for semi-automated improvement of smart factories

The continuous improvement process (CIP) involves small improvements in small steps and is based on a bottom-up approach. The idea of developing this innovative method to enrich the CIP is based exactly on this principle, using operational data (bottom) and constantly processing it to make new improvements for the whole (top) factory system. The enrichment of the CIP (see Fig. 1) with AI in the PLAN segment of "problem/potential analysis" uncovers hidden relationships between variables, enabling early detection of problems or opportunities. If detailed data is unavailable, synthetic data generation methods may be used. CER are then established through diagnostic analytics to analyse the production system [27].

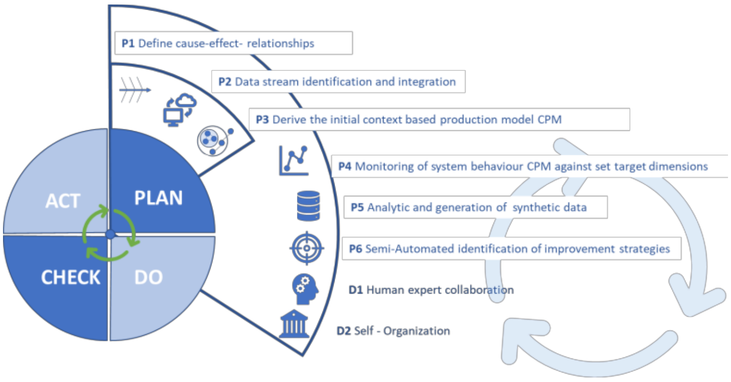


Figure 1: Enriched Continuous Improvement Process

The semi-automated measure generation through cause-and-effect relationships can contribute to increasing the efficiency of the CIP through digitalization. The partial solutions described below have been combined into a comprehensive method for semi-automated improvements. Smart factories, powered by data and AI, revolutionize industrial processes, boosting productivity and efficiency. To optimize them, a deeper understanding of cause-effect relationships is essential to spot potential improvements. Therefore, we propose a novel method that uses synthetic data and cause-effect relationships to create a production model for semi-automated improvements in smart factories (see Fig. 1).

The comprehensive method consists of: (P1) Utilizing Cause-Effect Relationships: Analysing critical factors in the smart factory environment; (P2) Implementation and Data Stream Integration: Testing improvement strategies in the real factory using continuous data streams; (P3) Development of a Context-Based Production Model: Building a comprehensive simulation model considering cause-effect-Relationships and the data streams; (P4) Monitoring of System Behaviour: Regularly observing and evaluating the production system against target dimensions for continuous improvement; (P5) Analytic and Generation of Synthetic Data: Using synthetic data to expand the data pool and conduct experiments safely; (P6) Semi-Automated Improvement Strategies: Employing AI algorithms to identify potential improvement strategies; (D1) Human Expert Collaboration: Factory personnel collaborate with AI to validate improvement strategies and (D2) Self-Organization: Enabling factories to autonomously adjust their structures and processes for optimal efficiency and adaptability.

4.1 Synthetic data generation

Synthetic data generation involves creating artificial data that resembles real-world data while excluding personally identifiable information or sensitive content. The main goal is to expand the dataset while retaining the statistical properties and patterns of the original data through methods like simulation studies. Following VDI 3633 seven steps have to be considered to perform a simulation study [31]. The procedure involves task definition, systems analysis, model formalization, implementation, simulation experiments, and result analysis. In this research the cause-effect-diagrams as well as the data streams will be used to formalize the model of the respective production system. Parallelly the phases of data collection and data preparation have to be considered. According to VDI 3633 [31], the mapping accuracy of the model should not be as detailed as possible, but as detailed as required to meet the specific objective.

For generating synthetical data a first minimal system model based structurally and process-wise on a real work system for the assembly of a product at Werk150, such as the MIMB box (see use cases 1 and 2), was designed and implemented [32], [33]. The major steps of the simulation study, including preparation, model implementation, and synthetic data generation as well as the results are described in chapter 5.1.

4.2 Cause-and-effect relationships

4.2.1 Development procedure of cause-and-effect relationships in general

The process for identifying and analysing problems and causes using Cause-and-Effect Diagrams (CED) and Detailed Cause-and-Effect Diagrams (DCED) are shortly described [29]. The first step involves identifying problems and causes through brainstorming and personal experience. Then, these problems and causes are clustered to prepare for the CED. The CED is created by categorizing main cause branches and identifying all possible causes. Causes are classified and analysed to understand their impact on the problem. The two-way relationship between problem class and cause class is determined based on predefined correlations and clustering. The DCED (Detailed Cause-Effect-Diagram) differs from the ACED (Abstract Cause-Effect-Diagram) as it only clusters problems [29]. The generation of a DCED is shown in Fig. 2. This process can be used to identify interrelationships in a product lifecycle, investigate potential problems and causes, and develop solutions. By understanding these interrelationships, processes can be derived to improve information flow and implement effective solutions, leading to problem elimination and prevention.

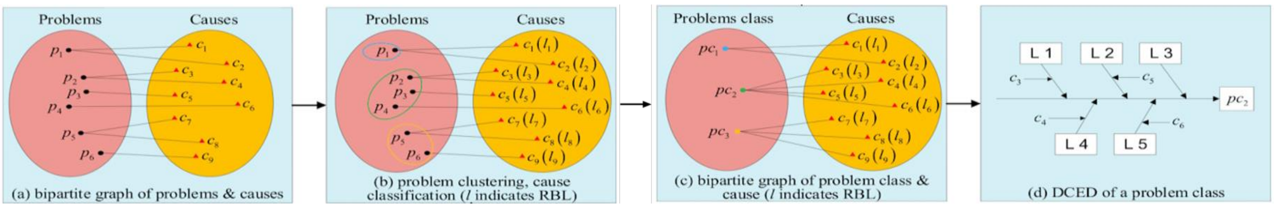


Figure 2: Generation of a DCED [29]

4.2.2 Definition of cause-and-effect relationships in process engineering and production

Based on literature [28], [30], [31], [32], [33], [34], [35], [36] and the above-described method Schnabel [37] defined cause-effect relationships for the process engineering as well as for production, structured them into classes, documented them into detailed cause-and-effect diagrams (see Fig. 3) for defined problem and challenge classes [38]. Both will be used for the design of the context production model CPM.

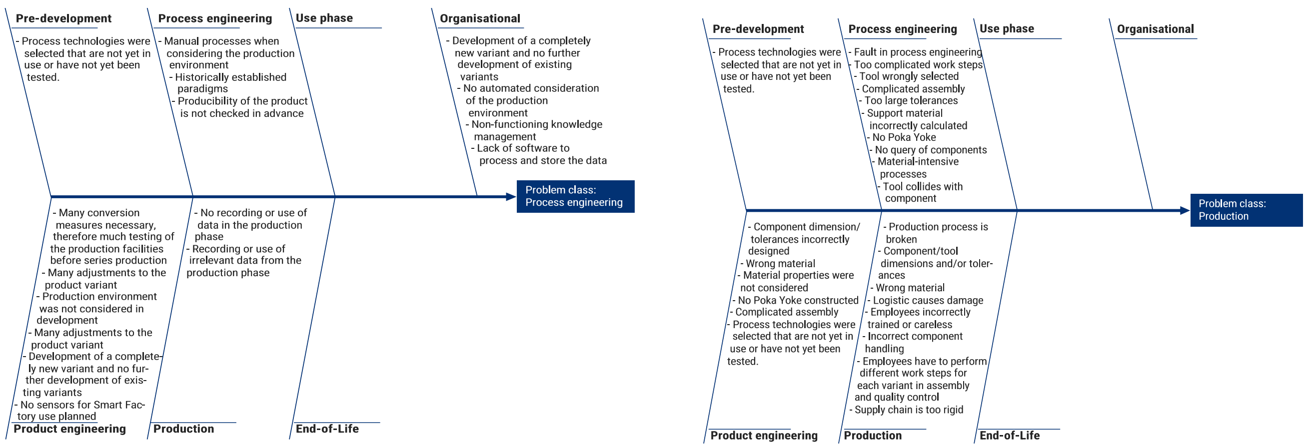


Figure 3: Cause-and-effect-diagram for problem class "process engineering" and “production” [37]

4.3 Data streams in process engineering and production

To identify relevant data in the product lifecycle, particularly for process engineering and production, the procedure developed by Günther et al. [39] is employed. Process analyses are recommended to identify relevant influencing factors and problem sources. Cause-and-effect relationships are used to create an overview of data streams in the product lifecycle. Relevant data sources are selected and evaluated based on criteria, including relevance, reliability, availability, data stream characteristics, and customer data security. In the next step additionally required data sources are determined based on systems’ requirements [37]. The relevant data type was assigned to the product life cycle phase and as input data required or as output generated. The integrated product engineering model (iPeM) [38] with the main phases pre-development, product engineering, process engineering, production, usage and end of life builds the basis. During process engineering, product data from previous phases and subsequent generations is utilized. This includes information on product properties, production capability factors, production processes, quality data, use phase data, and remanufacturing processes. In the production phase, data from product and process engineering is essential. To achieve continuous improvement, processes must be implemented based on data collected during series production, following the concept of self-organization. The data types developed are described and documented in Schnabel [37].

5. Validation

Validation is the process of checking whether the proposed solution meets the expected objectives. Verification (UC1) is to check if the requirements for the usage of the synthetically generated data are fulfilled. Here, the correctness of the overall result is validated [40]. To reuse the partial solution for future challenges, validation tests with use cases (see Fig. 4, UC2 and UC3) that interconnect on each other were built.

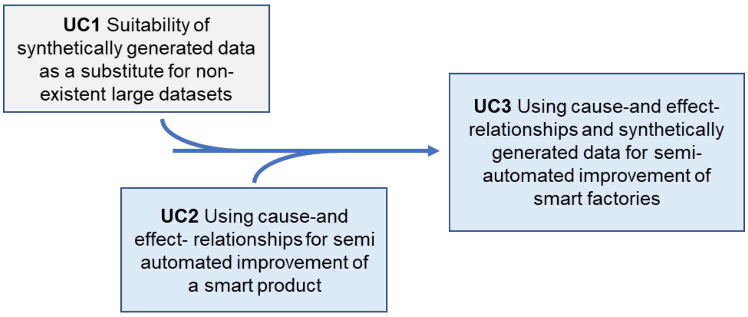


Figure 4: Verification and Validation approach

The chosen method for validation is experimentation where a specific assumption or conjecture is validated in a practice-oriented investigation.

5.1 Use case 1: Synthetic data generation

Use case 1 dealt with the investigation of the suitability of synthetically generated data of production and process data of a defined minimal system (see Fig. 5) with reduced structural complexity for a data-driven prediction of turbulence events and their effects on process and throughput times [33].

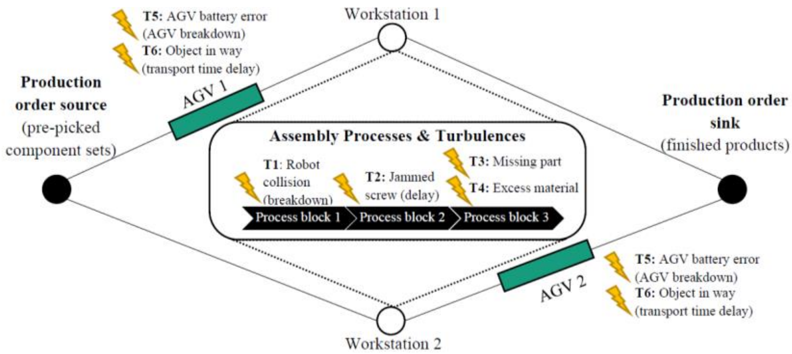


Figure 5: Defined minimal system with turbulence events (T) [33]

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 which are supplied with pre-picked component sets from the warehouse via automated guided vehicles (AGV). For the generation of the synthetic data set a rule-based simulative approach has been applied, since no real data on production systems' internal turbulences was available, but the effects of the turbulences on the production system was known. The simulation study to generate the synthetic data has been done following the procedure of VDI 3633 [31]. For the modelling of the defined minimal system, a multi-method simulation with agent-based modelling of the transport resources' autonomous behaviour and event-oriented modelling of the turbulence scenarios with stochastic turbulence events has been applied using the simulation tool AnyLogic. Detailed information about the considered turbulences, turbulence attributes, and considered data, values and distributions as well as about the entire simulation study can be found in Schuhmacher [33]. For the investigation of suitable data-driven prediction methods the generated 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. The considered 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) have been compared in terms of prediction accuracy for the respective turbulence, standard deviation and computation time. Based on this use case it has been shown and validated that a data-driven, probabilistic prediction can be achieved through a simulative generation of synthetic data. To transfer the identified potentials of the synthetic data generation to higher-level questions of the CIP despite the lack of real data, the developed "Enriched Continuous Improvement Process" (see Fig. 1) will be applied. By building up a simulation model (phase P3), monitoring the system behaviour (phase P4), generating and analysing the synthetic data (phase P5) a semi-automated identification of improvement strategies (phase P6) to reach the set targets should be achieved, incorporating expert knowledge of the employees (phase D1).

5.2 Use case 2: Using CER for semi-automated improvement of a smart product

The use case 2 was carried out in the smart factory Werk150, the factory of the ESB Business School on the Campus of the Reutlingen university as part of a comprehensive research project [37]. The Werk150 is a research and education environment with innovative industrial digital engineering and physical manufacturing infrastructure, a so called "Industry 4.0 Factory". Werk150 is a research environment where the latest production and logistics technologies are developed and represent a state-of-the-art CPS production system. To develop and test technologies a city scooter and a modular, intelligent mobility box is manufactured [32]. To define the limitations of the use case 2 the system to be investigated is described according to [41]. In this validation, the system to be examined is a product, which is developed with the i2PLM see [37]. The input variables that can be changed are in the engineering phase the construction of the product depending on use phase data. In the production phase, the 3D printing parameters can be adjusted based on the product quality data. The input variables which are non-changeable are the material of the product and the production process, with its work steps.

Figure 6: Smart lunchbox

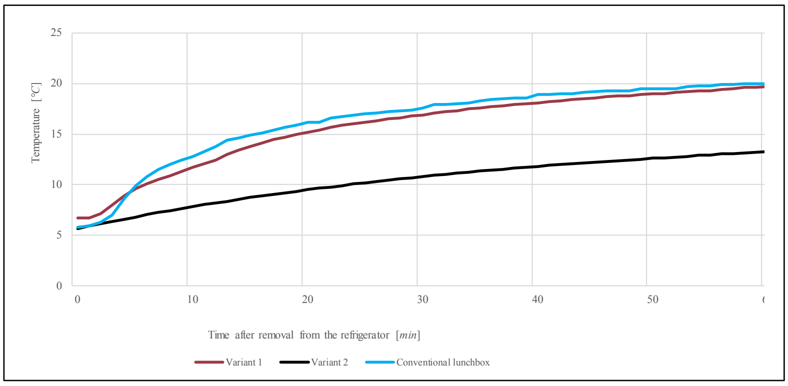


Figure 7: Temperature curve comparison of smart lunchbox Variant 1 and 2

The modular intelligent mobility box (MIMB) by Werk150 is a smart product (see Fig.6), with sensors for data storage and analysis. It connects to a network for data transmission and includes a 3D-printed top and bottom, a temperature and humidity sensor, data gateway, and velcro. The lunchbox's use case is to keep chilled food fresh during the commute, maintaining the temperature below 15 °C for one hour after removal from the refrigerator, with the sensor monitoring the internal temperature. The procedure for the experiment is based on the processes of the i²PLM and is shown in Fig. 8. In Variant 1 the lunchbox is already developed, and the process engineering has already been carried out. This is followed by the production of the lunchbox in Werk150 where data is generated on the quality characteristic. The product is used by experiment participants in the use phase where temperature data is generated while carrying out the use cases. These data are converted into a temperature curve which flows into a cause- and effect-relationship (CER) and triggers product and production changes for the subsequent generation (Variant 2). Variant 2 is a customized lunchbox. The changes in the product engineering of Variant 2 are mainly incorporated by changing the wall thickness, as this significantly influences the temperature curve on the product side. In process engineering, new requirements result in changes of 3D printing properties. Subsequently, the product is engineered, produced, and used and the same data types are recorded to validate product improvements.

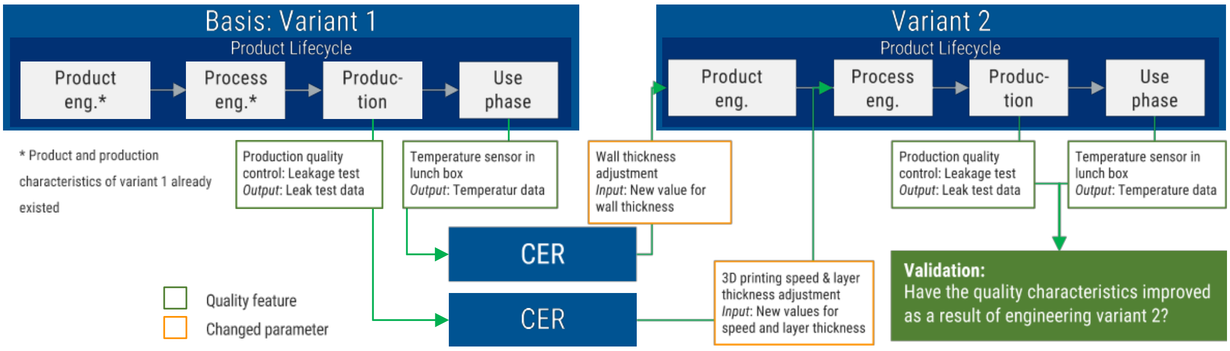


Figure 8: Schematic diagram of the experiment procedure

The results from production quality control are that Variant 2 is in contrast to Variant 1 leak-proof, and in addition, the surface is smoother, and the rework effort of the 3D printing is reduced. In the use phase, temperature curves are generated by 36 users and shown in the diagram in Fig. 7. The average temperature curve of Variant 1 is shown with a dotted line and Variant 2 with a solid line. Variant 2 meets the required temperature after one hour with 13.2 °C and improved by 6.5 °C compared to Variant 1. Improvements occurred in the product properties, as well as in the production time and quality. Use case 2 proofed that using the CER combined with the data streams the semi-automatic provision of the improvement potentials work in this use case quite well and will be the basis for the use case 3 for the validation of the comprehensive methods as presented in this paper.

6. Conclusion and outlook

The developed novel method for semi-automated improvement of smart factories using synthetic data and cause-effect relationships presents a promising approach to enhancing production efficiency and productivity. Both use cases have separately proven that the objective can be achieved. By leveraging the power of artificial intelligence, synthetic data, and cause-effect insights, factories can achieve intelligent decision-making and drive continuous improvements in their operations. The next steps for use case 3 (see Fig. 4) will involve the combined and integrated use of cause-and-effect-relationships and synthetically generated data for the semi-automated improvement of smart factories on the example of the complete production system of Werk150 to prove the path towards a truly optimized factory of the future. This will lead to deeper insights on the potentials and limitations of using synthetic data and cause-effect relationships for the semi-automated improvement of smart factories.

References

[1] Shi, Z., Xie, Y., Xue, W., Chen, Y., Fu, L., Xu, X., 2020. Smart factory in Industry 4.0. Syst Res Behav Sci 37 (4), 607–617.

[2] Arnold, C., Kiel, D., Voigt, K.-I., 2017. Innovative Business Models for the Industrial Internet of Things. Berg Huettenmaenn Monatsh 162 (9), 371–381.

[3] Hozdić, E., 2015. Smart factory for industry 4.0: A review. International Journal of Modern Manufacturing Technologies 7 (1), 28–35.

[4] Stock, D., Bauernhansl, T., Weyrich, M., Feurer, M., Wutzke, R., 2020. System Architectures for Cyber-Physical Production Systems enabling Self-X and Autonomy, in: 2020 25th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA). 2020 25th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), Vienna, Austria. 08.09.2020 - 11.09.2020. IEEE, pp. 148–155.

[5] Schuhmacher, J., Hummel, V., 2020. Development of a catalogue of criteria for the evaluation of the self-organization of flexible intralogistics systems. Procedia CIRP 93, 832–837.

[6] Wehberg, G.G. von, 2016. Logistik 4.0 – die sechs Säulen der Logistik in der Zukunft, in: Göpfert, I. (Ed.), Logistik der Zukunft - Logistics for the Future. Springer Fachmedien Wiesbaden, Wiesbaden, pp. 319–344.

[7] Holland, J.H., 2002. Complex Adaptive Systems and Spontaneous Emergence, in: Curzio, A.Q., Fortis, M. (Eds.), Complexity and Industrial Clusters. Dynamics and Models in Theory and Practice. Physica-Verlag HD, Heidelberg, pp. 25–34.

[8] Vec, M. (Ed.), 2006. Selbstorganisation: Ein Denksystem für Natur und Gesellschaft. Böhlau, Köln, 447 pp.

[9] Philipp, T., de Beer, C., Windt, K., Scholz-Reiter, B., 2007. Evaluation of Autonomous Logistic Processes – Analysis of the Influence of Structural Complexity, in: Windt, K., Hülsmann, M. (Eds.), Understanding autonomous cooperation and control in logistics. The impact of autonomy on management, information, communication and material flow. Springer, Berlin, New York, pp. 302–324.

[10] Windt, K., Hülsmann, M. (Eds.), 2007. Understanding autonomous cooperation and control in logistics: The impact of autonomy on management, information, communication and material flow. Springer, Berlin, New York, 417 pp.

[11] Klanitz, T., 2023. Kontinuierlicher Verbesserungsprozess (KVP). REFA AG. https://refa.de/service/refa-lexikon/kontinuierlicher-verbesserungsprozess-kvp. Accessed 24 October 2023.

[12] Helmold, M., 2021. Kaizen, Lean Management und Digitalisierung. Springer Fachmedien Wiesbaden, Wiesbaden.

[13] Ohno, T., 1988. Toyota production system: Beyond large-scale production. Productivity Press, Cambridge, Mass., 143 pp.

[14] Bauernhansl, T., 2017. Die Vierte Industrielle Revolution – Der Weg in ein wertschaffendes Produktionsparadigma, in: Vogel-Heuser, B., Bauernhansl, T., Hompel, M. ten (Eds.), Handbuch Industrie 4.0 Bd.4. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 1–31.

[15] Kettler, D., König, C., 2017. Lean 4.0 – Schlank durch Digitalisierung. BearingPoint. https://www.bearingpoint.com/files/Studie_Lean_4.0_Schlank_durch_Digitalisierung.pdf. Accessed 2 October 2023.

[16] Oztemel, E., Gursev, S., 2020. Literature review of Industry 4.0 and related technologies. J Intell Manuf 31 (1), 127–182.

[17] Yska, S., Bustos, D., Guedes, J.C., 2023. Machine Learning Applications for Continuous Improvement in Integrated Management Systems: A Short Review, in: Arezes, P.M., Baptista, J.S., Melo, R.B., Castelo Branco, J., Carneiro, P., Colim, A., Costa, N., Costa, S., Duarte, J., Guedes, J.C., Perestrelo, G. (Eds.), Occupational and Environmental Safety and Health IV, vol. 449. Springer International Publishing, Cham, pp. 541–551.

[18] Mjimer, I., Aoula, E.-S., Achouyab, E.H., 2023. Contribution of machine learning in continuous improvement processes. JQME 29 (2), 553–567.

[19] Mannino, M., Abouzied, A., 2019. Is this Real?, in: Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology. UIST '19: The 32nd Annual ACM Symposium on User Interface Software and Technology, New Orleans LA USA. 20 10 2019 23 10 2019. ACM, New York, NY, USA, pp. 549–561.

[20] Syntho, 2022. Was sind synthetische Daten? Syntho. https://www.syntho.ai/de/what-is-synthetic-data/. Accessed 24 October 2023.

[21] AnyLogic, 2023. Synthetic data generation. AnyLogic. https://www.anylogic.de/features/artificial-intelligence/synthetic-data/. Accessed 21 October 2023.

[22] 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.

[23] Sanchez, S.M., 2020. Data Farming. ACM Transactions on Modeling and Computer Simulation 30 (4), 1–30.

[24] 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.

[25] Schuh, G., Blum, M., Reschke, J., Birkmeier, M., 2016. Der Digitale Schatten in der Auftragsabwicklung. ZWF 111 (1-2), 48–51.

[26] Gartner, Inc., 2014. Gartner Says Advanced Analytics Is a Top Business Priority. Gartner, Inc. https://www.gartner.com/en/newsroom/press-releases/2014-10-21-gartner-says-advanced-analytics-is-a-top-business-priority. Accessed 24 October 2023.

[27] Olson, D.L., Lauhoff, G., 2019. Descriptive Data Mining, 2nd ed. 2019 ed. Springer, Singapore, 130 pp.

[28] MacDuffie, J.P., 1997. The Road to "Root Cause": Shop-Floor Problem-Solving at Three Auto Assembly Plants. Management Science 43 (4), 479–502.

[29] Xu, Z., Dang, Y., 2020. Automated digital cause-and-effect diagrams to assist causal analysis in problem-solving: a data-driven approach. International Journal of Production Research 58 (17), 5359–5379.

[30] Österle, H., Becker, J., Frank, U., Hess, T., Karagiannis, D., Krcmar, H., Loos, P., Mertens, P., Oberweis, A., Sinz, E.J., 2010. Memorandum zur gestaltungsorientierten Wirtschaftsinformatik. Schmalenbachs Z betriebswirtsch Forsch 62 (6), 664–672.

[31] Verein Deutscher Ingenieure, 2014. Simulation of systems in materials handling, logistics and production: Fundamentals. Beuth Verlag GmbH, Berlin ICS 03.100.10.

[32] Reutlingen University - ESB Business School, 2023. Werk150: Learning, research and development environment - ESB Business School's factory. Reutlingen University - ESB Business School. https://www.esb-business-school.de/en/research/research-activities/werk150. Accessed 24 October 2023.

[33] Schuhmacher, J., Bauernhansl, T., 2023. Data-driven Prediction of Internal Turbulences in Production Using Synthetic Data. Hannover : publish-Ing.

[34] Beckschulte, S., Kiesel, R., Schmitt, R.H., 2021. Manuelle Fehleraufnahme bei Mass Customization. ZWF 116 (4), 188–192.

[35] Klanitz, T. Poka Yoke. REFA AG. https://refa.de/service/refa-lexikon/poka-yoke. Accessed 2 October 2023.

[36] Rauch, E., Rojas, R., Dallasega, P., Matt, D.T., 2018. Smart Shopfloor Management. ZWF 113 (1-2), 17–21.

[37] Schnabel, B., 2023. Development of a Comprehensive Product Lifecycle based on Data of Smart Factories and Smart Products. Master Thesis.

[38] Gernhardt, B., Vogel, T., Hemmje, M., 2018. Knowledge-Based Production Planning for Industry 4.0, in: Hoppe, T., Humm, B., Reibold, A. (Eds.), Semantic Applications. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 181–202.

[39] Günther, R., Beckschulte, S., Wende, M., Schmitt, R.H., 2022. Wertschöpfungskettenübergreifendes Fehlermanagement. ZWF 117 (4), 187–191.

[40] Fenz, S., Ekelhart, A., 2011. Verification, Validation, and Evaluation in Information Security Risk Management. IEEE Secur. Privacy Mag. 9 (2), 58–65.

[41] Siebertz, K., van Bebber, D., Hochkirchen, T., 2017. Statistische Versuchsplanung: Design of Experiments (DoE), 2. Auflage ed. Springer Vieweg, Berlin, Heidelberg, 508 pp.

Biography

Vera Hummel (*1962) has been a professor at the ESB Business School (Reutlingen University) since 2010. She is Vice-Dean Research of the faculty and the initiator and head of the "Werk150 – The Factory of ESB Business School" for research, education and industry training on the campus of Reutlingen University. She is elected president of the International Association on Learning Factories IALF and holds an extraordinary professorship at the Stellenbosch University, Industrial Engineering department.”.

Jan Schuhmacher (*1987) has been a research associate at the ESB Business School (Reutlingen University) since 2014, involved in the establishment of the Industrie 4.0 Factory - Werk150 since 2015 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.

5th Conference on Production Systems and Logistics

A Methodological Framework for Analysis and Theorization of Circular Supply Chain at the System Context Level

Shiva Abdoli[1], Sijia Xie[1] , Bahador Bahramimianrood[1], Mohammed Malaibari[1], Thomas Stringer[2]

[1]*School of Mechanical and Manufacuring Engineerng, Univerity of New South Wales, Sydney, Asustralia*
[2]*Department of Industrial Engineering, Tecnológico de Monterrey, Monterrey, Mexico*

Abstract

Circular Economy concept (CE) revolves aims enhancing resource efficiency through product lifecycle in technical or biological cycles. The former aims to enhance resource efficiency through waste reduction, recycling, reuse, reducing material consumption, and so on. While in the latter, biodegradable materials are returned to earth through processes like composting. There is a lack of comprehensive theorization of CE concept, when focus is supply chain management/value regeneration at technical cycle. Such a lack and consequently a generic understanding can hinder realizing the full potential of CE. This research aims to propose a theorization of CE in the technical cycle through a supply chain management lens. To this end, the systems engineering approach and life cycle assessment (LCA) are integrated to analyse and theorize the circular supply chain/value regeneration. This paper proposed the novel perspective of supply chain as a system of systems (SoS), which allows identifying the enablers, players, and interactions that influence the realization of CE by implementing its known R-strategies. This paper suggested modification of the existing functional unit definition in LCA method such that the proposed definition takes into account the dynamic/evolving boundary of a supply chain when integrating the R-strategies. Moreover, this paper proposed the 'CE system context' for the supply chain SoS. The proposed structured approach allows the development of the Supply chain SoS within its CE context (Supply Chain SoS-CE context). Certain measures are introduced to assess the effectiveness of integrating R-strategies assuring they contribute to CE realization while network theory concepts are used to assess the criticality of various players in Supply Chain SoS-CE context. A roadmap for development of 'Supply Chain SoS-CE context' is introduced in the light of Industry 4.0.

Keywords

Circular Economy; Supply Chain; System Context; Systems Engineering

1. Introduction

Sustainable development seeks to reduce the Environmental Impact (EI) associated with product development. With the increase in population/demand, concerns of massive resource usage, depletion, and scarcity have risen, making material efficiency in product development a top priority. Broadly, efficiency means minimizing consumption of resources while achieving the same output. In product development context, material efficiency means producing same functional output by consuming less material in value creation process, known as supply chain [1] . This can contribute to reducing EI, such as waste generation. This idea has led to emergence of Circular Economy (CE), aiming at minimization of waste generation and resource consumption throughout life cycle of services and products while still meeting socioeconomic

DOI: https://doi.org/10.15488/15276
ISSN: 2701-6277

development goals [2, 3]. Various pathways have been suggested and explored in realization of CE [4], such as enhancing material recycling when product reached its End of Life (EoL) instead of landfilling or extending its lifecycle by different means, such as reusing product or some of its components. CE can strongly support Goal 12 of sustainable development goals (responsible production and consumption), for which Target 12.5 is about substantial waste reduction, through prevention, reduction, recycling, and reuse – which are the core aspects of CE [5]. Achieving this target requires accommodation of extra activities in supply chain, known as reverse logistics, such as product collection and value recovery. A supply chain that includes such activities is called a closed loop supply chain opposed to a linear one [6]. However, Supply Chain Management (SCM) – whether for linear or closed loop – is complex in today's business climate. SCM involves coordination of a diverse activities, from sourcing of input materials to production process, inventory management, and distribution of finished goods to consumers [6]. Due to this large-scale, multidisciplinary, and dynamic nature of involved activities in supply chains, they can be considered complex systems from system theory perspective [7]. Including reverse logistic activities in a supply chain can make SCM even more complex by adding extra activities while aiming to satisfy CE plus a firm's business objectives. This complexity and consequently poor large-scale data management is a substantial hurdle for CE progress and can be a reason why CE and its reverse logistics channel have not been explored/implemented in many supply chains [8]. Therefore, there is a need to utilize methods that allow achieving a proper understating of the complex structure of supply chains when including the reverse logistic activities. Researchers from different domains have investigated CE within their own discipline-specific aspects and as a result, there are various definitions for CE, classification of its activities, and their relationships [9-11]. Such diversity with a lack of comprehensive mapping and classification can lead to confusion and inhibiting realization of CE's full potential, especially when the focus is on a reverse SCM. System thinking is referred as the art of simplifying complexity by seeing through chaos, managing interdependency, and understanding choices [12]. Systems engineering is a well-known approaches in applying such an art, especially in engineering domains [10, 13]. Systems engineering can contribute to identifying the overlooked concepts that can benefit CE in a general sense by cross-examination of concepts that are only investigated in a specific domain with a narrow focus. In the report published by Ellen MacArthur Foundation, the importance of system thinking for CE realization is highlighted [4]: "*System thinking emphasises flow and connection over time and has the potential to encompass regenerative conditions rather than needing to limit its focus to one or more parts and the short term.*" This paper aims to utilize systems engineering approach for theorization of supply chain from CE perspective. This novel theorization promotes understanding of concepts, their relationship, and their roles in big picture of CE. Moreover, perspective offered in this research allows identifying challenges and limitations to realize CE in SCM domain and offering a road map for SCM to realize CE.

2. State of the Literature

CE has gained considerable interest recently [14] seeking to transit from conventional linear 'take-make-dispose' approach to a more sustainable/economically viable system. The value of a linear system is derived from maximisation of production and sales. The circular system emphasizes on continuous optimisation of value of products, components, and materials by ensuring their highest utility is maintained throughout their lifecycle [15]. Yet, the shift from a conventional to a Circular Supply Chain (CSC) entails numerous obstacles. De Angelis et al. emphasise the importance of fostering more collaboration, not only within immediate confines of industry, beyond its conventional boundaries [14].

Ada et al. classified several obstacles for implementation of CE [16] including business-related concerns, financial limitations, technological setbacks, management complexities, and SCM difficulties. Notwithstanding these significant obstacles, the authors posit that harnessing Industry 4.0 technologies, encompassing IoT, cloud-based technologies, machine learning, and blockchain, can serve as a viable remedy for surmounting these challenges.

There is consensus in the literature that there is a lack of a comprehensive framework for integration of CE within the realm of SCM [9-11]. For example, this reference [17] emphasised the significance of aligning product design with SCM decisions to effectively transition towards CE. The authors suggest that adopting a comprehensive approach has the potential to generate improved outcomes in terms of EI, society, and economy. Therefore, this research does not review the available literature on CE that have narrower and refers the interested readers for detail concepts to the existing literature.

3. Concepts and Methods

In system theory, a system is a set of interacting elements serving a purpose that cannot be achieved by individuals, as its emerging behaviour [18]. An 'open' system interacts with its environment. In systems engineering, System of Interest (SoI) operates in a wider system interacting with other systems. The system environment consists of open systems that can influence SoI. System 'Context' contains the environment. Boundary of a system defines its elements and their interaction with environment. SoS is a system whose elements are independent systems, called Constituent Systems (CSs). A system is considered socio-technical when it interacts with social aspects of environment and its behaviour is determined by technical elements and their interaction with social systems [13, 19]. In systems engineering, system architecture is a key artefact demonstrating overall topology of a system, its function, its elements, and their relationships. This paper proposes an approach for modelling the system context which contains a closed loop supply chain. Modelling a context can be done through observation and classification of elements with an abstract conceptualisation. To this end, in next section first the technical concepts of CE and supply chain are investigated, then they are integrated to develop the supply chain system of context from CE perspective to propose a theorization of supply chain-CE.

3.1 Technical Concepts

3.1.1 Circular Economy Cycles and R-Strategies

In CE domain, two types of nutrients are recognized: biological and technical [20]. Biological nutrients are organic materials that can be returned to environment where they biodegrade and contribute to natural cycles following natural ecosystems' principles (after product used in its life cycle). Technical nutrients are inorganic in the form of materials and components that can be reused in different ways within industrial systems, thus preserving the energy, labour, and resources went into their production. Technical nutrients are synthetics and CE aims to use them within closed-loop industrial cycles. An example is a modular smartphone, in which some components can be upgraded, repaired, or recycled. This keeps the technical nutrients within the product cycle and out of the waste stream for as long as possible. This paper focuses on technical cycles to manage the study scale and including the biological cycle will be investigated in future works.

CE revolves around a set of strategies, referred to R-strategies, as used to optimize lifecycle of products and materials. They range from original 3R approach - Reduce, Reuse, Recycle- to more comprehensive 9R frameworks [11, 21]. Each R-strategy offers a different level of circularity, resource efficiency, and EI mitigation; hence, their selection and implementation involve different stakeholders, technologies, and social aspects. The first six R-strategies explained below sit within this paper's scope.

- Repair: fixing a damaged product to extend its useful life.
- Refurbish: restoring a used product close to its original condition to extend its lifecycle and reducing waste, for example refurbishing older laptops for resale or donation.

- Reuse: For biological nutrients, this might involve creating compost from organic waste. With technical nutrients, this could entail reusing components from old devices in new ones.
- Remanufacture: dismantling a product, repairing, or replacing damaged parts then reassembling it to improve its performance or efficiency, such as rebuilding a car engine to extend its life.
- Recycle: converting waste materials into new materials, reducing raw material extraction, and conserving resources. An example of biological nutrients can be recycling plant-based packaging into new products, while for technical nutrients, melting down and reforming metal components from discarded electronics fits this strategy.
- Recover: obtaining value from waste. In biological nutrients, this could mean composting organic waste. For technical nutrients, it could involve energy recovery, such as incinerating non-recyclable plastics to generate heat or electricity.
- Reduce: In biological nutrients, this could involve minimizing packaging in a product. For technical nutrients, it may mean designing products for energy efficiency.
- Rethink: reevaluating the need for a product or service, potentially shifting consumption habits to more sustainable options.
- Refuse: actively choosing not to use or buy unsustainable products or services.

3.1.2 Reverse Supply Chain

Efficacy and efficiency of SCM system are contingent upon a seamless integration between logistical and cross-functional drivers that underpin supply chain performance, including facilities, inventory management, transportation, production planning, information systems, and sourcing strategies [22]. SCM approaches have undergone significant advancements for enhancing efficiency/effectiveness. These include Lean Manufacturing approach, focusing on waste reduction in manufacturing process and Enterprise Resource Planning (ERP) as a tool to facilitate integration of diverse SCM functions. Transition from a linear supply chain to a CSC can be achieved through implementation of three strategies: narrowing, slowing, and closing [23]. Narrowing strategy entails deliberate reduction of material/energy consumption within production process. In inventory management, CE ideology promotes adoption of practices that prioritize reuse/recycling of products. This approach holds potential to curtail demand for raw materials and mitigate waste generation. The initial phase in transition from a conventional supply chain to a CE is implementation of a narrowing strategy. The process of slowing resource loops encompasses implementation of various strategies, including repair, remanufacturing, and reuse to prolong products' lifecycle. The reverse supply chain assumes a pivotal position, encompassing a series of activities aimed at redirecting goods from their customary end-point to extract value or ensure appropriate disposal, as explained by remanufacturing, repair, and refurbishing [24].

3.2 Theorization of 'Supply Chain-Circular Economy' System of Systems Context

CE has a cyclic perspective while traditional forward/open SCM view has a sequential one [14]. The scale of involving players in a CE can be broad and dynamic which must be addressed when analysing integration of R-strategies with SCM. This paper orchestrates various methods/approaches to address the gap between linear and circular perspective while acknowledging the dynamic and evolving nature of CE. To this end, the systems engineering principle, particularly concepts of SoS and system context are used. Moreover, Life Cycle Assessment (LCA) method is used to assist in system boundary definition and providing a foundation for EI calculation. This helps to identify the best R-strategy or set of R-strategies in achieving CE objectives or reducing the total EI at higher supply chain SoS-CE context level. The proposed approach is demonstrated in Figure 1 and is explained below.

3.2.1 Supply Chain System of Systems

CSs in an SoS are networked to achieve a higher capability that may not be achieved with individual CSs that have their own stakeholders. SoSs are evolved by adding new or removing existing CSs in their lifetime to adapt to their environment. This paper proposes modelling a supply chain in CE context (from reverse supply chain perspective) as an SoS which includes various systems such as original manufacturer, assembly, and logistics systems. This perspective allows integration of R-Strategies with supply chain, which may require including new technological and social systems such as, recycling, re-manufacturing, and colleting systems. While all systems within both original and possible closed loop supply chain can function independently and have their own objectives, their integration allows achieving the supply chain and CE objectives. Such integration can happen or change over time, the proposing perspective (supply chain as an SoS) allows adapting to this evolving aspect of supply chains in CE context by including new systems or adapting the existing ones when its needed. This is referred to loosed coupling from the systems engineering perspective.

3.2.2 Supply Chain-SoS Boundary Definition and LCA

The boundary of a system defines its elements and their interaction with environment [13]. In adapting supply chains with CE concept, this paper defines the supply chain as the SoI (Supply chain System of Systems interest: Supply chain SoSoI) that delivers a product or service to customer. However, dynamic adaption of supply chain to integrate R-strategies dynamically evolve its system boundary. Yet, it is needed to have a measuring unit and a basis for comparison and to assess effectiveness of integration of any R-strategies in realization of CE objectives. Therefore, this research integrates LCA method in its proposed approach. In LCA, functional unit specifies the quantity of a product/service to be delivered to an end user. System boundary in LCA defines the processes that must be included in analysis to calculate EI associated with delivering the functional unit. To define the supply chain boundary, this research separates use cases that are internal to supply chain of a product/service from actors that are external to supply chain. Such systems belong to the context of the supply chain as shown in Figure 1.

For ease of reference, this paper calls the functional unit defined for a product/service without any CE strategy as forward functional unit, $Functional\ Value\ unit_{Forward}$. This is used to define the boundary for forward-supply chain. The integration of various R-Strategies from the planning stage or through the lifecycle of product/service might change that initial boundary. This research suggests adjusting the initial functional unit when integrating R-strategies. This helps to assess the efficacy of integration of R-Strategies and find the proper set of R-strategies. Accordingly, the EI associated with $Functional\ Value\ unit_{Forward}$ can be calculated using LCA. For example, the $Functional\ Value\ unit_{Forward}$ can be defined as10 years of car driving and landfill later, which its associated carbon footprint can be calculated using LCA. Then, remanufacturing of certain components can be analysed by defining a new functional unit, $Functional\ Value\ unit_{R-strategy}$, as delivering re-manufactured components to be used in a new car. This strategy requires integration of re-manufacturing facilities and collecting systems. As a result, EI associated with new functional unit, which are respectively called EI_{CE} and $Functional\ Value\ unit_{CE}$, should be updated as shown in (1) and (2). The environmental efficacy of R-strategy can be calculated as the ratio of EI_{CE} to the $Functional\ Value\ unit_{CE}$. However, this research proposed to modify the way that a functional unit is generally presented by demonstrating it as a value generation within economy. This allows comparing the ratios in Equations (3) and (4). Hence, traditional functional unit is called the functional value unit in this paper. For example, generating value of 10 years of car driving can be measured within the economy. Likewise, generating value of 10 years of car driving while certain components are re-manufactured to be used in the new car is a new functional value unit measured in the economy. This can be formulated as the ratio of economic value of generated function within current size of the economy. Another alternative would be to calculate the ratio of the addressed demand by generated function to the total demand within the economy. Both alternatives offer a ratio for the generated functional value unit. Integration of proposed approach with known Input-Output analysis in CE domain can be beneficial in this proposed framework which is part of the future research of current work. Either of these alternatives suggests extracting value from a product's life cycle and implying that products are containers of value that can be successively unlocked as they circulate through various R-strategies.

$$Functional\ Value\ unit_{CE} = Functional\ Value\ unit_{Forward} + Functional\ Value\ unit_{R-strategy} \quad (1)$$

$$\mathrm{EI_{CE}} = \mathrm{EI_{Forward}} + \mathrm{EI_{R-strategy}} \quad (2)$$

$$\text{R-strategy-Efficiency} = \mathrm{EI_{CE}} / \text{Functional Value unit}_{\mathrm{CE}} \quad (3)$$

$$\text{Forward-SCM Efficiency} = \mathrm{EI_{Forward}} / \text{Functional Value unit}_{\mathrm{Forward}} \quad (4)$$

From systems engineering perspective, the proposed approach allows to analyse effectiveness of each R-strategy from economic, performance, and CE objectives perspectives. When the product/service approaches its EoL in any of demonstrated cycles in Figure 1, the above measures can be calculated to identify the best set of future R-strategies. Because, depending on the value proposition, it might not be beneficial economically/environmentally to conduct some intermediate strategies and instead directly move to recycling. This depends on the level of upfront resource consumption of the components. Thus, an agreement can be made between stakeholders and developers in any of those lifecycles and future ones to implement a specific R-strategy with an agreed condition offering the chance of delivering an extra value for which they are willing to invest specific cost and other resources.

3.2.3 Supply Chain- Circular Economy System Context

A System context is a set of system interrelationships associated with a particular system of interest (SoI) within a real-world environment [13]. Generally, system context can be very helpful to get a better understanding of a problem and developing solutions which require a proper combination of social and technological enablers. These are called as socio-technical system contexts, which as explained implementation of R-strategies require both social and technological enablers and CE context fits well to socio-technical system context definition. Closing loops in supply chain from CE perspective, requires investments in recalibrating relationships with enablers of forward and backward supply chain.

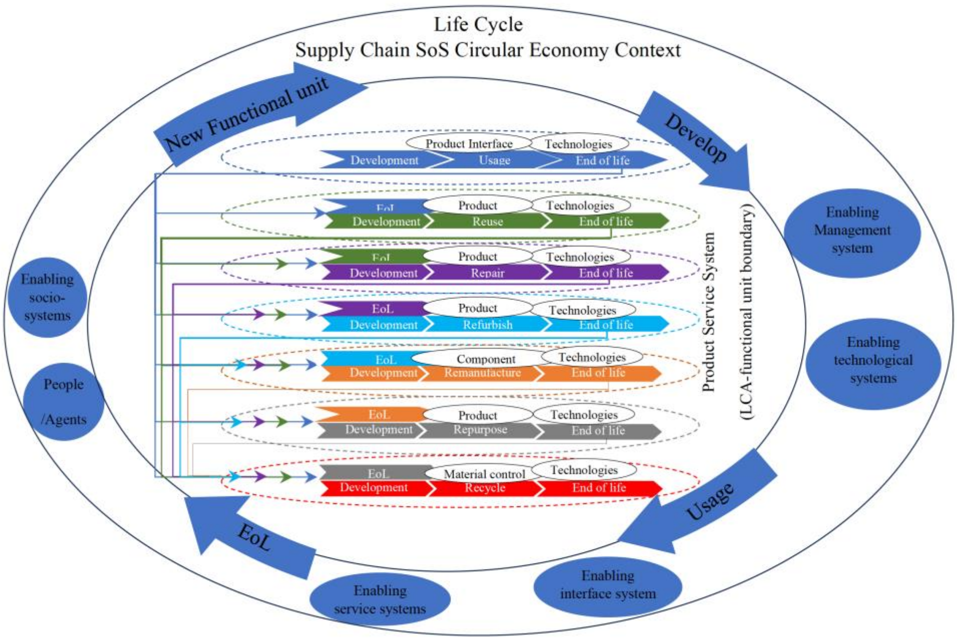


Figure 1: Supply chain SoS Circular Economy context

This paper proposes a novel perspective of looking at supply chain as SoI and an SoS that operates within its context. Integration of R-strategies in a Supply Chain SoS of Interest (SoSoI) impacts its context, meaning SoSoI not only might have an evolving and broader boundary but also a broader and evolving context too. This is called Supply Chain Circular Economy System of Systems Context in this paper: SC-CE-Context. The advantage of proposed view in this paper (developing SC-CE Context) would be allowing to focus on supply chain as SoI but not lose sight of its all-holistic relationships, interactions, and influences beyond boundary of supply chain itself, which implementation of CE view (R-strategies) require many relations/interactions. This approach allows identifying enabling systems and their activities focused on creation and re-creation of value promoting a holistic approach over a lifecycle. Based on systems engineering principles, this research suggests a novel procedure to understand supply chain SoSoI and its CE context. This allows capturing important relationships between its elements, the systems with which it works directly, and any other systems with which it might interact in its context. This approach combines various views to ensure capturing all the important elements, relationships, and interactions that are needed when applying the CE at the supply chain.

- Product/service system view
  - Define the lifecycle of the product/service system developed in the supply chain of interest.
  - Identify its needed technological and social enablers (systems) during its lifecycle.
- Forward view: open loop supply chain system and its context
  - Define the boundary of the forward supply chain system.
  - Define the elements within the forward supply chain.
  - Define external elements which interact across the boundary of a forward supply chain SoI
  - Identify enabling systems (following ISO 15288[25]): systems (or services) utilized at various stages in life (cycle, e.g., utilization) to facilitate the SoI in achieving its objectives.
- Cyclic view: Closed-loop supply chain system of interest and its context.
  - Define the R-strategies.
  - Define the enabling systems/services for each R-strategy.
  - Define the interactions/relationships between the supply chain elements and identified enabling systems/services for R-strategies.
- Integration:
  - Identify the possible overlap between the identified enabling systems/services.
  - Define the importance of enabling systems/services and supply chain systems elements based on the network theory measures (explained below)

The proposed approach started with product/service system view, because the product/service system within a supply chain is first focus of any supply chain, and its relation is one of the key objectives of supply chain. Yet, CE aims to enhance sustainability in product development during its lifecycle. The second step involves forward supply chain view, which allows theorization of supply chain that product/service system is intended to be developed with. However, application of CE requires embodiment of R-strategies and that requires step three. It is likely to have overlaps between the defined enabling systems in each of the first three steps, hence at last step all the identified systems are integrated to cross-off the overlaps and identify the critical systems. This research suggests using some key concepts of the network theory to identify critical enabling systems in SC-CE-Context perspective proposed by this research. The first measure that can be used is the "betweenness centrality", which allows analysing of how frequently an enabling system interacts with other systems in supply chain SoSoI (the evolving dimension of supply chain due to dynamic integration of R-strategies) and likelihood of interacting with other systems at SC-CE context (including enabling social/technical systems beyond Supply chain SoSoI). The next measure that can be used is "eigenvector centrality", which considers the number of connections that an enabling system has with the systems that have high betweenness centrality. In network theory, it is argued that sometimes some nodes (systems in this research) that have the high number of connections with other nodes play a critical role within the network and must be planned carefully. Therefore, this research also suggests using this measure to analyse the Supply chain SoS and identify those enabling systems that due to a higher number of interactions with systems with high betweenness to maximize their efficiency and increase objective satisfaction at supply chain SoS and realization of CE objectives.

4. Discussion and Future Directions

Analysing a supply chain that employs CE-driven R-strategies increases complexity of evaluating the performance of activities along the nodes of that supply. The proposed theorization offers a perspective that enhances understanding of practitioners, researchers or policymakers about functional value that is created or "recuperated" in a closed loop supply chain as opposed to that of a linear supply chain. The total value of the closed loop supply chain is sum of the value in a product's initial linear supply chain and the value generated by the R-strategies implemented in the supply chain. The same can be computed with the measure of EIs. These two measurements first highlight an important distinction in how functional value is created along a CE supply chain. For the environmental efficacy of a supply chain to improve with implementation of R-strategies, EI of R-strategies should try to be as small as possible while capturing the most functional value possible. This can sound obvious but can be misunderstood operationally, namely because of a lack of data or limiting measurement system's scope. For example, a printer manufacturing company that has recently implemented a remanufacturing program by collecting older printers from customers might only measure EI of actual remanufacturing when evaluating their R-strategy without including impact of additional warehousing and transportation required. This highlights the importance of evaluating all supply chain changes that go into implementing a new R-strategy. The complexity can increase radically when many different strategies are implemented at the same time. The methodology proposed in this paper addresses this issue by assessing each R-strategy within a wider system. This may not reduce the complexity of wider system per se, but certainly helps stakeholders to better understand this complexity and not isolating the effects of individual strategies on whole of the system. By dichotomizing the analysis of a closed loop supply chain into what could be called traditional supply nodes and R-strategies, the proposed approach allows better understanding of how new measures affect the overall environmental efficacy of the system.

The amount of data generated by industries is growing exponentially coming from variety of sources as called big data [26], presenting opportunities/challenges. The need to analyze big data arises from its potential insights that can be used to optimize operations and improve customer experience [27]. Big data is often characterized by its overwhelming volume, fast velocity, uncertain veracity, and varied formats [26]. Hence, new approaches including digital twin and semantic web technologies have emerged to effectively collect, store, manage, and analyse it [28] . A digital twin is a digital replica of a physical object based on data and models [29], which can be used for virtual experiments, performance prediction, optimization, monitoring, control, and data management [28, 30]. For data management, a digital twin provides a platform for collecting, integrating, and analysing different data types from various sources [31, 32]. From this paper's perspective, a digital twin can support CE by enabling better data structuring [33] (e.g., composition, origin, and history of materials and products, current condition, and their potential for reuse or recycling) for integration of R-strategies with supply chain nodes. Digital twin can strengthen collaboration among stakeholders by increasing transparency and facilitating information flow at right stages [33]. Semantic web technologies like ontologies and knowledge graph can play a critical role in data management by facilitating structuring, sharing, and reuse of data [34, 35]. Semantic technology can enhance CE by supporting design of sustainable products with their EI modelling/assessment and analysing/tracking their pathways through a supply chain. This knowledge can be used to identify opportunities for R-strategies application. Further research are necessary to fully realize benefits of digital twin and semantic web technologies for CE realization different product types.

References

[1] C. Sassanelli, P. Rosa, R. Rocca, and S. Terzi, "Circular economy performance assessment methods: A systematic literature review," Journal of Cleaner Production, vol. 229, pp. 440-453, 2019.

[2] P. Ghisellini, M. Ripa, and S. J. J. o. C. P. Ulgiati, "Exploring environmental and economic costs and benefits of a circular economy approach to the construction and demolition sector. A literature review," vol. 178, pp. 618-643, 2018.

[3] A. Murray, K. Skene, and K. J. J. o. b. e. Haynes, "The circular economy: an interdisciplinary exploration of the concept and application in a global context," vol. 140, pp. 369-380, 2017.

[4] E. MacArthur, "Towards the circular economy," Journal of Industrial Ecology, vol. 2, no. 1, pp. 23-44, 2013.

[5] P. Schroeder, K. Anggraeni, and U. Weber, "The relevance of circular economy practices to the sustainable development goals," Journal of Industrial Ecology, vol. 23, no. 1, pp. 77-95, 2019.

[6] K. Govindan, H. Soleimani, and D. Kannan, "Reverse logistics and closed-loop supply chain: A comprehensive review to explore the future," European journal of operational research, vol. 240, no. 3, pp. 603-626, 2015.

[7] K. E. Boulding, "General systems theory—the skeleton of science," Management science, vol. 2, no. 3, pp. 197-208, 1956.

[8] S. Ritzén and G. Ö. J. P. C. Sandström, "Barriers to the Circular Economy–integration of perspectives and domains," vol. 64, pp. 7-12, 2017.

[9] S. Geisendorf, F. Pietrulla, and E. Berlin, "Report on State-of-the-Art Research in the Area of the Circular Economy," R2pi: The Route to Circular Economy, 730378, 2017.

[10] V. Prieto-Sandoval, C. Jaca, and M. Ormazabal, "Towards a consensus on the circular economy," Journal of cleaner production, vol. 179, pp. 605-615, 2018.

[11] J. Kirchherr, D. Reike, and M. Hekkert, "Conceptualizing the circular economy: An analysis of 114 definitions," Resources, conservation and recycling, vol. 127, pp. 221-232, 2017.

[12] J. Gharajedaghi, Systems thinking: Managing chaos and complexity: A platform for designing business architecture. Elsevier, 2011.

[13] 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.

[14] R. De Angelis, M. Howard, and J. Miemczyk, "Supply chain management and the circular economy: towards the circular supply chain," Production Planning Control, vol. 29, no. 6, pp. 425-437, 2018.

[15] R. Hossain et al., "Plastic waste management in India: Challenges, opportunities, and roadmap for circular economy," Sustainability, vol. 14, no. 8, p. 4425, 2022.

[16] N. Ada, Y. Kazancoglu, M. D. Sezer, C. Ede-Senturk, I. Ozer, and M. Ram, "Analyzing barriers of circular food supply chains and proposing industry 4.0 solutions," Sustainability, vol. 13, no. 12, p. 6812, 2021.

[17] H. Burke, A. Zhang, and J. X. Wang, "Integrating product design and supply chain management for a circular economy," Production Planning Control, pp. 1-17, 2021.

[18] L. v. Bertalanffy, "General system theory: Foundations, development, applications," 1969.

[19] S. Abdoli, "A framework for analysing the environmental impact and support decision making in sustainable development context," Environment Systems Decisions, vol. 43, no. 2, pp. 281-297, 2023.

[20] J. Kirchherr, N.-H. N. Yang, F. Schulze-Spüntrup, M. J. Heerink, and K. Hartley, "Conceptualizing the Circular Economy (Revisited): An Analysis of 221 Definitions," Resources, Conservation and Recycling, vol. 194, p. 107001, 2023/07/01/ 2023.

[21] J. Potting, M. P. Hekkert, E. Worrell, and A. Hanemaaijer, "Circular economy: measuring innovation in the product chain," Planbureau voor de Leefomgeving, no. 2544, 2017.

[22] S. Choprar and P. Meindl, "Supply Chain Management Strategy, Planning, and Operation," ed: Upper Saddle River, NJ: Prentice Hall, 2001.

[23] L. Marques and M. D. Manzanares, "Towards social network metrics for supply network circularity," International Journal of Operations Production Management, vol. 43, no. 4, pp. 595-618, 2023.

[24] K. Lieckens and N. Vandaele, "Multi-level reverse logistics network design under uncertainty," International Journal of Production Research, vol. 50, no. 1, pp. 23-40, 2012.

[25] Systems and software engineering–system life cycle processes, 2015.

[26] Q. Qi and F. Tao, "Digital Twin and Big Data and Industry 4.0: 360 Degree Comparison," IEEE Access, vol. 6, pp. 3585-3593, 2018.

[27] J. Li, F. Tao, Y. Cheng, and L. Zhao, "Big Data in product lifecycle management," The International Journal of Advanced Manufacturing Technology, vol. 81, no. 1-4, pp. 667-684, 2015.

[28] F. Tao, J. Cheng, Q. Qi, M. Zhang, H. Zhang, and F. Sui, "Digital twin-driven product design, manufacturing and service with big data," The International Journal of Advanced Manufacturing Technology, vol. 94, no. 9-12, pp. 3563-3576, 2018-02-01 2018.

[29] B. R. Barricelli, E. Casiraghi, and D. Fogli, "A Survey on Digital Twin: Definitions, Characteristics, Applications, and Design Implications," IEEE Access, vol. 7, pp. 167653-167671, 2019.

[30] M. Perno and L. Hvam, "Developing a framework for scoping digital twins in the process manufacturing industry," in SPS2020 Proc. Swedish Prod. Symp, 2020, pp. 475-486.

[31] C. Zhuang, J. Gong, and J. Liu, "Digital twin-based assembly data management and process traceability for complex products," Journal of Manufacturing Systems, vol. 58, pp. 118-131, 2021.

[32] H. Dierend, O. Altun, I. Mozgova, and R. Lachmayer, "Management of Research Field Data Within the Concept of Digital Twin," Advances in System-Integrated Intelligence, pp. 205-214, 2023.

[33] A. Preut, J.-P. Kopka, and U. Clausen, "Digital Twins for the Circular Economy," Sustainability, vol. 13, no. 18, 2021.

[34] N. Sahlab, S. Kamm, T. Muller, N. Jazdi, and M. Weyrich, "Knowledge Graphs as Enhancers of Intelligent Digital Twins," presented at the 2021 4th IEEE International Conference on Industrial Cyber-Physical Systems (ICPS), 2021.

[35] B. Sridharan and A. Tretiakov, "Application of ontology to Knowledge Management in web based learning," in IEEE International Conference on Advanced Learning Technologies, 2004. Proceedings., 2004, pp. 663-665: IEEE.

1. 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.

Sijia Xie is a Master of Philosophy in the School of Mechanical and Manufacturing Engineering, UNSW. In 2022, she received her Master degree in Manufacturing Engineering and Management from UNSW. She is Casual Academic at UNSW. Her research interest includes Inventory management, Industry 4.0, Circular Economy, Supply chain management.

Bahador Bahramimianrood completed his Master's degree from Sichuan University in 2019. He is currently a Ph.D. student at the School of Mechanical and Manufacturing Engineering, University of New South Wales (UNSW), starting from 2023. His research interests focus on the Circular Economy, Industry 4.0, Sustainability and Optimization.

Mohammed Malaibari is a PhD student in the School of Mechanical and Manufacturing Engineering at UNSW Sydney. He holds a Master of Science in Mechanical and Manufacturing Engineering from UNSW Sydney. He worked as a researcher at Concordia University, Montreal. His main research interests are Digital Twin, Knowledge Graph, Data Management, Industry 4.0, and Circular Economy.

Thomas Stringer is a Professor in the Department of Industrial Engineering at Tecnológico de Monterrey. He holds a Ph.D. in Industrial Engineering from Polytechnique Montréal and his main research interests are public policy, transportation, energy economics and supply chain management. He previously completed his postdoctoral training at the University of British-Columbia.

CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
CPSL 2023-2

5th Conference on Production Systems and Logistics

Framework For The Successful Set-up Of A Common Data Model In The Context Of An Industry 4.0-ready Plant Design Process

Tobias Drees[1], Alexander Große-Kreul[1], Daniel Syniawa[1], Lars Niklas Josler[1], Alfred Hypki[1], Bernd Kuhlenkötter[1]

[1]*Ruhr-University Bochum, Chair of Production Systems, Industriestraße 38c, 44894 Bochum, Germany*

Abstract

The production plant design process consists of a multitude of individual engineering disciplines, which rely on a variety of digital models. The individual tasks build up on each other, while each discipline consumes information from the previous processes. However, sharing relevant data across multiple companies is challenging and susceptible to miscommunication and delays. Furthermore, integrating diverse software systems, tools, and technologies create compatibility issues and hinder seamless integration. As a result, a heterogeneous, non-automated data and information landscape is created, characterized by a high level of manual data transfer. This represents a major problem on the way towards Industry 4.0.

The goal of this paper is to provide a framework for the successful set-up of a common data model in the context of an Industry 4.0-ready plant design process across and along the value chain. For this purpose, a literature review of current problems in the cross-company and cross-departmental collaboration in the plant design process is provided and requirements for the framework are derived. Existing solutions and research projects are compiled and evaluated against the requirements, from which the framework's structure is concluded. The framework itself is intended to be holistic and must therefore not only include technical aspects (e.g. data interfaces, semantics) but also enable the entire organization and value chain to implement the common data model as part of the digital transformation process (e.g. employee skills, business strategy, legal conditions). Based on this, the framework is further elaborated by deducing calls for action for a successful set-up of a common data model within the research project *DIAMOND* (Digital plant modeling with neutral data formats). The focus should be on employees and their competencies, as these are prerequisites for shaping digital transformation. Future research must prioritize these actions to enhance technology readiness and organizational Industry 4.0 preparation.

Keywords

Common Data Model; Digital Transformation; Plant Design Process; Industry 4.0; Data Exchange

1. Introduction

The work environment is transforming with the increasing use of new and digital technologies as part of the fourth industrial revolution (Industry 4.0 – I4.0). However, the successful implementation of new technologies in existing work processes across the value chain remains difficult for various reasons, including a lack of awareness of the benefits of specific technologies, a shortage of employees and their expertise, or a lack of financial resources [1]. The company must be able to evaluate the technologies and assess them in terms of their potential and benefits [2]. Although automotive manufacturers and their suppliers have the highest I4.0 affinity compared to other industries in Germany [3], the slow introduction of new technologies also applies [4]. In comparing the nine main technology trends (= pillars) of I4.0 [5],

DOI: https://doi.org/10.15488/15309
ISSN: 2701-6277

the expertise in the *Big Data* pillar and thus, the management and analysis of data across different employee levels (managers, technical specialists, production employees) is the lowest. [6]

In present-day plant design processes, the exchange of data or information between employees across departmental and company boundaries is identified as a major shortcoming [7]. This is due to a heterogeneous tool landscape and specific data models in the individual disciplines, whose data is usually exchanged manually [8]. Manual data transfer is time-consuming and might lead to data inconsistency or loss, miscommunication and insufficient data quality [9]. Additionally, compatibility issues hinder seamless data integration into various tools [10]. Setting up a common data model (CDM) as a basis for data exchange promises to mitigate these challenges [10]. However, accompanying challenges of the digital transformation influence the implementation and must be addressed. Thus, the following research questions arise:

- What are the current challenges in the cross-company and cross-departmental collaboration in the plant design process?
- How can the challenges be categorized within I4.0 readiness models?
- What actions are needed to set-up a CDM, while holistically addressing the various challenges of digital transformation?

2. Background

2.1 Industry 4.0 readiness models

Nowadays, numerous assessment models and methods are available regarding the readiness or maturity of I4.0 implementation [11]. These I4.0 readiness models or maturity indexes are a measurement framework that assesses the level of digital transformation of a company in adopting I4.0-technologies. They provide a structured approach to evaluate and benchmark the maturity of various dimensions, such as technology, processes, organization, and strategy, indicating the extent to which an organization has embraced and implemented I4.0 concepts [12]. Existing literature reviews show a great variety of different models [11–14]. However, *Dikhanbayeva et al*. [15] conclude that the existing maturity models have certain deficiencies because they are incomplete, have limited access or miss important design principles of I4.0. Although most models follow general approaches [12], the variety of different ones shows the necessity to adapt the models to a specific use case with specific requirements to make them applicable. [9]

2.2 Common data model

A Common Data Model (CDM) is a standardized and structured representation of data that is understood across different systems and applications within an organization or across multiple organizations. It is the foundation of a central data store that manages engineering data from a wide variety of software tools [10]. A CDM serves as a common language for data integration, exchange, and interoperability, enabling seamless communication and interaction between various data sources and systems and collaboration among different stakeholders. In addition, a CDM acts as a mediator between various data sources and consumers, streamlining data integration and reducing the need for complex data mappings. This leads to more efficient collaboration in the design process. By implementing it, organizations can overcome data silos, reduce data redundancy, improve data quality, and enhance data analytics capabilities. Furthermore, a CDM facilitates efficient data sharing along the entire value chain, fostering collaboration and accelerating decision-making processes. Overall, a CDM plays a pivotal role in achieving a unified data landscape, promoting digital transformation, and supporting I4.0 initiatives in today's interconnected and data-driven business environment. [10,7]

3. State of the art

3.1 Challenges in the plant design process

To identify potentially relevant literature systematically four search term groups are formed, namely (1) plant planning/design process, (2) barriers, challenges or problems, (3) data management or common data model and (4) I4.0 maturity or readiness, and its variants and combinations are used. In addition, a backward and forward citation analysis is performed so that 47 papers are analyzed.

The papers cite 63 problems with the current plant design process, with varying degrees of frequency. Lack of soft skills and qualifications are cited most often (31 times), followed by cybersecurity concerns (27), lack of skilled workers (24), lack of financial resources (21), and clarification of standards, protocols, and contracts (19). Figure 1 shows a word cloud of the ten most frequently cited challenges.

The plant design process is carried out with the help of various companies involved and their corresponding software tools. This leads to a heterogeneous tool landscape [16]. Due to missing communication interfaces, information cannot be exchanged directly between different tools, leading to high efficiency losses [16]. Furthermore, there is a lack of a common data environment within the plant design process, resulting in fragmented information, data silos and a lack of version control [17]. The need for more data availability poses another main challenge, preventing employees from accessing specific information that they need to perform their jobs [18]. Consequently, the lack of a common data environment in the plant design process results in bad data quality and hinders seamless collaboration between companies. This creates barriers to information sharing, coordination, and effective decision-making, which impacts productivity, quality, and the overall project outcome.

In addition to data-related challenges the plant design process also encompasses challenges associated with employee competencies, strategic alignment, and external factors. The lack of soft skills and qualifications among employees contributes to delays in the development process, as they may lack problem-solving abilities, error analysis skills, and adaptability to changes [19]. Insufficient employee qualification aggravates these challenges, stressing the need for comprehensive training programs [17]. Strategic challenges arise within the organization and affect top management, departments, and cross-organizational activities. Many organizations need strategies to effectively align their internal processes with external partners, hindering coordination and cooperation [19]. These challenges include the need for cross-departmental agreements on the use of technology and standards to promote collaboration. Additionally, challenges originating from external factors impact the plant design process. A high level of bureaucracy imposes numerous requirements that restrict employee freedom and hinder process efficiency [18].

Figure 1: Word cloud of current I4.0 challenges in the plant design process based on the number of mentions

3.2 Existing solutions

Since several challenges in the plant design process might already be addressed, existing solution approaches are extracted from the literature. For this purpose, the papers selected during the problem analysis were examined for possible solutions. In total, nine different solution approaches are identified that range from intra-organizational to cross-company projects.

Müller et al. introduced a web-based platform that facilitates seamless communication and eliminates media breaks by utilizing various visualizations and file attachments [16]. Similarly, *Bartelt et al.* proposed an infrastructure for cross-company collaboration, incorporating an exchange format for tool-independent cooperation [20]. The *ENTOC* joint project aimed to optimize the engineering toolchain to enhance data availability across planning and development phases [21]. Additionally, the *BaSys4.2* project develops a middleware in the context of Industry 4.0 to enable cross-company data access in highly networked automation systems [22]. Moreover, the research association *ForBAU* focuses on ensuring consistency of 3D modeling throughout all construction planning steps [23]. Another notable solution (*Catena-X)* emphasizes standardized data exchange within the automotive industry's supply chains [24]. These solution approaches have a focus on technical and partnership problems.

Götz proposed an engineering community to address technical, partnership, human, and strategic challenges. This community fosters cross-divisional cooperation by facilitating knowledge and engineering data exchange [25]. The *AVILUS* project developed a cross-phase approach to information management that encompasses human resource and strategy challenges while focusing on creating, preparing, and utilizing digital information throughout the entire lifecycle [26]. Lastly, *Talkhestani et al*. proposed a solution approach that specifically identifies cross-domain data. Although this approach has a narrow focus, it addresses certain challenges present in the current plant design process [27].

In conclusion, the identified solutions address several challenges in the plant design process, including technical problems, partnership issues, human-related obstacles, education-related challenges, and strategic issues. However, some challenges remain unaddressed, especially regarding the employees and their competencies. This will be further elaborated in Chapter 4.

3.3 I4.0 knowledge, skills and abilities

Based on the most frequently cited challenges it becomes obvious that a prerequisite for any implementation of I4.0-technologies is a skilled and qualified workforce that not only reacts to the ongoing changes but also shapes the transformation proactively [28]. This becomes even more significant due to changes in work tasks and employees' job profiles. Need-based professional education and training offer great added value in terms of raising awareness of technologies and their implementation [29]. In this context, the competencies of the employees are of great importance for introducing new technologies since various studies have shown a correlation between using technologies and the availability of necessary competencies [28,1,2].

However, deficits in employee qualification are becoming apparent [30]. To counteract these deficits, new methods and strategies are needed for the targeted qualification of employees [31]. Although many learning concepts have already been developed for specific I4.0 applications, only a few focus on the digital transformation process of companies and the associated training of employees [30]. The 2022 *Digital Economy Index* indicates that only 54% of Europeans have at least basic digital skills, thus highlighting the need for innovative and efficient qualification strategies within digital transformation [32]. Moreover, digital competencies are less pronounced in SMEs than in large companies [33]. These aspects are in enormous discrepancy with the rapidly increasing need for digital skills in the context of Industry 4.0 in almost all occupational fields.

4. Establishing a framework

4.1 Mapping challenges within a plant design process to I4.0 readiness models

Regarding existing I4.0 readiness models, the identified challenges within the plant design process are analyzed, grouped, categorized and subsequently mapped to defined I4.0 maturity dimensions, as shown in Table 1. The dimensions are extracted and adapted from existing models: Technology (T), Human (H), Strategy (S), Organization (O), Partnership & Network (PN) and Environment (E). The categories themselves are elaborated by the grouping process. Consequently, by the combination of challenges and I4.0 maturity assessment, creating a framework on how to successfully set-up a CDM within the plant design process becomes possible, as will be elaborated within the following chapters. Furthermore, the matching table serves as a checklist for evaluating the current I4.0 maturity and improving results by indicating what evaluators must pay attention to.

The technology dimension refers to the level of adoption and integration of advanced technologies that enable digital transformation and automation, by assessing the organization's technological infrastructure, capabilities, and utilization of critical technologies. A human dimension considers human factors and capabilities in the digital transformation process and emphasizes preparing and empowering the workforce to effectively adapt to and utilize I4.0-technologies, encompassing knowledge, skills, competencies, and mindset. It acknowledges that successful implementation of I4.0 is not solely reliant on technology, but also on the people who interact with and leverage these technologies to drive organizational growth and success.

Table 1: Current challenges of the plant design process

Dimension	Category	Current Challenges
T	Data and information management	Lack of possibility to link data and information [16]; Lack of data quality control and validation mechanisms [18]; Unavailability of data [18]; Insecure data storage systems [34]; Imprecisely defined data access [35]; massive amount of data to manage, store and process [36]
	Technology integration	Immature technology [36]; Lack of back-end systems for integration [34]; Complex synchronization of the real and virtual model [27]; High heterogeneity of the different software solutions [18]; Heterogeneous tool environment [16]; Lack of clarity about the intended use [37]; Lack of technical support [17]; lack of technologies for providing information along the value chain [38]
	Standards and protocols	Lack of clear standards, protocols and contracts [34,17]
H	Attitude, mindset and culture	Resistance to further education [36]; Negative attitude towards change [39]; Different views of cooperation [17]; Negative social influence [37]; Lack of trust in the technology [37], Bad team composition [17]
	Existing knowledge, skills and abilities	Lack of soft skills and qualifications of employees [19]; Lack of sense of usefulness [37]; Limited digital literacy [28]; Limited understanding of I4.0-technologies [28]
	Access to specific employee training and education	Lack of education at universities [18]; Lack of collaboration education [17]; Lack of knowledge about the proper training [28]
S	Strategic Planning	Lack of cross-company strategy for an organization [19]; Contradictory views in different organizational units [34]; Management's reluctance to embrace new technologies [38]; Lack of clarity about the choice of the right technology [40],
	Benefits and value	Lack of clarity regarding general and economic benefits [8];
O	Leadership & management support	Lack of appropriate leaders [34]; Lack of top management support [35];
	Process and resource management	Inadequate planning of steps, goals and resources [34]; Missing benchmarks [41]; High level of bureaucracy [18], Inappropriate process organization [34]; Lack of agility and responsiveness [42]; Inefficient resource allocation and utilization [36]
	Company culture and technology awareness	Technology anxiety [37]; Lack of introduction of new roles [17]; Different views on cooperation [17]
PN	Vertical and horizontal exchange in the value chain	Different organizational structures [17]; Lack of guarantee for interoperability [18]; Misalignment of goals and objectives among partner organizations [34]
	Collaboration and trust	Low trust towards other parties [36]; No willingness to cooperate [34]; Lack of cooperation among departments [35]; Resistance towards sharing data and information [17]
	Information exchange, communication and collaboration with partners	continuous data exchange not possible [8]; lack of traceability and monitoring of changes [43,42]; lack of common data environments [17]; Failure to anticipate customer needs [44]; Unestablished collaboration between project teams [17];
	Data ownership	Concerns about data privacy [17]
E	IT infrastructure	Lack of upgradable infrastructure [40], insufficient data processing power [36]
	Data and IT security	Compliance with data protection regulations[18], ensuring secure data handling practices [18]
	Financial resources	Lack of financial resources [34]; Ignorance about the return on investment and profitability [34]; Lack of willingness to invest [18]
	Labor market	Fear of the loss of work [20]; Lack of skilled workers [34]

The strategy dimension examines the organization's strategic approach and alignment toward I4.0 adoption by assessing the extent to which a company has developed a clear vision, goals, and plans related to I4.0. The organization dimension refers to the organizational structure and culture to embrace and implement I4.0-technologies and practices. This dimension evaluates organizational preparedness to adapt and transform its structure, processes, and mindset to harness the potential of I4.0. In addition, collaborative efforts with external stakeholders to foster ecosystem collaboration are examined within the partnership dimension. The environment dimension assesses the business and macro-economic setting. A key point to note is that some challenges may span across multiple dimensions, indicating their multifaceted nature. However, the presented mapping attempts to link the challenges with their most related dimension.

4.2 Evaluation of existing solutions

Once the challenges have been identified and placed in the I4.0 readiness framework existing solutions can be evaluated for the extent to which they address and overcome the challenges. This is done by marking and summing up the challenges addressed by each solution. Table 2 provides the scope of current solutions.

In conclusion, existing solutions examined in this study do not comprehensively address all challenges identified in the current plant design process, focussing primarily on technological aspects and partnership/network issues. The absence of solutions that consider human challenges must be highlighted. Nevertheless, as demonstrated above, qualifying employees play a crucial role in successfully introducing new technologies within a company's design process. However, by not being comprehensively addressed in current approaches, it is detached from the development of the technology itself. This aspect remains a challenge that requires attention.

Moreover, none of the solutions investigated in this study have developed a comprehensive CDM within the plant design process yet, involving a representative number of key industry stakeholders. This underscores the need for a holistic approach that engages key stakeholders throughout value chains to address these challenges collectively. A framework for a successful implementation of a CDM in the plant design process must aim to fill these gaps and offer more comprehensive solutions that encompass all dimensions equally while involving key industrial stakeholders.

Table 2: Scope of current solutions

Existing Solutions & Description	T	H	S	O	PN	E
Müller et al.: Web-based communication platform for avoiding media discontinuities in plant planning [3]	◕	◔	◑	◔	◑	◔
Talkhestani et al.: Anchor point method for identifying cross-enterprise data and updating the virtual model [8]	◔	○	○	○	◔	◔
Götz: Development of an engineering community for interdisciplinary collaboration [21]	◔	◔	◔	◑	◔	○
Bartelt et al.: An approach to improve cross-company collaboration planning. [22]	◑	○	○	○	◑	◔
Schreiber et al.: Cross-platform information management [23]	◑	◑	◔	◔	◔	◑
BaSys4.2: Middleware for continuous engineering [24]	◑	◔	◔	◔	◑	◑
Catena-X: Networking the entire value chain with the help of a collaborative data ecosystem [25]	◑	○	◔	◔	◕	◑
ENTOC: Optimization of the Engineering toolchain with a focus on smart engineering [26]	◑	○	◔	◔	◑	◔
ForBAU: Optimization of processes regarding the involvement of subcontractors for construction planning [27]	◔	○	◔	◔	◔	◔

○ = not addressed, ◔◑◕ = partially addressed, ● = fully addressed

5. Calls for Action

Based on the identified problems and the proposed I4.0 readiness model, specific calls for action for setting up a CDM are derivable. These proposed tasks provide a framework for future work and suggest specific steps and solutions. For the technology dimension, it is necessary to develop a CDM that is ready to be implemented in real plant design processes with a sufficient technology readiness level [45,46]. Therefore, all features must be described and tested accordingly and a basic understanding of CDM must be created. *AutomationML* promises to serve as a suitable, open and adaptable XML-based data exchange format for seamless interoperability in industrial automation [38]. Within the human dimension, the acceptance of and trust in CDM must be improved. A valid tool that explains and predicts individuals' acceptance and adoption of new technologies based on their perceived usefulness and ease of use is the Technology Acceptance Model (cf. [37]), which can be employed. Additionally, necessary competencies can be identified by leveraging existing competency frameworks (e.g. [47]) and any competency gaps can be addressed accordingly. Customized training programs tailored to specific target groups can be developed to ensure context-sensitive learning. Barriers to training must be minimized by creating e.g. suitable learning nuggets (cf. [48]). Furthermore, making CDM a hands-on experience can be achieved by integrating the learning and research factory concept, which is a promising approach for qualifying employees and management to achieve the required skill levels [30]. These facilities aim to provide hands-on qualification, focusing on research, technology transfer, training, and education. They might serve as training centers for employees of different organizations and as demonstration facilities for introducing new approaches and technologies [49]. To foster an understanding of benefits and barriers of CDM, various initiatives such as public relations, use case demonstrations, dialogue rounds and networking events must be employed. Furthermore, organizations should establish a clear collaboration strategy with management commitment, develop a roadmap for CDM implementation, and incorporate procedures for updating CDM and the company's role by leveraging information on the latest technology trends, such as trend management and technology trend radars. To establish a cross-company process understanding, the *Conexing* platform might be used as a model, in which a unified working environment is created between different partners [50].

Table 3: Calls for action for successfully setting-up a CDM

Dim	Tasks to be completed	How / Tools / Measures
T	• Develop mature CDM (Technology Readiness Level ≥ 6) • Demonstrate at least technical feasibility • Describe features of CDM (e.g., language, attributes, interfaces, data inputs and outputs, data format, metamodel)	• Use the framework of *AutomationML* to create a common data model [51] • Develop prototype(s) with realistic and complex problems
	• Establish functional, modular Architecture	• Use, e.g., pattern-based microservice composition approach [52]
H	• Increase acceptance and trust in CDM • Identify needed competencies (skills and abilities) and competency gap	• Use of the technology acceptance model (TAM, cf. [37]) • Derive competencies from existing competency frameworks [47]
	• Offer context-sensitive training • Reduce barriers to training • Make CDM a hands-on experience • Create an understanding of benefits and barriers of CDM	• Develop customized training for different target groups • Develop suitable learning nuggets (cf. [48]) • Integrate the concept of learning and research factory (cf. [30]). • Enforce public relations and provide use cases, dialogue rounds, theme days and networking events, …
S	• Establish a clear strategy for collaboration and obtain management commitment • Develop a unique roadmap for CDM implementation. • Obtain information on latest technology trends and develop a procedure for updating CDM and the role of the company	• Setting up a defined framework for cooperation (Follow the rules of *Harris*, cf. [53]) • Recourse to roadmaps for the development of a CDM • Use trend management or technology trend radars [28]
	• Present clear standards for communication exchange	• Use of existing standards (e.g. ISO 18828)
O	• Record own processes in a suitable standardized way • predict and analyze the effects of CDM • Establish a procedure for adapting existing processes • Turn those affected into participants in the change process	• Use SIPOC (suppliers, inputs, process, outputs and customers) and map & analyze process landscape • Use of knowledge transfer methods (e.g., SECI model, cf. [54]) • Introduce change management
PN	• Promote cross-company process understanding and information exchange and harmonize processes	• Introduce Enterprise social network sites [32] • Integrate a shared work environment (e.g., *Conexing* platform, cf. [50])
	• Identify and promote the benefits of collaboration • Establish clear rules for data ownership and security	• Regular interactive team sessions • Provide Cross-company definition of standards and legal advice
E	• Increase agility of the enterprise • Comply with regulations and laws and ensure data security or infrastructure security • Obtain financial commitment for implementation of CDM	• Development of the Knowledge-Based Economy [55] • Compliance with the essential IT protection of the Federal Office for Information Security • Create a business plan and demonstrate long-term financial benefits

Within the partnership/network category cross-company process understanding and information exchange must be promoted to enable the harmonization of processes. For establishing a strategy for cross-company collaboration it is recommended to follow the rules of *Harris*, which encourage building and enforcing an awareness of cooperation [53]. Furthermore, data ownership and security rules must be established and collaboration benefits promoted. Table 3 sums up all derived actions. Based on these, the *DIAMOND* project [56] will develop a CDM for the plant design process.

6. Conclusion and Outlook

In conclusion, the diverse landscape of I4.0-technologies and the assessment of I4.0 readiness necessitate the identification of critical challenges impeding the adoption of specific technologies. Collaboration in big data spaces poses significant challenges that impact multiple organizations. They often need assistance managing digital transformation and the incorporation of new technologies within their organizational boundaries, further impeding the integration of technologies across the value chain. Thus, this paper investigated and categorized the challenges encountered in setting up a CDM within the plant design process and integrated them into an adapted I4.0 readiness model. 63 challenges were identified in response to the first research question, predominantly centered around technological challenges and a lack of knowledge, skills, and abilities. Regarding the second question, the challenges are mapped into an adapted readiness model encompassing six dimensions and 19 categories. Addressing these challenges requires targeted actions that are derived accordingly. Consequently, a comprehensive framework is provided that is suitable for the specific use case of setting-up a CDM in the plant design process. This framework answers the third research question by providing actions needed to set-up a CDM, while holistically addressing the various challenges of digital transformation. The development of CDM itself using *AutomationML* must be supported by enabling the organizations' employees to improve their skills and competencies through appropriate training. The framework serves as a holistic guideline for value networks.

Future research should prioritize these actions to enhance technology readiness and organizational preparedness for technology utilization by employees. The focus should be put on the employees and their competencies, as these are the enablers to shape the digital transformation. Therefore, it is crucial to better understand the current flow of data within the plant design process and evaluate the data quality along to identify specific training needs.

The transferability of knowledge, skills, and abilities as well as the organizational mindset developed during the implementation process of a CDM also facilitates the implementation of other I4.0-technologies due to interlocking effects. However, each technology implementation still presents its unique challenges. While this research only focuses on challenges regarding the plant design process, further challenges might hinder the implementation of other I4.0-technologies. Although the proposed calls for action do not serve as a one-fits-all solution, they are adaptable and extendable depending on other specific use cases and their requirements. The measures derived will be put into realization by the *DIAMOND* project. In it, a common data model that can be adapted to different use cases and a modern data exchange via common data spaces are being developed and tested. In addition to technical solutions, the organizations and needs of the people involved in the companies are also being considered. The project focuses on the process of plant design in the automotive industry and has 25 industry and research partners. Further tasks on how to create a CDM will be elaborated in later publications within the *DIAMOND* project. [56]

Acknowledgements

The DIAMOND research project is funded by the European Union (NextGeneration) and supported by the German Federal Ministry for Economic Affairs and Climate Action on the basis of a decision by the German Bundestag (Grant number 13IK011P).

References

[1] Stentoft, J., Adsbøll Wickstrøm, K., Philipsen, K., Haug, A., 2021. Drivers and barriers for Industry 4.0 readiness and practice: empirical evidence from small and medium-sized manufacturers. Production Planning & Control 32 (10), 811–828.

[2] Yu, F., Schweisfurth, T., 2020. Industry 4.0 technology implementation in SMEs: A survey in the Danish-German border region. International Journal of Innovation Studies 4 (3), 76–84.

[3] Hartmann, F., Mietzner, D., Dinh, H., 2015. Industrie 4.0 - Affinität von Branchen und Regionen.

[4] Sommer, S., Proff, H., Proff, H., 2021. Digital transformation in the global automotive industry. International Journal of Automotive Technology and Management 21 (4), 295–321.

[5] Rüßmann, M., Lorenz, M., Gerbert, P., Waldner, M., Engel, P., Harnisch, M., Justus, J., 2015. Industry 4.0: The Future of Productivity and Growth in Manufacturing Industries. BCG Global, April 9.

[6] Ligarski, M.J., Rożałowska, B., Kalinowski, K., 2021. A Study of the Human Factor in Industry 4.0 Based on the Automotive Industry. Energies 14 (20), 6833.

[7] Qi, Z., Schäfer, C., Klemm, P., 2005. General Engineering Data Model In Special Purpose Machine Engineering, in: Proceedings of the Second International Conference on Informatics in Control, Automation and Robotics, Barcelona, Spain, 348–354.

[8] Drath, R., Fay, A., Barth, M., 2011. Interoperabilität von Engineering-Werkzeugen: Konzepte und Empfehlungen für den Datenaustausch zwischen Engineering-Werkzeugen. at– Automatisierungstechnik (59), 451–460.

[9] Sharma, M., Luthra, S., Joshi, S., Kumar, A., 2022. Implementing challenges of artificial intelligence: Evidence from public manufacturing sector of an emerging economy. Government Information Quarterly 39 (4), 101624.

[10] Gujarathi, G.P., Ma, Y.-S., 2011. Parametric CAD/CAE integration using a common data model. Journal of Manufacturing Systems 30 (3), 118–132.

[11] Hizam-Hanafiah, M., Soomro, M., Abdullah, N., 2020. Industry 4.0 Readiness Models: A Systematic Literature Review of Model Dimensions. Information 11 (7), 364.

[12] Mittal, S., Khan, M.A., Romero, D., Wuest, T., 2018. A critical review of smart manufacturing & Industry 4.0 maturity models: Implications for small and medium-sized enterprises (SMEs). Journal of Manufacturing Systems 49, 194–214.

[13] Nick, G., Kovács, T., Kő, A., Kádár, B., 2021. Industry 4.0 readiness in manufacturing: Company Compass 2.0, a renewed framework and solution for Industry 4.0 maturity assessment. Procedia Manufacturing 54, 39–44.

[14] Zoubek, M., Poor, P., Broum, T., Basl, J., Simon, M., 2021. Industry 4.0 Maturity Model Assessing Environmental Attributes of Manufacturing Company. Applied Sciences 11 (11), 5151.

[15] Dikhanbayeva, D., Shaikholla, S., Suleiman, Z., Turkyilmaz, A., 2020. Assessment of Industry 4.0 Maturity Models by Design Principles. Sustainability 12 (23), 9927.

[16] Müller, R., Vette, M., Hörauf, L., Speicher, C., Müller, J., Roch, F., Obele, J., 2017. Kommunikation im Anlagenentstehungsprozess: Plattform zur unterstützung der Kommunikation zwischen Kunde und Anlagenbauer. wt Werkstatttechnik 107 (9), 647–651.

[17] Oraee, M., Hosseini, M.R., Edwards, D.J., Li, H., Papadonikolaki, E., Cao, D., 2019. Collaboration barriers in BIM-based construction networks: A conceptual model. International Journal of Project Management 37 (6), 839–854.

[18] Perno, M., Hvam, L., Haug, A., 2022. Implementation of digital twins in the process industry: A systematic literature review of enablers and barriers. Computers in Industry 134, 103558.

[19] Mohamed, M., 2018. Challenges and Benefits of Industry 4.0: An overview. International Journal of Supply and Operations Management (5), 256–265.

[20] Bartelt, M., Schyja, A., Kuhlenkötter, B., 2014. More than a Mockup. Prod. Eng. Res. Devel. 8 (6), 727–735.

[21] Bundesministerium für Bildung und Forschung (BMBF), 2023. Verbundprojekt: ENTOC - Engineering Tool Chain for Efficient and Iterative Development of Smart Factories. Accessed 27 June 2023.

[22] Fraunhofer IESE, 2023. Basissystem Industrie 4.0. https://www.softwaresysteme.dlr-pt.de/de/basys-4-0.php. Accessed 27 June 2023.

[23] Dipl.-Ing. Cornelia Klaubert, 2023. FORBAU - BayFOR. Bayerische Forschungsallianz GmbH. https://www.bayfor.org/de/unsere-netzwerke/bayerische-forschungsverbuende/forschungsverbuende/association/forbau.html. Accessed 27 June 2023.

[24] Catena-X Automotive Network e.V., 2023. Vision & Ziele | Catena-X. https://catena-x.net/de/vision-ziele. Accessed 27 June 2023.

[25] Götz, J., 2015. Community-basierte Optimierung des Anlagenengineerings. Dissertation.

[26] Schreiber, W., Zimmermann, P. (Eds.), 2011. Virtuelle Techniken im industriellen Umfeld: Das AVILUS-Projekt - Technologien und Anwendungen. Springer, Berlin.

[27] Talkhestani, B.A., Jazdi, N., Schlögl, W., Weyrich, M., 2017. A concept in synchronization of virtual production system with real factory based on anchor-point method. 11th CIRP Conference on Intelligent Computation in Manufacturing Engineering.

[28] Drees, T., Nagarajah, A., 2023. Status Quo der Digitalisierung von KMU im Ruhrgebiet – Eine quantitative Erhebung im Weiterbildungsverbund WIN 4.0, in: Proff, H. (Ed.), Towards the New Normal in Mobility. Springer Fachmedien Wiesbaden, Wiesbaden, 713–730.

[29] Hermann, T., Hirschle, S., Kowol, D., Rapp, J., Resch, U., Rothmann, J., 2017. Auswirkungen von Industrie 4.0 auf das Anforderungsprofil der Arbeitnehmer und die Folgen im Rahmen der Aus- und Weiterbildung, in: Andelfinger, V.P., Hänisch, T. (Eds.), Industrie 4.0. Springer Fachmedien. Wiesbaden, 239–253.

[30] Öztürk, E., Hulla, M., Prinz, C., Kuhlenkötter, B., Ramsauer, C., 2022. Digital Transformation Methods in Learning Factory Based Trainings. Proceedings of the 12th Conference on Learning Factories (CLF 2022).

[31] Calà, A., 2019. A novel migration approach towards decentralized automation in cyber-physical production systems. Dissertation, Magdeburg.

[32] European Commission, 2022. Digital Economy and Society Index (DESI) 2022, Brussels, https://digital-strategy.ec.europa.eu/en/policies/desi. Accessed 13 July 2023.

[33] Czernich, N., Fackler, T., Falck, O., Schüller, S., Wichert, S., Keveloh, K., Vijayakumar, R.M., 2019. Digitale Kompetenzen – Ist die deutsche Industrie bereit für die Zukunft?. https://www.ifo.de/publikationen/2019/monographie-autorenschaft/digitale-kompetenzen-ist-die-deutsche-industrie-bereit. Accessed 13 July 2023.

[34] Horváth, D., Szabó, R.Z., 2019. Driving forces and barriers of Industry 4.0: Do multinational and small and medium-sized companies have equal opportunities? Technological Forecasting and Social Change 146, 119–132.

[35] Müller, J.M., 2019. Assessing the barriers to Industry 4.0 implementation from a workers' perspective. IFAC-PapersOnLine 52 (13), 2189–2194.

[36] Bajic, B., Rikalovic, A., Suzic, N., Piuri, V., 2021. Industry 4.0 Implementation Challenges and Opportunities: A Managerial Perspective. IEEE Systems Journal 15 (1), 546–559.

[37] Kamal, S.A., Shafiq, M., Kakria, P., 2020. Investigating acceptance of telemedicine services through an extended technology acceptance model (TAM). Technology in Society 60, 101212.

[38] Schröder, C., 2016. The challenges of industry 4.0 for small and medium-sized enterprises. Friedrich-Ebert-Stiftung, Division for Economic and Social Policy, Bonn.

[39] Yaqub, M.Z., Alsabban, A., 2023. Industry-4.0-Enabled Digital Transformation: Prospects, Instruments, Challenges, and Implications for Business Strategies. Sustainability 15 (11), 8553.

[40] Machado, C.G., Winroth, M., Carlsson, D., Almström, P., Centerholt, V., Hallin, M., 2019. Industry 4.0 readiness in manufacturing companies: challenges and enablers towards increased digitalization. Procedia CIRP 81, 1113–1118.

[41] Jones, M.D., Hutcheson, S., Camba, J.D., 2021. Past, present, and future barriers to digital transformation in manufacturing: A review. Journal of Manufacturing Systems 60, 936–948.

[42] Essakly, A., Wichmann, M., Spengler, T.S., 2019. A reference framework for the holistic evaluation of Industry 4.0 solutions for small-and medium-sized enterprises. IFAC-PapersOnLine 52 (13), 427–432.

[43] 2005. Proceedings of the Second International Conference on Informatics in Control, Automation and Robotics.

[44] Naeem, H.M., Di Maria, E., 2022. Customer participation in new product development: an Industry 4.0 perspective. EJIM 25 (6), 637–655.

[45] Angreani, L.S., Vijaya, A., Wicaksono, H., 2020. Systematic Literature Review of Industry 4.0 Maturity Model for Manufacturing and Logistics Sectors. Procedia Manufacturing 52, 337–343.

[46] Sadin, S.R., Povinelli, F.P., Rosen, R., 1989. The NASA technology push towards future space mission systems. Acta Astronautica 20, 73–77.

[47] DIN, 2020. A common European Framework for ICT Professionals in all sectors – Part 1: Framework.

[48] Oliveira, A., Assumpcao, H., Queiroz, J., Piardi, L., Parra, J., Leitao, P., 2022. Hands-on Learning Modules for Upskilling in Industry 4.0 Technologies, in: 5th International Conference on Industrial Cyber-Physical Systems (ICPS). Coventry, United Kingdom. IEEE, 1–6.

[49] Schallock, B., Rybski, C., Jochem, R., Kohl, H., 2018. Learning Factory for Industry 4.0 to provide future skills beyond technical training. Procedia Manufacturing 23, 27–32.

[50] Bartelt, M., Kuhlenkötter, B. (Eds.), 2016. Conexing Abschlussbericht. Westdeutscher Universitätsverlag, Bochum.

[51] Schroeder, G.N., Steinmetz, C., Pereira, C.E., Espindola, D.B., 2016. Digital Twin Data Modeling with AutomationML and a Communication Methodology for Data Exchange. IFAC-PapersOnLine 49 (30), 12–17.

[52] Yussupov, V., Breitenbucher, U., Krieger, C., Leymann, F., Soldani, J., Wurster, M., 2020. Pattern-based Modelling, Integration, and Deployment of Microservice Architectures, in: 24th International Enterprise Distributed Object Computing Conference (EDOC), Eindhoven, Netherlands. IEEE, 40–50.

[53] Harris, M., 2010. Interdisciplinary Strategy and Collaboration: A Case Study of American Research Universities. Journal of Research Administration 41 (1), 22–34.

[54] Choo, C.W., Bontis, N. (Eds.), 2002. The strategic management of intellectual capital and organizational knowledge. Oxford University Press.

[55] Trzcielinski, S., 2015. The Influence of Knowledge Based Economy on Agility of Enterprise. Procedia Manufacturing 3, 6615–6623.

[56] Diamond, 2023. Digitale Anlagenmodellierung mit neutralen Datenformaten. https://diamond-project.de/. Accessed 27 July 2023.

Biography

Tobias Drees (*1993) has been a research assistant at the Chair of Production Systems (LPS) at the Ruhr-University Bochum since 2023. He is focussing on the design of employee trainings in the context of Industry 4.0. Previously, after graduating in Automotive Engineering & Management with distinction in 2019, he worked as research assistant at the Institute of Product Engineering (IPE) in Duisburg.

Alexander Große-Kreul (*1997) completed his master's degree in mechanical engineering in 2023 at the Ruhr-University Bochum. Since June 2023 he has been working as a research associate at the chair of production systems. His thematic focus is on data consistency in the plant design process and mobile robotics.

Daniel Syniawa (*1996), M.Sc., works as a research assistant at the Chair of Production Systems (LPS) at the Ruhr-University Bochum. His current research topics include the digitalization of engineering processes in electrolyzer production and standardized data models in the context of Industry 4.0.

Lars Niklas Josler (*1993), M.Sc. worked as a research assistant at the Chair of Production Systems (LPS) at the Ruhr-University Bochum from 2018 to 2023. His research activities focused on industrial robotics, service robotics, and digitization. Since March 2023, he has been working at Evonik Operation GmbH.

Dr.-Ing. Alfred Hypki (*1963) has been chief engineer at the Chair of Production Systems (LPS) at the Ruhr-University Bochum since 2015. His main research activities are robot simulation, robot programming and human-robot collaboration. Until 2009 he was a research assistant at the Institute of Robotics Research at TU Dortmund University, where he received his doctoral degree. From 2009 to 2015 he was chief engineer at the Institute for Production Systems at TU Dortmund University.

Prof. Dr.-Ing. Bernd Kuhlenkötter (*1971) has been head of the Chair of Production Systems at Ruhr University in Bochum since April 2015. He received his doctoral degree in 2001 at Dortmund University. In April 2009, after working for ABB Automation GmbH as head of product management and technology, he took over the Professorship for Industrial Robotics and Production Automation at TU Dortmund, where he founded the Institute for Production Systems in 2012 and acted as manager until March 2015.

CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
CPSL 2023-2

5th Conference on Production Systems and Logistics

Polygon Interface Analysis: A Concept For Analyzing Production Site Interactions In Urban Areas

Severin J. Görgens[1,2], Kolja H. Meyer[1,2], Anne Wetzel[2], Mark Mennenga[2]
[1]*Technische Universität Braunschweig, Junior Research Group Urban Flows and Production, Langer Kamp 19 b, Braunschweig 38106, Germany*
[2]*Technische Universität Braunschweig, Institute of Machine Tools and Production Technology, Langer Kamp 19 b, Braunschweig 38106, Germany*

Abstract

Urban production bears the potential to not only reduce the negative impacts of production processes and global supply chains but also to generate a positive contribution to society and the environment when integrated symbiotically into the urban context. However, especially in urban areas, production is often associated with negative impacts on the surrounding environment. Therefore, the interactions between producing companies and their environment need to be considered and analysed. Hence, we derive a conceptual model that allows the exploitation of the potentials of urban locations for production by focusing on the interfaces between urban production and the urban environment. For this purpose, the Polygon Interface Analysis [P.I.A.] is introduced. It makes use of the principle of a Rubik's Cube or a Caesar Cipher by altering layers for matchmaking and integrates the business, city and interface perspective into an applicable analysis approach. To conceptualize this model existing approaches from the fields of factory planning and strategy development are examined in regard to their suitability for applying those for a location analysis of urban factories. Based on this, a suggestion for the application of the P.I.A. is given. The application of the model allows for the improvement of manufacturing integration in urban environments by supporting factory planning decisions, production system design, as well as location and site analysis for urban production.

Keywords

Urban Production; Urban Manufacturing; Interface Analysis; Location Analysis; Polygon Interface Analysis

1. Introduction

More than half of the world's population now lives in cities [1]. Trends such as urbanization, combined with population growth, will continue to intensify this development in the future. Cities have become the center of value creation due to their high density of knowledge, labor, infrastructure and proximity to potential customers [2,3]. While the production of consumer goods was also integral to urban crafts during pre-industrial times [4,5], locations for industrial mass production gradually clustered and relocated outside cities [6–8]. These relocations were primarily driven by the need to mitigate the adverse effects of production and were accompanied by a strong focus on infrastructure development. In particular, advancements in logistics facilitated the emergence of new production concepts in locations outside city centers [9]. Consequently, specialized companies have been established which followed the economy of scale paradigm, which lead to significant economic implications, like the emergence of centralized production sites. [10,11]. This separation of production and consumption consequently resulted in the emergence of global supply chains, which are vulnerable to diverse kinds of shocks. These shocks can be addressed through the

DOI: https://doi.org/10.15488/15245
ISSN: 2701-6277

relocalization of the production to the city [12]. To achieve this, planning decisions must be supported by suitable planning approaches.

There are different approaches and methods available that support the strategic planning of site localization and factory planning [13–21]. These methods and models relate to the macro and micro environments of the business in different ways. The term environment is used in this paper in two complementary ways. This includes both tangible and intangible environments as seen from a strategic management perspective, as well as the physical environment. These two readings are obviously interrelated and therefore are not referred to differently, but are used contextually. When considering a production site in the city, the unique potentials and requirements of this environment must be taken into account. [5,22–24]. For instance, Herrmann et al. identified impact categories of factories in the urban environment, which are domains of interaction, in the three dimensions of sustainability: economic, environmental and social [25]. With respect to these interactions in the case of urban production, the aim is to achieve a positive impact on the surrounding [26]. This is to be strived for not only in new establishments but also in the shaping and improvement of the integration of existing sites in the urban environment. The mentioned common methods have emerged in times of global value networks [13–17,27,18,28,19–21]. In addition, the understanding of what makes a city livable, and thus what urban sites must respect, has evolved [29–33]. A connection between the city and the production location is thus a central element, that needs consideration in location decisions and developments of urban production. There are approaches in the literature to describe this connection [34–36]. However, these approaches only address specific aspects of the connection or present it in a manner unsuitable for constructing an applicable, user-friendly model. This is because these approaches describe higher-level systematics, some of which are complex in structure or do not provide sufficient depth. Against the backdrop of changing production paradigms and technologies, which can enable establishments in environments with strict requirements [37,25,23,38] and to increase urban resilience [39,12], it is necessary to consider urban locations as an option in strategic decisions. An applicable model must therefore be available as a tool for various stakeholders and decision makers. It should provide a way to decipher the multi-layered interactions for the involved stakeholders and their various use-cases. This prompts the following research questions:

RQ1: Are currently used location analysis models applicable to the case of urban production?

RQ2: How can a model be designed to take the requirements of urban production into account?

To address RQ1, this paper performs an evaluation of commonly used approaches to site assessment. For this purpose, it is examined whether the previously mentioned models take the requirements of the urban area into account, which result from the research on interactions of production with the urban environment. Subsequently, the perspectives that are elementary for a suitable model are identified and introduced. It is shown how the business and the urban perspectives can be represented. Also, an approach to describe the interfaces between both perspectives is outlined. To address RQ2, these three perspectives are combined into a single model and a description of the application of this model is shown. The paper concludes with a critical discussion and limitation of the presented model and providing an outlook on potential future research topics.

2. Evaluation of existing models

Authors from diverse fields have proposed models and approaches for analyzing production sites and their interactions with the environment. On the one hand, there are numerous methods for selecting a factory location in the field of factory planning [14,40,27]. These methods are categorized into those with a singular objective, such as optimizing transport costs, and those that consider a variety of location factors [15]. On the other hand, there are various methods from strategy development that can be used to consider the factors and forces affecting a company [16,18,41,21].

2.1 Methods from the domain of factory planning

Methods of location analysis with singular objectives form the basis of location theory [42,27]. These objectives encompass cost reduction, market access, and material availability, often formalized through mathematical approaches [42,27]. For instance, with the location triangle Weber [20] focuses on minimizing transport costs by finding the optimal location of a factory located in a triangle between two input sources and the output market [13,27]. A more comprehensive way of selecting a location is to determine the factors that influence the respective production site, the so-called location factors [13]. Authors such as Sharma et al. and Kimelberg & Williams present a series of location factors that are intended to enable evaluation of the production site on the basis of various target criteria [42,40]. In addition, the factors are often classified into individual clusters. Kimelberg & Williams developed a classification according to six categories: business environment; development and operating costs; labor; permitting processes; quality of life/social environment; transportation and access [42]. Furthermore, a factor rating method is required to ensure the comparability of different sites based on these location factors [40].

2.2 Methods from the domain of strategy development

Additionally, there are approaches from strategy development that analyze a company's micro and macro environment to inform strategic decisions and business model development. A common framework to illustrate the macro environment of a business is the so-called PESTEL analysis. This approach identifies the opportunities and risks of a business in its environment through six categories of factors: political, economic, socio-cultural, technological, environmental and legal [16]. However, conducting an objective analysis of the factors is challenging due to the framework's predominantly qualitative structure [21]. Authors such as Schallmo [41], Yüksel [21], Kaufmann [16] provide numerous examples of factors, which are taken into account in each category. Another method in the field of strategy development is the Five Forces concept according to Porter which allows an analysis of the micro environment of a company [18]. This framework outlines an industry's structure through five forces: existing competitors, new competitors, customers, substitutes and suppliers. The characteristics of the individual forces allows conclusions to be drawn about the competitiveness of the company [43].

			Factory Planning			Strategy Development	
			Weber's Location Triangle	**Business Location Factors**	**Factors Rating**	**PESTEL Analysis**	**Five Forces Analysis**
			[20]	[13, 42]	[40]	[16, 21, 41]	[18]
Resources of the urban factory	Energy		●	○	●	●	○
	Materials		●	○	●	●	◐
	Human	Consumers	●	○	◐	●	●
		Workers	○	●	●	◐	○
		Neighborhood	○	●	●	◐	○
	Space		○	●	◐	○	○
	Knowledge		○	◐	○	○	○
	Justice & Culture		○	●	●	●	○
	Mobility		●	●	●	●	○
	Image & Appearance		○	◐	◐	○	○
Spatial reference	Global Context		○	○	○	x	x
	City Region		◐	◐	◐	x	x
	Quarter		●	●	●	x	x
	(Factory) Location		●	●	●	x	x

●	applicable	○	not applicable
◐	applicable in aspects	x	not assessable

Figure 1:Evaluation of factory planning methods and strategic decision-making models.

In order to evaluate the suitability of the mentioned methods for the urban context, an assessment is made of the extent to which the resources of the urban factory as well as the different spatial dimensions are taken into account. One method to describe the interaction are the resources of the urban factory introduced by Juraschek et al. [34]. They represent a high-level agglomeration of parameters to enable interactions and their description in the factory-city system. This makes it possible to assess the extent to which the special interactions between the city and the factory are taken into account. Urban resources include energy, knowledge, materials, human, space, justice/culture, mobility and image/appearance [34]. Furthermore, an analysis of spatial context is necessary. This helps to determine whether only global-level factors are considered or if the impact on the urban neighborhood is examined in detail. The spatial dimension can be divided into different levels following Herrmann et al. [26], shown in Figure 1 as the spatial references. Figure 1 shows a Harvey Ball Matrix which addresses whether and to which extent predefined criteria are matched.

With respect to spatial reference, the methods from the domain of factory planning focus particularly on the local environment and are suitable for urban analysis in this respect. However, for the approaches of strategy development an evaluation based on the spatial reference is not possible, since these are only frameworks and therefore depend on the selected factors. Regarding the resources of urban factories, no differentiation can be made between the two domains of methods, as they each contribute to these resources in distinct ways. The approaches according to Von Thünen and Lösch were deliberately not listed, as they are missing consideration of social, cultural and environmental factors and therefore have the same deficiencies as Weber's location triangle [13,27]. However, location analysis methods based on location factors appear to be particularly suitable to address the resources of urban factories. Accordingly, the consideration of explicit location factors is identified as a suitable approach to describe interactions between city and factory. Thus, the following conclusion can be drawn for the research question **RG1**: A complete coverage of the resources of the urban factory is not given to a sufficient extent in any of the methods. Accordingly, a method is needed that maps the analysis of locations in relation to their interaction with their environment.

3. Perspectives of location analysis and determination of the Polygon Interface Analysis [P.I.A.]

This section outlines different perspectives concerning urban production sites and their interactions. Based on this, the main components for an analysis model are derived. These are combined to develop a novel approach for a holistic analytic method. Different authors recognize the connection between production and an urban environment and the need for a formalized description of both [26,5,44,12,36,33]. The described connections focus on different aspects like the influence of the product produced [36], sustainable development [44], the utilization of urban flows [12] or the urban resources [33]. Moreover, it is shown that the urban environment has an influence on the selection and design of production systems through its characteristics [23]. Essentially, the urban environment has an influence on the selection and design of production systems through its characteristics. An analysis of production sites in urban areas must include the perspective of the production business as well as the perspective of the city. Moreover, it's evident that a third perspective must be considered, representing the connection between the aforementioned perspectives—these are the interfaces. These identified perspectives are introduced below, establishing a foundational basis for a model design process.

3.1 Perspectives on location analysis

The first perspective focuses on the **production business** itself. In this regard, a formalization of the production entities is necessary. Following a compositional approach, businesses can be described by the division into systems and subsystems of different complexity [45–47]. This bears the potential to focus on separate areas and to reach deeper levels of technical observation such as production system design processes or manufacturing systems [48]. While describing businesses as systems has limitations in capturing business processes [46], it facilitates a seamless connection between the design and assessment of production systems, which enables a holistic understanding of businesses and their interactions with urban surroundings [49]. Including different perspectives such as the cooperation system-of-systems framework of Vinakota [49] and the system-of-systems network approach by Arnautovic et al. [50], [50,4,49] different subsystems are described for a holistic business description. To develop a structured design for a location analyses model and an improved usability a clustering of the systems is proposed. The systems within the clusters can be mutually interrelated with other systems of the same cluster, but also with systems of other clusters. These interdependencies of the system elements are initially mostly disregarded in this draft of the model for a better creation process, interpretability and application. The clustering of systems streamlines the application of the model by individuals from diverse professional backgrounds, and enables faster targeted analysis with respect to particular use cases. A categorization of the systems into two main clusters is proposed here. Aligned with Arnautovic et al. and Hahn and Laßmann, one of these clusters originates from organizational aspects, while the other significant cluster encompasses technical aspects [50,4]. The systems and subsystems are arranged hierarchically, while an order of individual clusters and systems is generally not provided, but can emerge in specific cases. For the definition of a model, it distinguishes between organizational and physical systems. Organizational systems pertain to the business's organizational components, whereas physical systems encompass the tangible aspects of a business that interact with the surroundings on a physical and technological level. In addition to this distinction, an assignment of subsystems to another cluster, regarding their interaction capability, is proposed. Following the arguments of Rudolf et al., Juraschek, and Herrmann et al. production businesses can unfold a positive impact on their surrounding by providing services and infrastructure which contribute to the provision of urban functions [5,51,36]. Given that the integration of a factory into the urban environment is pivotal in urban production [26] systems aligned with this objective can be grouped within a designated cluster. This cluster of functional elements describes systems which are not necessarily represented by the previously mentioned clusters and which a business can provide to support the integration into the urban environment. Existing systems can be transformed or enhanced to serve as a functional element. Therefore, the assignment of a system to this cluster may not be distinct in some cases. Especially when a location analysis is conducted to explore a site's potential for improved urban integration, systems can be further allocated to this cluster. It thus offers a simplification of the application, in this case.

The second perspective focuses on the role of the **urban area** in relation to the business' systems. Urban areas can also be described from a system perspective [52–55]. This approach bears the potential for an extensive analysis of urban areas with a connection to businesses by focusing on elements of the city systems. This results in a high complexity which hampers the applicability for non-experts in system engineering. In this regard, it is still only possible to focus on the interaction of single physical entities but more of a city as a livable environment in its entirety. Definitions and descriptions of cities as a whole are various from different scientific disciplines with different objectives [30,56–60]. One way to holistically describe cities with a focus on liveability are city functions. Juraschek shows different functions within the city-factory-product nexus [44]. These functions are utilized to develop a structured and applicable model for the analysis of urban production sites. This approach is feasible and suitable for urban production location analyses on the city level, if the systems of businesses on the one hand will be linked to the city functions on the other hand by distinguished interfaces.

The third perspective consists of **interfaces and influencing factors** to define the connection and interactions between the urban and the business perspective. The urban resources, described as potentially shared resources of the site and the city, are one approach to define fields of interactions [33]. These resources build a framework to describe interactions between factories and cities [61]. Since the resources-based approach provides a broad overview of interaction domains, a more detailed classification into socio-economic, physical-technological and physical-urban interfaces can be performed. **Socio-economic interfaces** focus on human related or economic fields of interaction. **Physical-urban interfaces** are close related to the services or supply of physical entities of the urban environment, which can also be provided by companies. In contrast thereto, **physical-technical interfaces** predominantly originate more from the technical site perspective. These can be roughly divided into physical inputs and outputs and thus represent the interaction with the immediate environment through material flows. They have their theoretical origin predominantly in the production factors after Gutenberg and Heinen [62,63]. The different interfaces can be influenced in various ways [13]. To enable a description and quantification of the dimensions, aspects and weighting of interactions, we introduce different influencing factors. An example for such an influencing factor from the domain of the socio-economic interfaces are the prices suppliers demand, another one from the domain of physical-urban interfaces are the road load boundaries of the streets as part of the traffic infrastructure. An example from the physical-technical interfaces domain are the geometric dimensions of a product.

Figure 2 gives an overview on proposed elements of the three aforementioned perspectives. These lists show a proposed selection of elements partly derived from various sources and extended by own suggestions [30,64,62,4,63,22,16,42,31,27,18,36,19–21]. With this list a fundamental introduction of a created model should be given and should enable the explanation of its functioning. This depiction has no claim to be complete, as it can be extended by experts from different disciplines and adjusted to various use-cases.

Production business
[4, 16, 18, 19, 21, 22, 26, 42, 62, 63]

Organizational systems
- *Strategic management*: Planning, Organization, Governance and management, Control, Corporate strategy, Product program planning
- *Tactical management*: Planning, Organization, Governance / Management, Control
- *Operative management*: Planning, Organization, Governance and management, Control, Production planning, personnel planning
- *Services*: Product related services, Non product related services
- *Corporate citizenship*: Social sustainability management, Ecological sustainability management

Physical systems
- *Spatial design and influences*: Location internal, Physical location interfaces, External physical systems
- *Technology and production system*: Technical building equipment, Machines, Tools and equipment

Functional elements
- *Canteen*: Kitchen, Seating area
- *Semi-public transport*: Busses, Parking lots, Driving staff

+ more

Interfaces
[16, 18, 19, 22, 36, 62-64]

Physical-urban interfaces
- *Energy*: Electric energy, Heat
- *Water*: Fresh water, Waste water
- *Communication*: Internet, Public media, Network coverage
- *Safety facilities*: Fire department, Crime prevention and prosecution, IT security infrastructure
- *Traffic (moving)*: Streets, Public transport, Local public fright transport, Waterways, Parking
- *Site and building*: Real estate, Building

Socio-economic interfaces
- *Business to business*: Competitors, Suppliers and sources of supply
- *Individuals*: Workforce, Proximate neighborhood

Physical-technological interfaces
- *Physical input*: Raw materials and semi-finished products, Auxiliary materials, other operation resources
- *Physical output*: products, By-products, Waste

+ more

Urban area
[44]

Urban functions
- Work
- Education
- Innovation
- Living
- Value creation
- Identification
- Recreation
- Services
- Production of goods
- Local supply
- Communication
- Ecology
- Mobility
- Culture
- Safety
- Micro climate
- Logistics
- Diversity
- Justice
- Resilience

+ more

Figure 2: Proposed structure and elements of the perspectives of a location analysis model for urban production

3.2 Polygon Interface Analysis [P.I.A.]

The assembling of the three described perspectives, the production site in form of business systems, the urban area, described by city functions, and the connecting interfaces with their assigned influencing factors, into a joint theoretical model can be visualized by a multi-layer polygon, presented in figure 3. The different layers contain individual elements to be considered in an analysis of the interactions of the urban area and producing businesses. The elements can be exchanged within their respective layer. Thus, the individual polygon elements can be shifted against each other creating a variety of possible combinations of interactions, if quantified leading to a variety of KPIs. Influencing factors also affect the interfaces, and thus influence the KPIs that can be obtained from relating the perspectives of production businesses, interfaces, and urban area. Consequently, the functioning of P.I.A. is comparable to a Rubik's cube or a multi-layer Caesar cipher, allowing for two perspectives in the analysis:

1) On the one hand, it is possible to start the analysis from the inner circle, thus from the producing business. Here, the influence factors of the sub-systems and related systems of the producing business on the urban functions via interfaces can be described.

2) On the other hand, the analysis can start from the outer circle, thus from the urban area, taking a close look on different city functions and their potential interconnection to the sub-systems of the producing company via the interfaces.

In this way, P.I.A. can be used for analysis of a multitude of possible combinations, and to accentuate fields that might not have been considered otherwise. It should be noted that not all combinations make sense. In figure 3, a hypothetical subsystem $_{2.2}$ – system $_{2}$ – interface $_{2}$ - city function $_{2}$ is shown. The position of 2.2, 2, 2, 2 is just chosen for aesthetic reasons and has no further relevance.

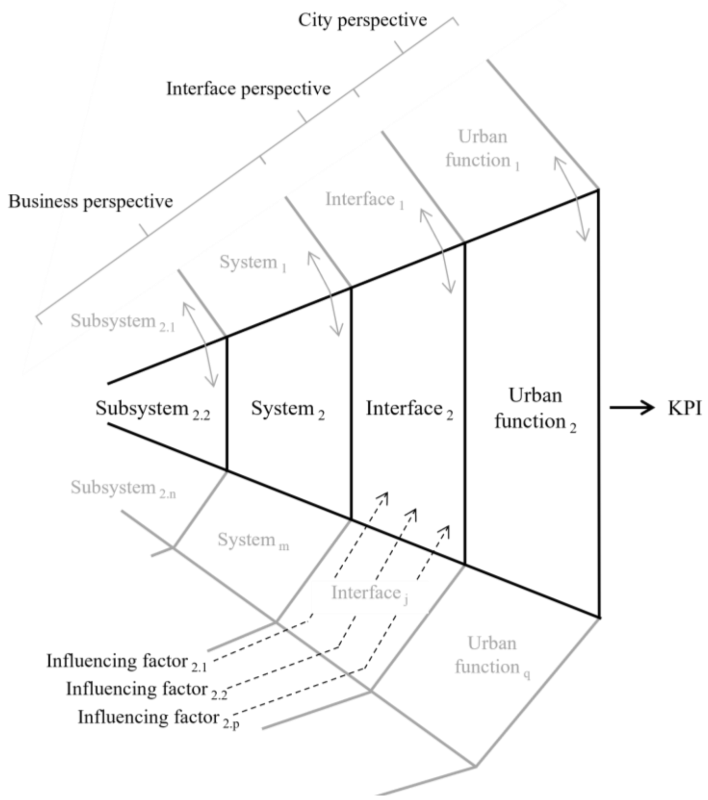


Figure 3: Polygon Interface Analysis [P.I.A.] scheme

4. Theoretical application example

To emphasize a possible application and the way this model can be applied, a theoretical example is given in the following. The scenario consists of a production site that is located within an urban area and produces metal parts. For a simplified presentation, only the following elements are initially provided: the city functions of local supply and logistics, the physical-urban interfaces of electric energy and the physical-technical interface of raw material, while influencing factors are left out for simplification reasons, the production system from the system perspective with the subsystems of a milling machine (CNC-mill) and a machine for metal additive manufacturing (AM machine). These subsystems have designated requirements and properties. The energy consumption and the material consumption are two of these which differ.

In the initial state the CNC-mill is used at the specific location. Its energy consumption is related to the interface of electric energy and through this connected to the city with its function of local supply. If the subsystem part of the model is shifted towards an alternative subsystem like the AM machine the energy consumption changes and therefore the influence on the city function of local supply changes. A shift in of raw material demand will change the interaction with the city in regards of its function of local supply as well, but to represent this within the model the perspective of the interfaces has to be adjusted to the physical-technical interface of raw material. These changes are visualized in figure 4. While changing the subsystem and keeping the other perspectives, a direct comparison between these subsystems is possible. Also, the influence on other city functions can be analyzed. Assuming that the raw material demand varies between the machines, the influence on the city function logistics would change by a switch of the considered subsystem. Beside these mentioned subsystems, interfaces and city functions there are various other options to consider based on this model. A possible changing influence of a subsystem on a city function can thus be pointed out even at a non-intuitive interface and with an initially not considered interaction. This highly simplified theoretical example shows the extensive potential of the P.I.A. model.

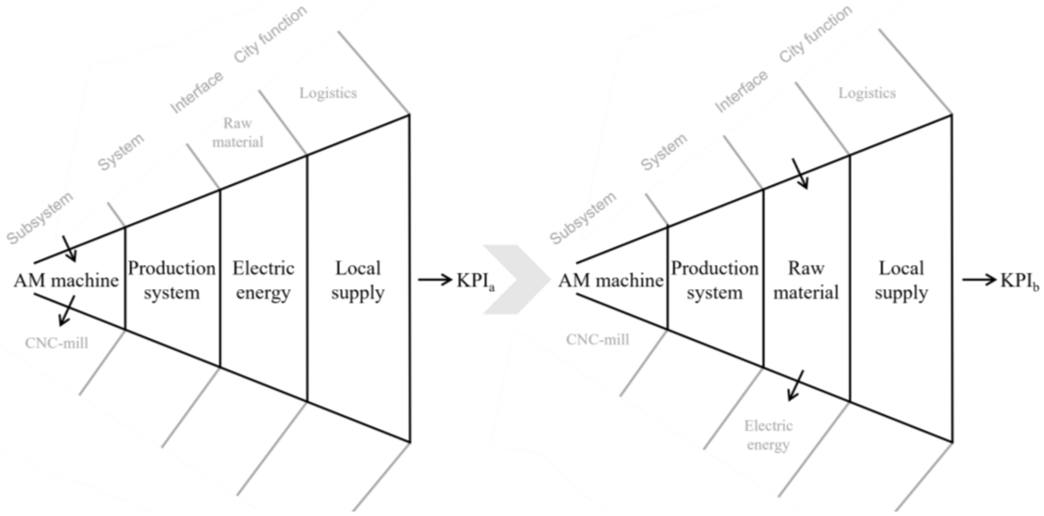


Figure 4: Polygon Interface Analysis [P.I.A.] application scenario

5. Discussion, limitation and outlook

Beside this highlighted potential of the model, it also bears the challenge of its intricate interdisciplinary and complex nature. This makes it challenging to create comprehensive lists of all systems and subsystems to be considered, as well as interfaces and influencing factors. The list of city functions and their definitions got enhanced, improved and adjusted over time by diverse scholars from various fields of research [29,30,64,65,61,66,31–33,67]. When applying a model that contains these functions, users can select the list of city functions to suit the specific use case. The presented structure of systems can also be refined and the analysis can be brought to different, very specific levels. An enhancing approach treating the city as a system of systems is conceivable. The city functions could work as another layer of interfaces or high-level systems in this case. This would enable new potentials for connections between the business systems and the city systems but also makes the model less usable for users, which are not experts in the field of systems of systems. Nevertheless, collaborative automation efforts and the ongoing digital transformation towards interconnected business ecosystems for flexible production can benefit from such system-of-systems approaches, where an integration of this model can be beneficial in the future, if applied to connect business entities with each other [68]. As a prerequisite for further enhancements the systems, subsystems, interfaces, and city functions presented here need to be verified and refined in further research. The entire approach of the model also needs to be validated by use cases in the future. Also, an extension of the business systems by the aforementioned functional elements would be beneficial to increase the use cases of the model. In this context, functional elements represent not only physical entities, but also potentially services. By deploying such elements as systems in the understanding of this model, the inclusion of site locations into the city can be improved and the transformation of sites into a positive impacting plant can be supported. Shaping the model based on practical data would be beneficial. As a subject of further research, not only the verification of the model based on this data and the refinement of it can be pointed out, but also the creation of KPIs for as many perspective combinations as possible. Therefore, a quantitative elicitation of the interactive relationships is necessary, which necessitates mathematical approaches within holistic, model-based approaches. The subject of future research can be a systematic approach with which these KPIs can be formed for diverse combinations of systems, interfaces and city functions.

Acknowledgments

The authors are thankful to the Deutsche Forschungsgemeinschaft (DFG) for funding the Junior Research Group Urban Flows and Production as part of the DFG Universitätspauschale (Grant number UP 8/1).

References

[1] United Nations, 2018. Revision of World Urbanization Prospects | United Nations. https://www.un.org/en/desa/2018-revision-world-urbanization-prospects. Accessed 8 August 2022.

[2] Juraschek, M., Thiede, S., Herrmann, C., 2018. Urbane Produktion, in: Corsten, H., Gössinger, R., Spengler, T.S. (Eds.), Handbuch Produktions- und Logistikmanagement in Wertschöpfungsnetzwerken. De Gruyter, pp. 1113–1133.

[3] Juraschek, M., Vossen, B., Hoffschröer, H., Reicher, C., Herrmann, C., 2018. Urbane Produktion: Ökotone als Analogie für eine nachhaltige Wertschöpfung in Städten, in: Redlich, T., Moritz, M., Wulfsberg, J.P. (Eds.), Interdisziplinäre Perspektiven zur Zukunft der Wertschöpfung. Springer Fachmedien Wiesbaden, Wiesbaden.

[4] Hahn, D., Laßmann, G. (Eds.), 1999. Produktionswirtschaft — Controlling industrieller Produktion. Physica-Verlag HD, Heidelberg.

[5] Herrmann, C., Juraschek, M., Burggräf, P., Kara, S., 2020. Urban production: State of the art and future trends for urban factories. CIRP Annals 69 (2), 764–787.

[6] Erickson, A., 2012. The Birth of Zoning Codes, a History. https://www.bloomberg.com/news/articles/2012-06-19/the-birth-of-zoning-codes-a-history. Accessed 15 March 2023.

[7] Fee, E., Brown, T.M., 2005. The Public Health Act of 1848. Bulletin of the World Health Organization.

[8] Lesger, C., van Leeuwen, M.H.D., 2012. Residential segregation from the sixteenth to the nineteenth century: evidence from the Netherlands. The Journal of interdisciplinary history 42 (3), 333–369.

[9] Kellett, J.R., 2014. The Impact of Railways on Victorian Cities. Taylor and Francis, Hoboken, 516 pp.

[10] Jewkes, J., 1952. The Size of the Factory. The Economic Journal 62 (246), 237.

[11] O'Brien, A.P., 1988. Factory size, economies of scale, and the great merger wave of 1898–1902. J. Eco. History 48 (3), 639–649.

[12] Meyer, K., Görgens, S., Juraschek, M., Herrmann, C., 2023. Increasing resilience of material supply by decentral urban factories and secondary raw materials. Front. Manuf. Technol. 3.

[13] Bankhofer, U., 2001. Industrielles Standortmanagement. Deutscher Universitätsverlag, Wiesbaden.

[14] Bodenmann, B.R., 2005. Modelle zur Standortwahl von Unternehmen.

[15] Burggräf, P., Schuh, G. (Eds.), 2021. Fabrikplanung. Springer Berlin Heidelberg, Berlin, Heidelberg.

[16] Kaufmann, T., 2021. PESTEL-Analyse, in: Kaufmann, T. (Ed.), Strategiewerkzeuge aus der Praxis. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 19–28.

[17] Pászto (Ed.), 2020. Spationomy: Spatial exploration of economic data and methods of interdisciplinary analytics. Springer International Publishing, Cham, Switzerland, 1 online resource.

[18] Porter, M.E., 2008. The Five Competitive Forces That Shape Strategy. Harvard Business Review, 25–40.

[19] Vlados, C., 2019. Porter's Diamond Approaches and the Competitiveness Web. IJBA 10 (5), 33.

[20] Weber, A., 1922. Ueber den Standort von Industrien, zweite gedruckte Auflage ed. J.C.B. Mohr (Paul Siebeck), Tübingen.

[21] Yüksel, I., 2012. Developing a Multi-Criteria Decision Making Model for PESTEL Analysis. IJBM 7 (24).

[22] Juraschek, M., Bucherer, M., Schnabel, F., Hoffschröer, H., Vossen, B., Kreuz, F., Thiede, S., Herrmann, C., 2018. Urban Factories and Their Potential Contribution to the Sustainable Development of Cities. Procedia CIRP 69, 72–77.

[23] Meyer, K., Aschersleben, F., Reichler, A.-K., Mennenga, M., Dröder, K., Herrmann, C., 2023. Dezentrale Fabriken als Chance für die Produktion in der Stadt? Anforderungen, Fertigungsverfahren und Produktpalette, in: Gärtner, S., Meyer, K. (Eds.), Die Produktive Stadt. (Re-) Integration der Urbanen Produktion, 1st ed. 2023 ed. Springer Berlin Heidelberg; Imprint Springer Spektrum, Berlin, Heidelberg, pp. 99–115.

[24] Moerlen, D., Evrard, D., 2021. Proposal for a procedure to design multipurpose urban factories. Procedia CIRP 98, 412–417.

[25] Herrmann, C., Juraschek, M., Kara, S., Thiede, S., 2019. Urban Factories: Identifying Products for Production in Cities, in: Hu, A.H., Matsumoto, M., Kuo, T.C., Smith, S. (Eds.), Technologies and Eco-innovation towards Sustainability I. Springer Singapore, Singapore, pp. 185–198.

[26] Herrmann, C., Blume, S., Kurle, D., Schmidt, C., Thiede, S., 2015. The Positive Impact Factory–Transition from Eco-efficiency to Eco–effectiveness Strategies in Manufacturing. Procedia CIRP 29, 19–27.

[27] Pászto, V., 2020. Economic Geography, in: Pászto, V., Jürgens, C., Tominc, P., Burian, J. (Eds.), Spationomy. Springer Nature, Cham, pp. 173–192.

[28] Porter, M.E., 1996. Wettbewerbsvorteile: Spitzenleistungen erreichen und behaupten = (Competitive advantage), 4., durchges. Aufl. ed. Campus-Verl., Frankfurt/Main, 688 pp.

[29] Boesler, K.-A., 1960. Die städtischen Funktionen. Reimer, Berlin.

[30] de Waal, M., 2023. The City as Interface: Digital Media and the Urban Public Sphere. Dissertation, Groningen, 19 pp.

[31] Le Corbusier, 1962. An die Studenten - Die <Charte d‘ Athènes>. Rowohlt Taschenbuch Verlag GmbH, Reinecke bei Hamburg.

[32] Reicher, C., 2017. Städtebauliches Entwerfen. Springer Fachmedien Wiesbaden, Wiesbaden.

[33] Rudolf, S., Juraschek, M., Mennenga, M., Herrmann, C., 2023. Urbane Produktion: Potenziale der funktionalen Integration von Stadt und Fabrik, in: Gärtner, S., Meyer, K. (Eds.), Die Produktive Stadt. (Re-) Integration der Urbanen Produktion, 1st ed. 2023 ed. Springer Berlin Heidelberg; Imprint Springer Spektrum, Berlin, Heidelberg, pp. 117–138.

[34] Juraschek, M., Kreuz, F., Bucherer, M., Sonntag, R., Schnabel, F., Hoffschröer, H., Vossen, B., Söfker-Rieniets, A., Thiede, S., Herrmann, C., 2018. Die Ressourcen der urbanen Fabrik: Definitionen und Erläuterungen aus dem Forschungsprojekt Urban Factory.

[35] Mennenga, M., Siemon, L., Rudolf, S., 2023. A System of Systems Approach to Support the Sustainable Integration of Factories into Urban Areas. Procedia CIRP 116, 708–713.

[36] Rudolf, S., Dellbrügge, M., Kreuz, F., Juraschek, M., Mennenga, M., Clausen, U., Herrmann, C., 2023. Influencing Factors of Urban Factories and Their Products for Sustainable Urban Development. Procedia CIRP 116, 167–172.

[37] Busch, H.-C., Mühl, C., Fuchs, M., Fromhold-Eisebith, M., 2021. Digital urban production: how does Industry 4.0 reconfigure productive value creation in urban contexts? Regional Studies 55 (10-11), 1801–1815.

[38] Rückert, P., Tracht, K., Wulfsberg, J., 2020. Elementary systems design for urban production and through life engineering services. Procedia Manufacturing 49, 38–41.

[39] Dellbrügge, M., Rudolf, S., Kreuz, F., Juraschek, M., Herrmann, C., Clausen, U., 2023. Resilience of Urban Factories and Their Supply Chains – Identification of Indicators and Recommendations for Increasing Resilience, in: Clausen, U., Dellbrügge, M. (Eds.), Advances in Resilient and Sustainable Transport. Springer International Publishing, Cham, pp. 293–305.

[40] Parveen Sharma, Rakesh Kumar Phanden, Vinod Baser, Haryana Kurukshetra, 2012. Analysis of site selection based on factors rating, 616 pp.

[41] Schallmo, D., 2013. Geschäftsmodelle erfolgreich entwickeln und implementieren: Mit Aufgaben und Kontrollfragen; Lehrbuch. Springer Gabler, Berlin, Heidelberg, 270 pp.

[42] Kimelberg, S.M., Williams, E., 2013. Evaluating the Importance of Business Location Factors: The Influence of Facility Type. Growth Change 44 (1), 92–117.

[43] Kaufmann, T. (Ed.), 2021. Strategiewerkzeuge aus der Praxis. Springer Berlin Heidelberg, Berlin, Heidelberg.

[44] Juraschek, M. (Ed.), 2022. Analysis and Development of Sustainable Urban Production Systems. Springer International Publishing, Cham.

[45] Kozaczynski, W., 1996. Categorization of business systems components, in: Joint proceedings of the second international software architecture workshop (ISAW-2) and international workshop on multiple perspectives in software development (Viewpoints '96) on SIGSOFT '96 workshops. SOFT96: SIGSOFT '96, San Francisco California USA. 16 10 1996 18 10 1996. ACM, New York, NY, USA, pp. 58–61.

[46] Santos, J.M., Graciano Neto, V.V., Nakagawa, E.Y., 2020. Business Process Modeling in Systems of Systems, in: Anais do Workshop em Modelagem e Simulação de Sistemas Intensivos em Software (MSSiS 2020). Workshop em Modelagem e Simulação de Sistemas Intensivos em Software, Brasil. 10/19/2020. Sociedade Brasileira de Computação - SBC, pp. 26–35.

[47] Sato, R., Praehofer, H., 1997. A discrete event system model of business system-a systems theoretic foundation for information systems analysis. I. IEEE Trans. Syst., Man, Cybern. A 27 (1), 1–10.

[48] Bjelkemyr, M., 2009. System of systems characteristics in production system engineering. Skolan för industriell teknik och management, Kungliga Tekniska högskolan, Stockholm, viii, 76 s.

[49] Vinnakota, T., 2012. System of systems understanding of Modern Corporations, in: 2012 IEEE International Conference on Management of Innovation & Technology (ICMIT). 2012 IEEE 6th International Conference on Management of Innovation & Technology (ICMIT 2012), Bali, Indonesia. 11.06.2012 - 13.06.2012. IEEE, pp. 637–642.

[50] Arnautovic, E., Svetinovic, D., Diabat, A., 2012. Business interactions modeling for systems of systems engineering: Smart grid example, in: 2012 7th International Conference on System of Systems Engineering (SoSE). 2012 7th International Conference on System of Systems Engineering (SoSE), Genova. 16.07.2012 - 19.07.2012. IEEE, pp. 107–112.

[51] Juraschek, M., 2022. Analysis and Development of Sustainable Urban Production Systems, 1. Auflage ed. Springer International Publishing; Imprint Springer, Cham, 162 pp.

[52] Gardner, G., 2016. The City: A System of Systems, in: State of the World. Island Press/Center for Resource Economics, Washington, DC, pp. 27–44.

[53] Johnson, J., 2012. Cities: Systems of Systems of Systems, in: Portugali, J., Meyer, H., Stolk, E., Tan, E. (Eds.), Complexity Theories of Cities Have Come of Age. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 153–172.

[54] Kasai, S., Li, N., Fang, D., 2015. A system-of-systems approach to understanding urbanization – state of the art and prospect. Smart and Sustainable Built Environment 4 (2), 154–171.

[55] Pumain, D., 2011. Systems of Cities and Levels of Organisation, in: Bourgine, P., Lesne, A. (Eds.), Morphogenesis. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 225–249.

[56] Eurostat, 2021. Applying the Degree of Urbanisation - international comparisons: A methodological manual to define cities, towns and rural areas for. Eurostat. https://ec.europa.eu/eurostat/en/web/products-manuals-and-guidelines/-/ks-02-20-499. Accessed 2 June 2023.

[57] Eurostat, 2022. Eurostat regional yearbook: 2022 edition, 2022 edition ed. Publications Office of the European Union, Luxembourg, 222 pp.

[58] Maunier, R., 1910. The Definition of the City. American Journal of Sociology 15 (4), 536–548.

[59] UN Statistical Commission, 2020. A recommendation on the method to delineate cities, urban and rural areas for international statistical comparisons. UN. https://unstats.un.org/unsd/statcom/51st-session/documents/BG-Item3j-Recommendation-E.pdf. Accessed 2 June 2023.

[60] United Nations Department of Economic and Social Affairs, 2008. United Nations Demographic Yearbook 2005. UN.

[61] Juraschek, M., Kreuz, F., Bucherer, M., Sonntag, R., Schnabel, F., Hoffschröer, H., Vossen, B., Söfker-Rieniets, A., Thiede, S., Herrmann, C., 2020. Resources of the urban factory: Definitions and findings from the Urban Factory research project.

[62] Gutenberg, E., 1951. Grundlagen der Betriebswirtschaftslehre. Springer Berlin Heidelberg, Berlin, Heidelberg.

[63] Heinen, E., 1983. Betriebswirtschaftliche Kostenlehre. Gabler Verlag, Wiesbaden.

[64] European Council of Town Planners, 1998. New Charter Of Athens 1998. European Council of Town Planners. https://archive.ectp-ceu.eu/ectp-ceu.eu/images/stories/download/Athens-Charter-1998.pdf. Accessed 5 June 2023.

[65] Eyles, J., 2007. Urban assets and urban sustainability: challenges, design and management, in: Sustainable development and planning III. Papers presented at the 3rd International Conference on Sustainable Development and Planning, held in Algarve, Portugal, 2007. SUSTAINABLE DEVELOPMENT 2007, Algarve, Portugal. 4/25/2007 - 4/27/2007. WIT Press, Southampton, pp. 135–143.

[66] Kusch-Brandt, S., 2020. Underutilised Resources in Urban Environments. Resources 9 (4), 38.

[67] Tan, L.M., Arbabi, H., Densley Tingley, D., Brockway, P.E., Mayfield, M., 2021. Mapping resource effectiveness across urban systems. npj Urban Sustain 1 (1).

[68] Colombo, A.W., Karnouskos, S., Bangemann, T., 2013. A system of systems view on collaborative industrial automation, in: 2013 IEEE International Conference on Industrial Technology (ICIT). 2013 IEEE International Conference on Industrial Technology (ICIT 2013), Cape Town. 25.02.2013 - 28.02.2013. IEEE, pp. 1968–1975.

Biography

Severin J. Görgens (*1991) is research associate at the Technische Universität Braunschweig since 2021. He is member of the Junior Research Group "Urban Flows and Production" and works at the chair of Production Technologies & Process Automation at the Institute of Machine Tools and Production Technology.

Kolja H. Meyer (*1990) is the leader of the Junior Research Group "Urban Flows and Production" at the Technische Universität Braunschweig since 2021. Dr.-Ing. Kolja H. Meyer's research focuses on the development of sustainable production processes in urban areas.

Anne Wetzel (*1997) was a research associate at the Technische Universität Braunschweig in 2023. She worked at the chair of Sustainable Manufacturing and Life Cycle Engineering at the Institute of Machine Tools and Production Technology.

Mark Mennenga (*1983) is deputy head of the chair of Sustainable Manufacturing and Life Cycle Engineering at the Institute of Machine Tools and Production Technology, Technische Universität Braunschweig. As research group leader "systems of system engineering" Dr.-Ing. Mark Mennengas main research areas are methods and tools for the engineering of sustainable systems, as well as of data-based business models and industrial product and production service systems.

CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
CPSL 2023-2

5th Conference on Production Systems and Logistics

Manufacturing Change Management – A Survey On Current Challenges, The State Of Digitalization And The Application Of Change Impact Analysis In Industrial Practice

Jan-Philipp Rammo[1], Jennifer Graf[1]

[1]*Institute for Machine Tools and Industrial Management (iwb), Technical University of Munich, Boltzmannstraße 15, 85748 Garching near Munich, Germany*

Abstract

Modern manufacturing companies operate in a complex and highly dynamic environment. External factors such as new legislations and customer demands, as well as internal factors such as fluctuations in production rates and frequent product changes, make it essential for companies to respond quickly and effectively to changes of all kinds. Scientific literature already provides various processes and methods to manage Manufacturing Changes (MCs) efficiently and to precisely assess their possible impacts. Building upon the existing literature, this survey-based study aims to gain practical insights into the implementation of Manufacturing Change Management (MCM) and Change Impact Analysis (CIA) in real-world industrial settings. By examining the current challenges and exploring the state of digitalization, this research provides valuable insights to complement and further develop the existing theoretical frameworks. In order to gather diverse knowledge from experts across various industries, a web-based survey was conducted, with 99 participants representing 15 different industries. After introducing the necessary theoretical foundations and the current state of research in MCM literature, this contribution describes in detail the methodology of the survey development. The survey findings are then outlined and discussed thoroughly. Finally, the contribution concludes by offering an outlook on future research perspectives based on the identified industry challenges.

Keywords

Manufacturing Change Management; Change Impact Analysis; Digitalization; Web-based Survey; Industrial Practice

1. Introduction

Manufacturing companies are facing an increasingly turbulent environment influenced by external and internal factors [1]. For instance, shorter innovation cycles lead to a more frequent introduction of new technologies, which, combined with more rapidly changing customer demands, lead to shorter product life cycles (PLC). Political and legal factors also contribute to the turbulent environment [2], particularly regarding the transformation towards sustainable manufacturing. Both, external and internal drivers favor the increasing number and variety of Manufacturing Changes (MCs) [3]. The consequences of inefficiently managing these changes are far-reaching and can, among other things, pose existential risks for factories [3] and entire companies. A functional Manufacturing Change Management (MCM) is therefore essential for the effective and efficient management of MCs and thus for securing the competitiveness of companies in the turbulent environment [4]. In particular, processes for the systematic management of changes and

DOI: https://doi.org/10.15488/15247
ISSN: 2701-6277

methods for the precise analysis of the potential impacts of changes are essential in a functioning MCM system.

This contribution focuses on the industrial application of MCM and aims to present the status quo of MCM in industrial practice. In addition to the application of change processes and impact analysis, current challenges and the potential of digitalization are examined. To this end, a web-based survey with experts from various manufacturing industries was conducted.

The remainder of this contribution is structured as follows. Section 2 outlines the research approach of this study. Section 3 introduces the necessary terms and definitions as well as similar studies conducted in this area of research. The following section describes the structure of the study. Section 5 introduces the study's participant distribution, while Section 6 details the study's outcomes. Section 7 discusses the findings and limitations and provides an outlook for future research. Section 8 concludes the study.

2. Objective and research methodology

The goal of this contribution is to analyze the contemporary significance and application of MCM in industrial practice. The focus is particularly on different change processes and approaches for Change Impact Analysis (CIA) as well as current challenges in the field of MCM. Furthermore, the state of digitalization and the potential of applying digital tools are examined.

To achieve this goal, a survey was developed following the six-step questionnaire development methodology according to [5] (see Figure 1). Due to numerous advantages, such as reaching a large number of experts at a relatively low cost and the immediate availability of data [6], a web-based survey was chosen as the data collection method in the first step of the methodology. For the question-and-answer types in step two, mainly closed and semi-open questions were used in order to achieve the highest possible information density and enable a targeted evaluation [5]. In step three, the questions were formulated using a top-down approach, in which the overarching topics to be covered are first defined and subdivided into further topic blocks. Then, individual questions are derived from these using simple and unambiguous language [7]. The respondents' willingness to participate is influenced by the questionnaire's content as well as the design of the form and layout. In principle, attention should be paid to an appealing appearance, which can be achieved by keeping the font size and the numbering consistent. This is also closely related to the survey tool chosen in step five. According to [8], the survey software should have a participant management system, a user-friendly interface, and reliable and secure data management. Taking into account several other economic and functional criteria, the software "easy feedback" [9] was chosen. Once the questionnaire is developed, it is necessary to test it before it goes into the field. This is done by means of a pretest, in which a selected group of people, who should be similar to the target group, carry out the test under actual test conditions [10].

The quality of research work is largely dependent on the quality of the data and therefore on how the survey is conducted and how the questionnaire is designed. Scientific literature usually distinguishes between three primary quality criteria: objectivity, reliability and validity. Additionally, there are secondary criteria such as standardization, comparability, economy and usefulness, which can all be divided into further sub-criteria [11,12]. However, [13] state that the choice of criteria is highly dependent on the use case and the people conducting the survey. They distinguish between general criteria, which can be applied to all surveys, and specific criteria, which should be used for complex tasks such as the extrapolation of conclusions or the feasibility of diagnostic decisions based on the survey results. The specific criteria require knowledge of classical test theory, item response theory, and advanced analysis techniques. As the requirements for the secondary criteria exceed the requirements for this survey, the general criteria are considered to be entirely sufficient. These include objectivity of implementation, objectivity of evaluation, objectivity of interpretation, economy, usefulness, appropriateness, fairness, and non-falsifiability, all of which are considered in this survey.

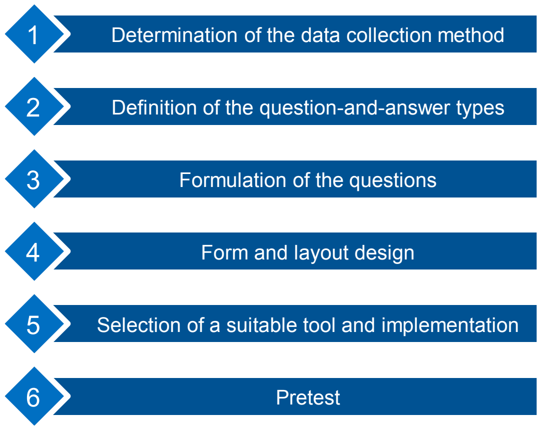


Figure 1: Steps of the questionnaire development according to [5]

3. Terms and definitions

3.1 Fundamentals on Manufacturing Change Management

According to [14], changes in manufacturing companies can be distinguished primarily by the object of change, whereby a differentiation is usually made between three different objects: the product, the production (consisting of technical and logistical processes as well as production facilities), and the company organization [14]. Changes to the product and the factory can be grouped under the term Technical Changes, as opposed to Organizational Changes [15]. In contrast to the management of changes in production, also called Manufacturing Change Management (MCM), the management of changes to the product, called Engineering Change Management (ECM), has already been widely researched. According to [16], ECM primarily refers to "the organization and management of the process of product changes”. The goal of ECM is to ensure that changes are implemented effectively and efficiently without compromising the product’s functionality, quality, or safety. The first clear definition of MCM is provided by [4]: "Manufacturing Change Management refers to organizing and controlling the process of making alterations to a factory. This includes the totality of measures to avoid and specifically front-load as well as efficiently plan, select, process, and control Manufacturing Changes" [4]. In addition to minor changes, such as parameter changes on machines, significant changes, such as a redesign of the factory layout, can be considered an MC. ECM and MCM are summarized under the term Technical Change Management (TCM).

3.2 Change Impact Analysis

A fundamental aspect of both ECM and MCM is the CIA, which aims to assess the potential impact of proposed changes [17]. It involves a systematic evaluation of the impact of a change on resources, such as equipment, materials and personnel, as well as on related activities and systems [18]. This analysis helps to identify potential risks, dependencies, and interrelationships among different components of the product or the factory system, enabling informed decision making and effective planning for change implementation. Especially in ECM, many methods have been developed to analyze the impact of changes on products as in [19–21]. In recent years, approaches for CIA in manufacturing systems have also been developed [22], [17], [23].

3.3 Past studies on MCM

To determine the current state of research in the MCM literature, a comprehensive literature review was conducted using the Webster & Watson methodology [24]. The literature review focused on studies that examine the industrial practice of TCM and specifically MCM.

The literature review identified six significant publications that present studies on either ECM or MCM. While the studies by [25–28] provide valuable insights into ECM, the studies by [29,30] focus on MCM. Both studies underscore the growing importance of MCM and offer first insights into possible advances through digitalization.

Despite the valuable insights provided by the study in [29], which included a significant number of 85 relevant datasets, it is worth noting that the study dates back to 2015. In addition, a significant portion of the participants (70%) belonged to the automotive and machinery industries. On the other hand, the more recent study [30], conducted in 2021, captured a smaller sample size of 34 participants, but still showed a predominant focus on the automotive and machinery industries (76%). Given the rapid advances in the field of manufacturing, particularly in the area of digitalization, there is a clear need for a new study that can provide a fresh perspective and encompass a more extensive and diverse pool of participants.

4. Structure of the study

The questionnaire consists of 36 questions, some of which are combined in a matrix format. Only mandatory questions were used to prevent skipping or over-reading individual questions. Filter questions were used to ensure that previous answers were taken into account. As a result, the number of participants for each question varies throughout the questionnaire. The survey is divided into four sections (Figure 2). At the beginning of each section, the necessary definitions are explained. The first section deals with the characterization of the field of participants. The second section is dedicated to MCs in the industrial practice. The third section analyzes the current application and different approaches of MCM, especially the CIA. The last section deals with the state of digitalization and its potential in MCM.

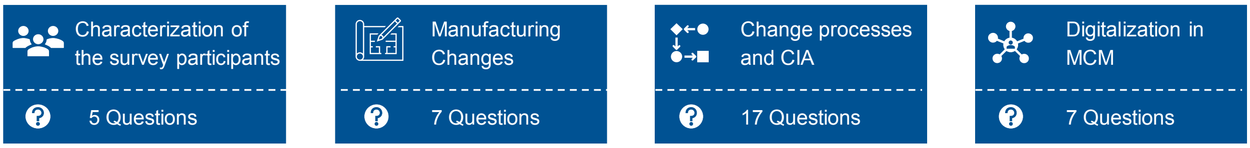


Figure 2: Structure of the study

5. Study participants

After contacting over 250 people through personal contacts of the authors and several mailing lists, a total of 108 people participated in the survey. Of these, 92 completed and returned the questionnaire. In order to include the insights of those experts who did not complete the questionnaire in full, and thus increase the number of useful datasets, a minimum of 16 answered questions, representing more than the first two sections of the questionnaire, was defined as the threshold for inclusion in the evaluation. This increased the number of records evaluated to a total of 99 questionnaires.

The study represents a broad range of participants. In total, the study includes participants from 15 different industries. 56% of the companies thereby surveyed belong to the mechanical engineering and automotive sectors. Various sectors such as medical technology, biotechnology, steel processing and automation technology were grouped under "other". Figure 3 shows the distribution of respondents by industry.

The study also represents a wide range of company sizes. Almost half (49%) of the 99 respondents indicated that they work for a company with over 10,000 employees. Nearly three-quarters (71%) of all respondents work for companies with over 1,000 employees. 13% of the participating companies have more than 250 but less than 1,000 employees. Only 5% of the participating companies have less than 50 employees.

The survey also covers a wide range of production types. Almost all (94%) participating companies have a production facility, with a large series or mass production together representing the dominant production types at 62%. Small batch production is represented in the survey by 17%, and individual one-off production by 14%. The high proportion of production companies is due to the scope of the survey, which was aimed at employees with a production background. The remaining 6% are consulting companies that do not possess production facilities but are currently involved in production-related projects.

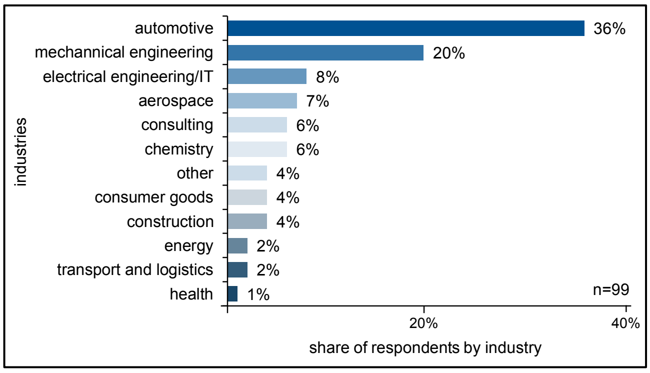


Figure 3: Distribution of the respondents by industry

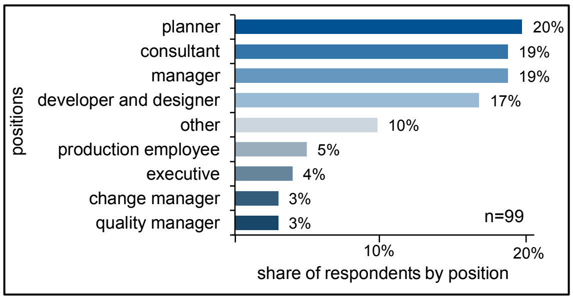


Figure 4: Distribution of the respondents by position

More than half of the respondents (58%) are involved in planning, consulting and management. Other roles include development and design (17%), production (5%) and executive roles (4%). Technical administrators, process planners, and product managers were grouped under "other”. Figure 4 shows the respondents' positions in the company.

6. Survey results

6.1 Importance of MCM

54% of the respondents currently consider MCM important or very important. In the future (next five to ten years), its importance will increase significantly. In fact, 94% of the respondents rate MCM as important or very important in the future. Figure 5 shows the respondents' assessment of MCM’s current and future importance.

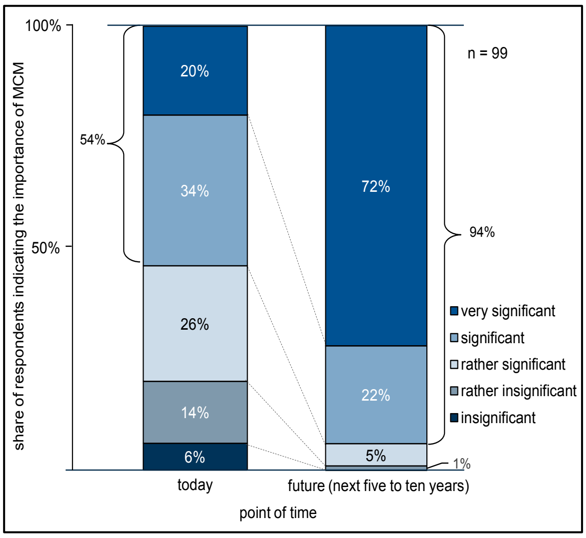


Figure 5: Current and future importance of MCM

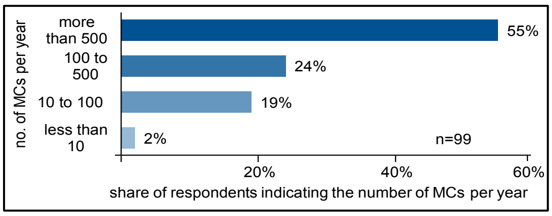


Figure 6: Number of MCs per year

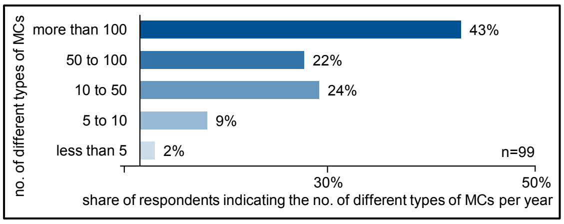


Figure 7: Number of different types of MCs per year

A large proportion of the respondents (55%) indicate that they record more than 500 Manufacturing Changes per year (see Figure 6). In addition, 24% of the respondents conduct between 100 and 500 MCs annually. This means that, on average, 79% of the respondents make an MC at least once every three days. Not only is the number of MCs high, but also the variety. Currently, almost half of all companies have to deal with more than 100 different types of changes per year (see Figure 7). In addition, 85% of the respondents expect the variety of changes to increase significantly in the years to come.

6.2 Manufacturing change process

As shown in Figure 8, about half (52%) of the respondents use at least one defined process specifically for MCs. Just under a third (32%) do not have a separate MCM process but have at least one process for product changes that is also used for MCs. 5% have a product process that is not used for MCs and 11% have neither an MCM process nor an ECM process.

When companies do have a process for handling MCs, almost half of them (48%) have individual processes for the different types of changes. The remaining 52% of the companies that have a process for managing product and process changes have a holistic process for the different types of changes.

In this context, many respondents indicated that the process currently used in their company has shortcomings. The most common criticisms are the lack of flexibility and the inability to adapt the process to changes. Other process shortcomings include a lack of support in the selection of technologies and methods.

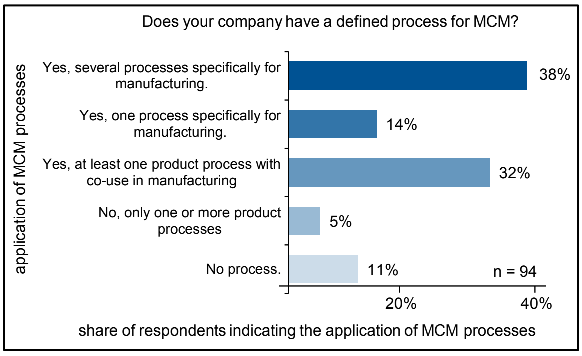


Figure 8: Change processes in industrial practice

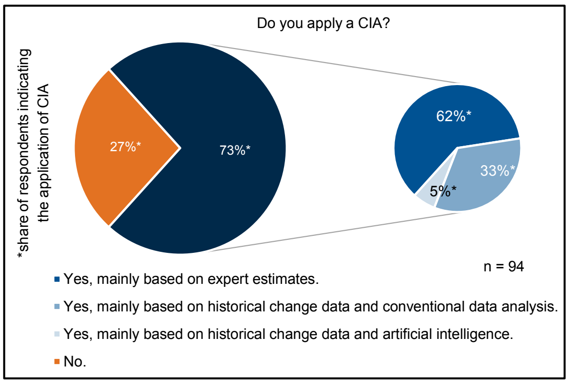


Figure 9: CIA in industrial practice

6.3 Change Impact Analysis

27% of the respondents indicated that they do not perform a CIA (see Figure 9). The main reason given for this was the cost and the effort of applying a CIA. The remaining companies (73%) use a CIA, 62% of which is based on expert estimates. 33% of the respondents use historical change data in combination with traditional data analysis for the CIA. The remaining 5% use historical change data and artificial intelligence methods for the CIA.

6.4 Status of digitalization of MCM

Today, more than two-thirds (68%) rate the digitalization of MCM as significant or rather significant. In the future, this importance is expected to increase significantly. A total of 98% of all respondents rate the digitalization of MCM as significant or rather significant in the coming years.

89% of the respondents currently use digital support to manage MCs. The most commonly used software programs are SAP, Excel, and tools for workflow management. Artificial intelligence and machine learning are used by 10% of the respondents for digital support. Other digital tools were grouped under "other“, including Microsoft Teams, SharePoint/Jira, Windchill, enterprise resource planning systems, and email.

In summary, many companies see great potential in digitalization to support MCM. For example, only 3% of the respondents indicated that the potential of digitalization for MCM is fully exploited in their organization, while 72% feel that the potential is not fully exploited or not exploited at all. In particular, the use of digital technologies in specific process steps and improving employees' digital skills are seen as major potentials in MCM (Figure 10).

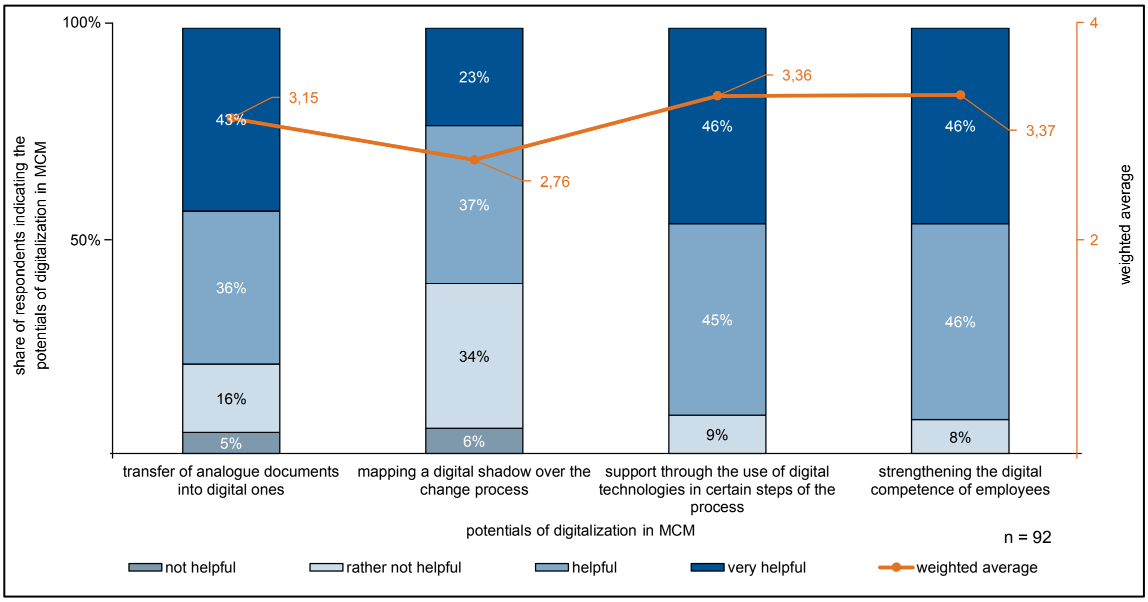


Figure 10: Potential of digitalization in MCM

6.5 Challenges and potentials for improvement

In addition to digitalization, the survey identified several other challenges and opportunities for improvement in MCM today. The most significant potential for improvement is seen in learning from changes. A total of 68% of the respondents see great potential for development in this area. Further potential is seen in communication, meeting deadlines, documentation, and planning. It can be concluded that human factors in particular play an essential role in improving MCM. Figure 11 shows the potential for improvement in MCM.

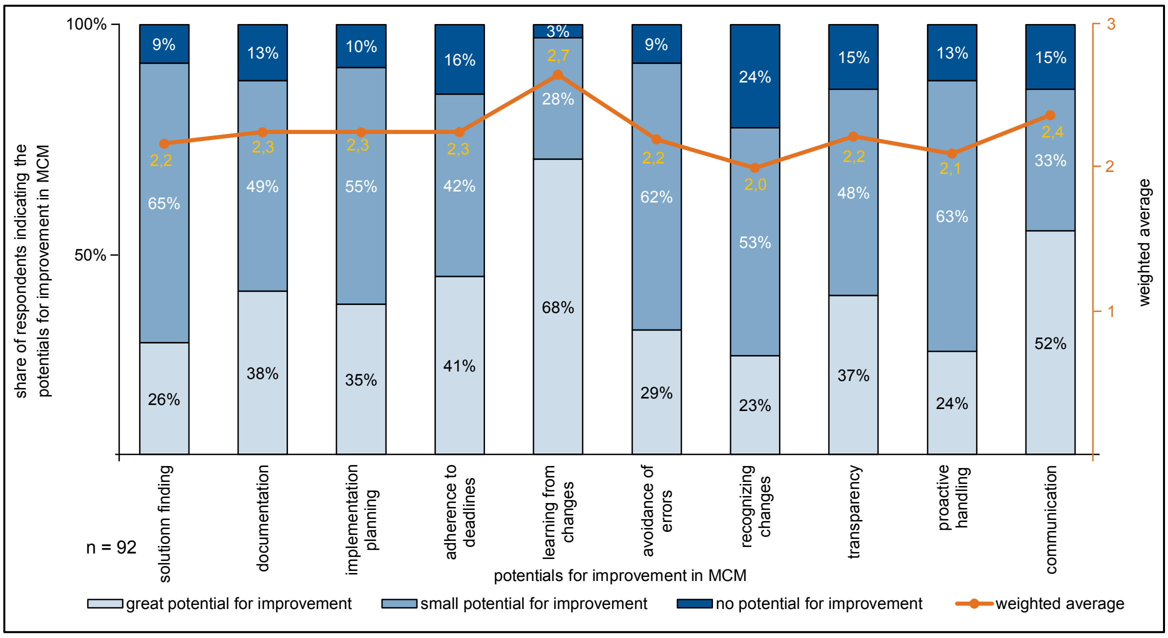


Figure 11: General challenges and potential for improvement in MCM

7. Discussion

The quality criteria presented in section 2 could be achieved as follows. The objectivity of the implementation was ensured by using the same questionnaire and additional information for all participants and by selecting participants with similar knowledge and manufacturing backgrounds. Only the implementation time varied, but this can be neglected in this survey as it was not a performance test or anything similar. In questionnaires with mostly bound answer options, the objectivity of evaluation is almost exclusively given [13]. The objectivity of the interpretation was ensured by the fact that different persons interpreted the data and came to the same conclusion, which fulfills the objectivity of the interpretation according to [13]. The costs of the study were very low due to the online survey. Participation took an average of 18 minutes, demonstrating the study's economy and reasonableness, as participants were not exposed to extraordinary stress as they were free to complete the task at their own pace. The usefulness of the study was emphasized by several participants and was also partially reflected in the responses. The results do not lead to systematic disadvantages for certain persons, which is why the study can be considered fair. The non-falsifiability cannot be clearly demonstrated; at this point, it must be assumed that the experts answered the questions to the best of their knowledge and belief. The high number of participants ensures that individual outliers are compensated for.

In summary, this study provides a current and comprehensive overview of the application of MCM. With 99 participants, the study exceeds previous surveys on this topic. The results of this study are suitable to show trends and developments in MCM, especially in large companies. A particular strength of this research is that it represents the knowledge of participants from a total of 15 different industries and thus provides a differentiated picture of the current application of MCM in industrial practice.

8. Summary and Conclusion

In this contribution, a study was conducted to analyze the application of MCM and CIA in industrial practice, as well as the current challenges and state of digitalization in MCM. A web-based survey was conducted with 99 participants representing over 15 different manufacturing industries. The survey provided insights into MCM from the current industry perspective. The importance of the research area today and in the future was recognized by a large number of participants, as many companies report that the volume and variety of MCs constitute a significant challenge. In summary, the following key takeaways can be derived from the results of the study:

- MCM processes and CIA are applied by the majority of companies.
- Many processes lack the flexibility to handle the wide variety of changes.
- Most processes lack the technological and methodological support to manage MCs efficiently.
- Human factors play an essential role in the success of MCs.
- Digitalization is not yet far advanced in MCM but is considered to have a great potential.

The findings of this study reveal a wide range of diverse challenges in Manufacturing Change Management, encompassing human, technological, and organizational aspects. Moving forward, future research activities should prioritize holistic approaches encompassing all facets of MCM, aiming to foster more effective and efficient handling of the large number and variety of MCs. This may involve the integration of advanced technologies, such as artificial intelligence or virtual reality, alongside the development of comprehensive and flexible frameworks and methodologies that support decision making and human involvement in change management processes.

Acknowledgements

Funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – 465491927. We would like to express our sincere thanks to the DFG for funding this research.

References

[1] Vega-Jurado, J., Gutiérrez-Gracia, A., Fernández-de-Lucio, I., Manjarrés-Henríquez, L., 2008. The effect of external and internal factors on firms' product innovation. Research Policy 37 (4), 616–632.

[2] Westkämper, E., Zahn, E., 2009. Wandlungsfähige Produktionsunternehmen. Springer Berlin Heidelberg, Berlin, Heidelberg.

[3] Bauer, H., Schoonmann, A., Reinhart, G., 2017. Approach for model-based change impact analysis in factory systems, in: 2017 IEEE International Systems Engineering Symposium (ISSE). 2017 IEEE International Systems Engineering Symposium (ISSE), Vienna, Austria. 11.10.2017 - 13.10.2017. IEEE, 1–7.

[4] Koch, J., 2017. Manufacturing Change Management – a Process-Based Approach for the Management of Manufacturing Changes. Dissertation, München, 258 pp.

[5] Köstner, H., 2022. Empirische Forschung in den Wirtschafts- und Sozialwissenschaften klipp & klar. Springer Fachmedien Wiesbaden, Wiesbaden.

[6] Heiervang, E., Goodman, R., 2009. Advantages and limitations of web-based surveys: evidence from a child mental health survey. Social Psychiatry and Psychiatric Epidemiology 2011 (76), 46–69.

[7] Kaiser, R., 2014. Qualitative Experteninterviews. Springer Fachmedien Wiesbaden, Wiesbaden.

[8] Lozar Manfreda, K., Vehovar, V., 2008. Internet surveys. International Handbook of Survey Methodology.

[9] easyfeedback GmbH. easyfeedback. https://easy-feedback.de/. Accessed 5 July 2023.

[10] Berger-Grabner, D., 2022. Wissenschaftliches Arbeiten in den Wirtschafts- und Sozialwissenschaften. Springer Fachmedien Wiesbaden, Wiesbaden.

[11] Ahlem Assila, Káthia Marçal de Oliveira, Houcine Ezzedine, 2016. Standardized Usability Questionnaires: Features and Quality Focus. electronic Journal of Computer Science and Information Technology 6 (1).

[12] Bryman, A., Becker, S., Sempik, J., 2008. Quality Criteria for Quantitative, Qualitative and Mixed Methods Research: A View from Social Policy. International Journal of Social Research Methodology 11 (4), 261–276.

[13] Moosbrugger, H., Kelava, A., 2020. Qualitätsanforderungen an Tests und Fragebogen („Gütekriterien"), in: Moosbrugger, H., Kelava, A. (Eds.), Testtheorie und Fragebogenkonstruktion. Springer Berlin Heidelberg, Berlin, Heidelberg, 13–38.

[14] 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.

[15] Rößing, M., 2007. Technische Änderungen in der Produktion: Vorgehensweise zur systematischen Initialisierung, Durchführung und Nachbereitung. Dissertation.

[16] Jarratt, T., Eckert, C., Caldwell, N., Clarkson, P., 2011. Engineering change: An overview and perspective on the literature. Research in Engineering Design, 103–124.

[17] Bauer, H., Haase, P., Sippl, F., Ramakrishnan, R., Schilp, J., Reinhart, G., 2020. Modular change impact analysis in factory systems. Prod. Eng. Res. Devel. 14 (4), 445–456.

[18] Aurich, J.C., Rößing, M., 2007. Engineering change impact analysis in production using VR. Digital Enterprise Technology.

[19] Clarkson, P.J., Simons, C., Eckert, C., 2004. Predicting Change Propagation in Complex Design. Journal of Mechanical Design 126 (5), 788–797.

[20] Hamraz, B., Caldwell, N.H.M., John Clarkson, P., 2012. A Multidomain Engineering Change Propagation Model to Support Uncertainty Reduction and Risk Management in Design. Journal of Mechanical Design 134 (10).

[21] Raffaeli, R., Germani, M., Graziosi, S., Mandorli, F., 2007. Development of a multilayer change propagation tool for modular products. Proceedings of ICED 2007, the 16th International Conference on Engineering Design 42.

[22] Plehn, C., 2017. A Method for Analyzing the Impact of Changes and their Propagation in Manhufacturing Systems. Dissertation, München.

[23] Schuh, G., Guetzlaff, A., Sauermann, F., Krug, M., 2021. Data-based improvement of engineering change impact analyses in manufacturing. Procedia CIRP 99, 580–585.

[24] Webster, J., Watson, R. Analyzing the Past to Prepare for the Future: Writing a Literature Review. MIS Quarterly 2002 (26), 13–23.

[25] Deubzer, F., Kreimeyer, M., Rock, B., Junior, T., 2005. Der Änderungsmanagement Report 2005. Competence in Design and Development (01).

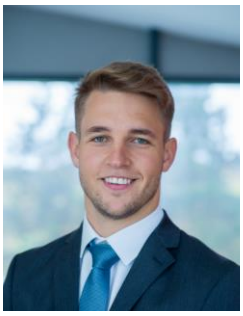
[26] Huang, G., Yee, W., Mak, K., 2003. Current practice of engineering change management in Hong Kong manufacturing industries. Journal of Materials Processing Technology 139 (1-3), 481–487.

[27] Huang, G.Q., Mak, K.L., 1999. Current practices of engineering change management in UK manufacturing industries. International Journal of Operations & Production Management (19), 21–37.

[28] Langer, S., Wilberg, J., Maier, A., Lindemann, U. Änderungsmanagement-Report 2012: Studienergebnisse zu Ursachen und Auswirkungen, aktuellen Praktiken, Herausforderungen und Strategien in Deutschland.

[29] Koch, J., Hofer, A., 2016. Änderungsmanagement in der Produktion*/Manufacturing Change Management - Challenges and approaches in Industry. wt 106 (07-08), 520–526.
[30] Sippl, F., Schellhaas, L., Bauer, H., 2021. Umfrage zum Änderungsmanagement in der Produktion: Status quo, industrielle Anwendung der Änderungsauswirkungsanalyse und Stand der Digitalisierung. Zeitschrift für Wirtschaftlichen Fabrikbetrieb (116).

Biography



Jan-Philipp Rammo, M.Sc. (*1997) is a research associate in the production management and logistics group at the Institute for Machine Tools and Industrial Management (*iwb*) at the Technical University of Munich. He studied mechanical engineering (B.Eng.) at the University of Applied Sciences in Saarbruecken and production management (M.Sc.) at the University of Kassel and has years of industry expertise.

Jennifer Graf (1998) is studying development, production and management in mechanical engineering in the Master's programme at the Technical University of Munich. She was involved in the conception and implementation of the present study as part of her bachelor's thesis at the Institute for Machine Tools and Industrial Management (*iwb*) at the Technical University of Munich.

CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
CPSL 2023-2

5th Conference on Production Systems and Logistics

Comparing Research Trends And Industrial Adoption Of Manufacturing Operations Management Solutions

Michael Oberle[1], Daniel Schel[1], Monika Risling[1], Thomas Bauernhansl[12]

[1]Fraunhofer Institute for Manufacturing Engineering and Automation IPA, Nobelstraße 12, 70569 Stuttgart, Germany

[2]Institute of Industrial Manufacturing and Management, University of Stuttgart, Nobelstr. 12, 70569 Stuttgart, Germany

Abstract

For decades, the operations on the shop floor of manufacturing organizations have been supported by Manufacturing Execution Systems. In this paper, we investigate the trends of Manufacturing Operations Management in the research community and analyse the adoption in the industry. Our literature review identifies the following trends for Manufacturing Operations Management: distributed system architectures, cloud technology, and use of standards. We conducted a survey targeting Manufacturing Operations Management solution providers and adopters to explore the adoption of these trends. The survey results show that the use of standards is already addressed to some extent by the industry. Practitioners anticipate distributed system architectures for Manufacturing Operations Management solutions in the future. However, practitioners are still reluctant towards cloud-only technology and will continue to be so in the foreseeable future.

Keywords

Manufacturing Execution System; Manufacturing Operations Management; Cloud technology, Microservices; VDI 5600; IEC 62264

1. Introduction

Classical Manufacturing Execution Systems (MES) and their extension, Manufacturing Operations Management (MOM) systems, have long been used for managing shop floor operations, including tracking production orders, monitoring equipment, and managing inventory in manufacturing organizations [1]. The advent of Industry 4.0 promised many technological advancements from which MES/MOM systems could benefit [2].

This has sparked great interest among researchers to propose new concepts and develop new artefacts in the realm of MES/MOM. However, as a discipline in which design science is a major paradigm, these artefacts should also benefit practitioners [3]. For this purpose, it is essential to make the streams of MES/MOM research in terms of its prominent topics visible and to analyse their industry adoption. However, this has not been the focus of any study so far.

To address this issue, this paper seeks to identify the gaps between MES/MOM research and industrial adoption. Specifically, we aim to understand the current research trends in MES/MOM systems in the context of Industry 4.0 opportunities and how industry practitioners are adopting these trends. We do this by conducting a thorough literature review of the development of MES/MOM.

DOI: https://doi.org/10.15488/15248
ISSN: 2701-6277
publish-Ing.

We then derive hypotheses from our literature review, which are tested through a survey of industry practitioners. Our survey aims to understand the extent of the adoption of MES/MOM research trends in manufacturing organizations.

The remainder of the paper is organized to highlight our findings. We first review the historical development of MES systems to provide a foundation for understanding the current state of MES/MOM systems. Next, we present the results of our systematic literature review, which helps us to identify the latest research trends in MES/MOM systems. We then present the results of our industry survey, which provides a comprehensive understanding of the current adoption of MES/MOM systems in manufacturing organizations. We then discuss our study's limitations and conclude with our study's main points for practitioners and the future direction of MES/MOM system research.

2. Related Work

Reviewing the existing literature, it becomes clear that while many authors have addressed the future and state of MES/MOM in the context of Industry 4.0, there has been little work on the specific advances promised by Industry 4.0 and how practitioners adopt them in the field: [4] propose a taxonomy that addresses business and manufacturing factors and technology for characterizing MES, and discuss how MES can benefit from Industry 4.0. [5] analyse the trends that will determine the development of the next generation of MES and highlight the need for semantic metadata to support interoperability and modular development. [6] identify the importance of MES for Industry 4.0, but stress that how an enterprise utilizes MES features will determine whether it can achieve its Industry 4.0 goals. [2] argues that Industry 4.0 has created unique opportunities for defining target roadmaps for manufacturing operations and IT systems, but centralized and monolithic production monitoring and control applications will eventually give way to solutions capable of supporting a radically different vision of connected yet decentralized production and supply chain processes. Despite the valuable insights these authors offer, there has been no research on the specific advances that Industry 4.0 promises and how practitioners adopt them to our knowledge. Our work aims to address this gap in the literature by comparing research trends with the industrial adoption of MES/MOM.

3. Systematic literature review

We conducted a systematic literature review to identify the advances that Industry 4.0 concepts have brought to MES/MOM systems. According to [7], a systematic literature review (SLR) is a thorough, methodical, and repeatable technique used to identify, evaluate, and combine current research findings in a particular subject area. The SLR concentrates on a specific research field, for which the reviewers must evaluate the current research before beginning. The literature review is a secondary analysis of previously published research contributions. The SLR follows a six-phase methodological approach based on [7], which includes: (1) establishing a research hypothesis, (2) identifying relevant databases, (3) determining appropriate search terms for each database, (4) defining screening criteria for search results, (5) performing and documenting the literature review by reviewers, and (6) synthesizing the SLR results.

Table 1: Search Strategy

Search Fields	Main Terms	Context Terms
Title	Manufacturing Execution System	Design
Abstract Keywords	Manufacturing Operations Management	Architecture

The hypothesis that guided our literature review is that there are topics and topics enabled by Industry 4.0 - as envisioned by the previously mentioned work in section 2 - and that they have been implemented in the design and architecture of MES/MOM. Due to the computer-science nature of the hypothesis, we chose the most relevant databases in this field. In contrast to [6], who specifically excluded papers focusing on MES/MOM design and architecture, we were especially interested in these papers as they relate to our hypothesis and thus used them as shown in table 1.

The screening process, including all filtering at each stage, is visualized in figure 1. We filtered out any work that only refers to the general Industry 4.0 work in which MES/MOM was only a part of a broader Industry 4.0 architecture concept. We also excluded all work in which MES/MOM was only seen as an enabler for a specific function (e.g., MES enabling predictive maintenance) that was described in further detail in the paper. For the remaining papers, we identified the key research topic.

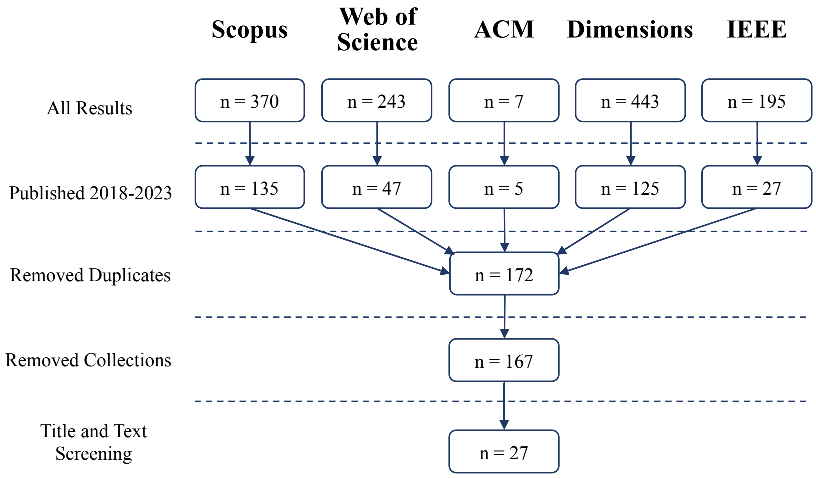


Fig. 1 Number of papers at each stage of the screening process

The result of this process can be found in table 2. Not all papers had a guiding topic identifiable for the MES/MOM design and/or architecture. In total, four topics were identified. The topic "collaboration" could only be identified in one of the papers and thus was not further considered for the study, as it can be argued that this topic has not yet gained momentum in the research community and thus is unlikely to be relevant in the practitioner's community.

The transfer of the remaining three topics in the practitioner's community, "Use of Standards", "Cloud Technology", and "Collaboration" were investigated in an industry survey.

Table 2: Topics identified in the review

Topic	Description	Paper
Use of Standards	Use of Standards, specifically for ISA95/IEC62264 for designing the functionality of the MES/MOM solution.	[8], [9], [10], [11]
Distributed Architecture	Design of the MES/MOM solution as non-monolithic system. This can be either app-based, microservices or agents.	[8], [9], [10], [12], [13], [14], [15]. [16], [11], [17]
Cloud technology	MES/MOM solution hosted in the cloud as in contrast to systems that are hosted on premise, enabling SaaS payment.	[18], [19], [9], [20], [16], [17], [21]
Collaboration	Support of "order-design-production-delivery" value chain in personalized products	[18]

4. Industry survey

For conducting the industry survey, we formulated a hypothesis for each identified topic. We formulated accordingly associated questions that aimed at testing these questions more specifically, as shown in table 3. As with every survey design, there is a trade-off between the richness of the information that can be gained from the questions and the time required from the responders to complete the questionnaire. As we included these questions in a larger survey (with over 19 questions in total), we prioritized simplicity for the responder over information richness. For this reason, we do not base our questions on Likert-type scales. Instead, we use ordinal scales to identify the standard relevance (H1) level and modularity of an MES/MOM solution (H2) across different time horizons.

Regarding the operation mode of MOM solutions (H3), we use a categorical scale (public cloud vs. hybrid cloud/edge) across the same time horizons we use for H2. For H1, we consider the MES/MOM standards VDI5600, IEC 62264, NAMUR, and MESA, which have been mentioned in the relevant literature of our systematic review. We measure the relevance levels on a scale from standard unknown, over standard irrelevant, planned to use the standard to standard already in use. In order to ensure a common understanding of the granularity measure of the MES/MOM solution, we worked with pictograms in the questionnaire showing a monolithic package at the one end, over a smaller monolithic package supplemented by smaller independent services, to only independent software services.

As we want to study how the industry adopts the topics identified in our literature review, we use three time horizons for H2 and H3: today, the future up to three years, and the future between three and five years. We did not use this time frame for H1 as the time horizon is included in the scale, and we wanted to limit the extent of the questions in the overall questionnaire. The questionnaire was distributed among manufacturing organization contacts from our research institute in Germany, Austria, and Switzerland. We also advertised at the institute's LinkedIn presence. The survey was open from the 31st of October to the 21st of December 2022. In total, 100 participants answered the questionnaire.

Table 3: Hypotheses and survey questions

#	Hypothesis	Survey Questions	Response Options
H1	Standards MES/MOM have no relevance in practice.	Q1: Do you consider one of the following standards your MES/MOM solution? Q1a: IEC62264 Q1b: VDI5600 Q1c: MESA Q1d: NAMUR	R1: Use of the standard R2: Planned use of the standard R3: Standard not relevant R4: Standard unknown
H2	Monolithic architectures are still prevalent for MES/MOM systems.	Q2: Which of the following architecture is the best representation of your MES/MOM in the following time frame? Q2a: Today Q2b: 3 years in the future Q2c: 3 to 5 years in the future	R1: Monolith R2: Monolith supplemented with services/applications R3: Independent Single services/applications R4: No solution
H3	Manufacturing organizations are reluctant to use cloud only technology for	Q3: How shall your MES/MOM solution be operated in the following time frame? Q3a: Today	R1: Public Cloud (national) R2: Public Cloud (international) R3: Edge supplemented with Public Cloud (national)

their MES/MOM solution.		Q3b: 3 years in the future Q3c: 3 to 5 years in the future	R4: Edge supplemented with Public Cloud (international)

5. Analysis and results

We performed statistical tests on the survey responses to address the hypotheses above. Each question required specific statistical tests according to the scale and variable structure. For each test, we used $\alpha=5\%$ ($p<0.05$) level to reject the null hypothesis.

5.1 H1 – Standard relevance

For H1, we could reject the null hypothesis that the responses for the various standards have the same distributions. We then conducted pairwise comparisons between the responses for the different standards. In these tests, we could only identify that there are differences between VDI5600 and NAMUR, and VDI5600 and MESA standards, as indicated in table 4. To assess how relevant the standards are, we first conducted a chi-square test to ensure that there are statistically significant differences between each response level. We then analysed the frequency distribution table (see table 7 in the appendix). Except for the VDI5600, over 50% of the survey participants did not know each standard. Looking at the actual usage of the standard, the VDI5600 is also leading the frequency count with 17 mentions, followed by the IEC 62264 with 16. However, considering the planned standard usage, the VDI5600 is again greater than IEC 62264, with 13 over six mentions. As a consequence of the statistical tests and the response frequencies, we conclude that MES/MOM standards play a role for practitioners, and thus, we reject H1.

Table 4: H1 Statistical tests and results

Test	Variables	Test statistic	P-value	H_0 Decision
Kruskal-Wallis H test	All H1 variables	12.48	0.0059	Reject
Mann-Whitney U test	IEC 62264 vs VDI 5600	1789.5	0.1860	Accept
	IEC 62264 vs NAMUR	2373.0	0.0786	Accept
	IEC 62264 vs MESA	2214.5	0.3729	Accept
	VDI5600 vs NAMUR	2724.5	0.0005	Reject
	VDI5600 vs MESA	2510.5	0.0172	Reject
	NAMUR vs MESA	1883.5	0.3660	Accept
Chi-square test	VDI5600	10.875	0.0124	Reject
	IEC 62264	37.625	<0.00001	Reject
	NAMUR	58.875	<0.00001	Reject
	MESA	44.375	<0.00001	Reject

5.2 H2 – Prevalence of monolithic architectures

To investigate the development of the adoption of distributed architectures, we first tested the equality of distributions across all time horizons. This null hypothesis could be rejected, indicating a development from now on till five years in the future is taking place. We then conducted a pairwise comparison using the Wilcoxon test to identify which time horizons differ in their distributions. This was the case for all comparisons, indicating that development occurs between each time horizon under consideration. To analyse further which development is taking place, we first tested that there is no equal distribution of the granularity levels (see table 5). We then analysed the frequency table (see appendix table 8). This response shows that today, almost 25% of the responders operate or offer MES/MOM solutions that are monolithic. However, almost 60% of a core monolithic solution is supplemented with individual services. Already within three years in the future, the number of monolithic-only solutions will drop to just under 10%, whereas solutions fully composed of individual software services rise to just under 19%. This trend continues in the further distant future to only 3% of monolithic-only solutions and over 60% of solutions composed of individual software services. We conclude that currently, monolithic architectures are still prevalent to some extent, but there is a noteworthy development towards distributed architectures in the near future.

Table 5: H2 statistical tests and results

Test	Variables	Test statistic	P-value	H_0 Decision
Friedman Test	All time horizons	52.26	<0.00001	Reject
Wilcoxon Test	Today vs <3 years future	42.0	<0.00001	Reject
	Today vs. 3-5 years future	39	<0.00001	Reject
	<3 years future vs. 3-5 years future	0.0	<0.00001	Reject
Chi-square test	Today	19.91	<0.00001	Reject
	3 years future	29.45	<0.00001	Reject
	3-5 years future	34.64	<0.00001	Reject

5.3 H3 –Use of cloud-only technology

For analyzing the industry's stance towards cloud-only technology, we followed a procedure similar to H2 but with tests adjusted to the categorical scale type. The null hypothesis that the three distributions differ statistically could not be rejected. This was also the case for the pairwise comparisons (see table 6). This can be easily confirmed by the frequency tables (see appendix table 8), which show hardly any difference for the three time horizons. Around 80% of the responders do not want to operate the MES/MOM solution through cloud technology only across all time horizons. In consequence, it also confirms the statistical difference between the two levels. In conclusion, the industry widely rejects cloud-only MES/MOM solutions across all time horizons under consideration.

Table 6: H3 statistical test results

Test	Variables	Test statistic	P-value	H_0 Decision
Cochran's Q Test	All time horizons	0.100	0.951	Accept
McNemar's test	Today vs <3 years future	0.011	1.000[1]	Accept
	Today vs. 3-5 years future	0.011	1.000[1]	Accept
	<3 years future vs. 3-5 years future	0.0	1.000[1]	Accept
Chi-square test	Today	64.58	<0.00001	Reject
	3 years future	73.34	<0.00001	Reject
	3-5 years future	81.50	<0.00001	Reject

[1] P-value adjusted for multiple test according to Bonferroni method.

6. Limitations

It is important to acknowledge the limitations of our study. Firstly, the sample size of our survey is too small to conclude for the general population. While our sample size was sufficient for our analysis, a larger sample size would allow for a more comprehensive analysis and generalizability of our findings. Additionally, as we recruited survey participants through the contacts of our research institute, there may be a bias introduced in our results. Companies cooperating with research institutes may be more inclined to adopt new technologies, which could impact our findings. Another limitation of our study is that the researchers may bias the construction of the hypotheses. We involved three MES/MOM systems experts to help us construct the hypotheses to mitigate this bias. While this approach may not eliminate bias entirely, it has minimized the impact of our own biases on the hypotheses. Despite these limitations, our study provides valuable insights into the current state of MES/MOM systems and their adoption by industry practitioners.

7. Conclusion

In the paper, we aim to clarify the gap between research trends and industrial adoption of MES/MOM design and architecture. We first identify the trends systematically. In the research community, distributed system architectures, cloud technology, and the use of standards for designing and building MES/MOM systems can be identified. To clarify the adoption of these trends by the industry, we conducted a survey among industry practitioners from manufacturing-related organizations in Germany, Austria, and Switzerland. The statistical testing of these results shows that at least the VDI5600 standard is relevant in practice. Although there is still a considerable share of monolithic MES/MOM systems today, the analysis shows that practitioners anticipate a noteworthy shift to more distributed architectures in the near future. However, regardless of the time frame, practitioners are reluctant towards cloud-only technology.

Our results are relevant for practitioners and researchers. For practitioners, it provides information on which standards to consider when implementing MES/MOM solutions and which architecture style to use. This can be valuable to both solutions providers and users regarding their MES/MOM strategy.

This poses further interesting questions for the research community about the reluctance to use cloud-only technology. Furthermore, anticipating more non-monolithic MES/MOM solutions will require new concepts for testing, integrating, and operating. The research community needs to go beyond showing the feasibility of these solutions to the efficient and practical use of such distributed solutions in alignment with industrial requirements.

Acknowledgements

This work was partially supported through the project ExElPro, which the Federal Ministry for Economic Affairs and Climate Action funds under grant number 16BZF353D.

Appendix

The following tables show the response frequencies for the survey questionnaire related to H1, H2, and H3.

Table 7: H1 frequency table

IEC 62264	VDI 5600	NAMUR	MESA
R1: 16	R1: 17	R1: 5	R1: 10
R2: 7	R2: 13	R2: 2	R2: 7
R3: 5	R3: 8	R3: 16	R3:8
R4: 36	R4: 26	R4: 41	R4: 39
Missing: 36	Missing: 36	Missing: 36	Missing: 36

Table 8: H2 frequency table

Today	< 3 years in the future	3 to 5 years in the future
R1: 15	R1: 4	R1: 2
R2: 39	R2: 40	R2: 23
R3: 12	R3: 22	R3: 41
Missing: 34	Missing: 34	Missing: 34

Table 9: H3 frequency table

Today	< 3 years in the future	3 to 5 years in the future
R1 + R2: 18	R1 + R2: 19	R1 + R2: 18
R3 + R4: 71	R3 + R4: 70	R3 + R4: 71
Missing: 11	Missing: 11	Missing: 11

References

[1] Shojaeinasab, A. et al. Intelligent manufacturing execution systems: A systematic review. J. Manuf. Syst. 2022. 62: 503–522. doi: 10.1016/j.jmsy.2022.01.004

[2] F. Almada-Lobo. The Industry 4.0 revolution and the future of Manufacturing Execution Systems (MES). J Innovation Management 2016. 4: 16–21. doi: 10.24840/2183-0606_003.004_0003.

[3] A. R. Hevner et al. Design science in information systems research. MIS Quarterly: Management Information Systems 2004; 1: 75–105. doi: 10.2307/25148625.

[4] E. Arica and D. J. Powell. Status and future of manufacturing execution systems. Ieee Int Conf Industrial Eng Management 2017. pp. 2000–2004. doi: 10.1109/ieem.2017.8290242.

[5] S. Jaskó, A. Skrop, T. Holczinger, T. Chován, and J. Abonyi. Development of manufacturing execution systems in accordance with Industry 4.0 requirements: A review of standard- and ontology-based methodologies and tools. Computers in Industry 2020; 12: 103300. doi: 10.1016/j.compind.2020.

[6] S. Mantravadi and C. Møller. An Overview of Next-generation Manufacturing Execution Systems: How important is MES for Industry 4.0? Procedia Manufacturing 2019; 588–595. doi: 10.1016/j.promfg.2019.02.083.

[7] A. Fink. Conducting research literature reviews: from the Internet to paper. Sage publications, 2019. doi: 10.5860/choice.42-6198.

[8] C. Li, S. Mantravadi, and C. Møller. AAU Open Source MES Architecture for Smart Factories – Exploiting ISA 95. IEEE 18th Int Conf Industrial Informatics Indin 2020; 369–373. doi: 10.1109/indin45582.2020.9442130.

[9] M. Oberle, S. Gärtner, O. Yesilyurt, F. Maier, and D. Brandt. An Approach for Designing and Developing Microservices-enabled Manufacturing Operations Management in Greenfield Environments. Proceedings of the Conference on Production Systems and Logistics: CPSL 2022. doi: 10.15488/12132.

[10] S. Mantravadi, C. Møller, C. LI, and R. Schnyder. Design choices for next-generation IIoT-connected MES/MOM: An empirical study on smart factories. Robots and Computer Integrated Manufacturing 2022; 02: 102225. doi: 10.1016/j.rcim.2021.102225.

[11] Václav Kaczmarczyk, František Zezulka, Tomáš Benešl, Jakub Arm, Petr Marcoň, Jan Jirsa, Lukáš Venkrbec. Revisiting the Role of Manufacturing Execution Systems in Industry 4.0. Ifac-papers online 2022; 4: 151–157. doi: 10.1016/j.ifacol.2022.06.025.

[12] K. Benfriha et al.Development of an advanced MES for the simulation and optimization of industry 4.0 process. International Journal for Simulation and Multidisciplinary Design Optimization 2022; 12: 23ff. doi: 10.1051/smdo/2021022.

[13] P. Novák, J. Vyskočil, and P. Kadera. Plan Executor MES: Manufacturing Execution System Combined with a Planner for Industry 4.0 Production Systems. Lecture Notes in Computer Science 2019; 11710: 67–80. doi: 10.1007/978-3-030-27878-6_6.

[14] P. Novák, P. Douda, P. Kadera, and J. Vyskočil. PyMES: Distributed Manufacturing Execution System for Flexible Industry 4.0 Cyber-Physical Production Systems. IEEE International Conference on Systems, Man and Cybernetics 2022. pp. 235–241. doi: 10.1109/smc53654.2022.9945350.

[15] J. Zhou, L. Li, and N. Zhou. Research and Application of Battery Production Data Management System Based on Microservice," 2019 Ieee 9th Int Conf Electron Information Emerg Commun Iceiec, vol. 00, pp. 1–5, 2019, doi: 10.1109/iceiec.2019.8784670.

[16] Z. Yi, W. Meilin, C. RenYuan, W. YangShuai, and W. Jiao, "Research on Application of SME Manufacturing Cloud Platform Based on Micro Service Architecture," Proc Cirp, vol. 83, pp. 596–600, 2019, doi: 10.1016/j.procir.2019.04.091.

[17] S. Do, W. Kim, H. Cho, and J. Jeong, "SaaMES: SaaS-Based MSA/MTA Model for Real-Time Control of IoT Edge Devices in Digital Manufacturing," Sustainability-basel, vol. 14, no. 16, p. 9864, 2022, doi: 10.3390/su14169864.

[18] M. Ko, C. Lee, and Y. Cho, "Design and Implementation of Cloud-Based Collaborative Manufacturing Execution System in the Korean Fashion Industry," Appl Sci, vol. 12, no. 18, p. 9381, 2022, doi: 10.3390/app12189381.

[19] T. H. Kim, J. Jeong, and Y. Kim, "A Conceptual Model of Smart Manufacturing Execution System for Rolling Stock Manufacturer," Procedia Comput Sci, vol. 151, pp. 600–606, 2019, doi: 10.1016/j.procs.2019.04.081.

[20] K. Wang et al., "Development and Application of MES Based on Cloud Platform for Steel Structure Enterprises," 2019 Ieee Int Conf Industrial Eng Eng Management Ieem, vol. 00, pp. 521–525, 2019, doi: 10.1109/ieem44572.2019.8978516.

[21] A. Z. C. Bawono and K. Komarudin, "Towards Industry 4.0: Manufacturing Execution System (MES) Design for Mass Customization," 4th Asia Pac Conf Res Industrial Syst Eng 2021, pp. 269–276, 2021, doi: 10.1145/3468013.3468342.

[22] M. A. Sellitto and E. J. de Vargas, "A method to align functionalities of a manufacturing execution system with competitive priorities," J Manuf Technology Management, vol. 31, no. 2, pp. 353–369, 2019, doi: 10.1108/jmtm-11-2018-0424.

[23] W. Qu, W. Cao, and Y.-C. Su, "Design and implementation of smart manufacturing execution system in solar industry," J Amb Intel Hum Comp, pp. 1–17, 2020, doi: 10.1007/s12652-020-02292-5.

[24] J. Du, G. Kang, and S. Qiao, "Design of Intelligent Factory Line Integrated Management System," Lect Notes Electr En, pp. 242–253, 2022, doi: 10.1007/978-981-19-3842-9_20.

[25] P. Zeng, Y. Hao, C. Wu, C. Shi, and Y. Hao, "Development of Workshop Management System for Assembly Production Process," Lect Notes Comput Sc, pp. 435–446, 2019, doi: 10.1007/978-3-030-27529-7_37.

[26] J. Zhang and M. Zhang, "Digital Workshop Design Scheme of Microcircuit Module Based on MOM and SCADA System," Lect Notes Electr En, pp. 538–546, 2019, doi: 10.1007/978-981-32-9437-0_56.

[27] J. Chen et al., "HANA-MES: A HMI-awared Manufacturing Execution System," 2021 Ieee 23rd Int Conf High Perform Comput Commun 7th Int Conf Data Sci Syst 19th Int Conf Smart City 7th Int Conf Dependability Sens Cloud Big Data Syst Appl Hpcc Dss Smartcity Dependsys, vol. 00, pp. 1863–1869, 2021, doi: 10.1109/hpcc-dss-smartcity-dependsys53884.2021.00276.

[28] S. M. Favela-Camacho, J. Molina-Salazar, and L. Rico-Pérez, "Manufacturing Execution System State-Of-The-Art: Its Evolution and Dynamism Focused on Industry 4.0," Trends in Industrial Engineering Applications to Manufacturing Process, pp. 245–262, 2021, doi: 10.1007/978-3-030-71579-3_11.

[29] Y. HE and Z. YIN, "Research and Design of Manufacturing Execution System in a Bicycle Smart Factory," Destech Transactions Comput Sci Eng, no. ica, 2019, doi: 10.12783/dtcse/00/30739.

[30] T. Song and J. Zhou, "Research on Lean Shipbuilding and Its Manufacturing Execution System," J Ship Prod Des, vol. 38, no. 03, pp. 172–181, 2022, doi: 10.5957/jspd.01220001.

[31] Salvadorinho and L. Teixeira, "Shop floor data in Industry 4.0: study and design of a Manufacturing Execution System," Conferência da Associação Portuguesa de Sistemas de Informação, 2020.

[32] J. Salvadorinho, L. Teixeira, B. S. Santos, and C. Ferreira, "Supporting Production Management in the Fourth Industrial Revolution: A Framework Based on Shop-Floor Data," Automation Collab E-services, pp. 47–63, 2022, doi: 10.1007/978-3-031-10780-1_2.

Biography

Michael Oberle (*1984) is a computer scientist working in the field of smart manufacturing. He obtained his Master's degree from the University of Auckland, New Zealand, in 2012 and joined the Fraunhofer Institute for Manufacturing Engineering and Automation (IPA), Germany, working as a researcher in the Competence Center for digital tools in manufacturing. Initially focusing on manufacturing control in the semiconductor industry, he began leading projects with a focus on the digitalization of battery manufacturing since 2014. One of his main achievements is the fully connected cloud-controlled battery manufacturing pilot line at the Fraunhofer IPA center for battery cell manufacturing. Today, he leads the group for Data and Application Services for Digital Production, focusing on data-driven and event-driven production control services.

Daniel Schel (*1986) is group manager of the team "IT Architectures for Digital Production" in the department "DigITools for Manufacturing" at Fraunhofer IPA. He is active in the field of IT-based manufacturing systems, including the topics Dynamic Manufacturing Networks, Cloud-based Manufacturing, Industrie 4.0 and Smart Production using cyber-physical systems. He holds a bachelor's degree in software engineering and has managed and conducted a number of research projects as technical director and software architect, focusing on novel approaches to IT solutions in production.

Monika Risling (*1997) is a research associate 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. She studied Industrial Engineering with focus on Digital Production Management and Computer Science.

Thomas Bauernhansl (*1969) has been Director of the Fraunhofer Institute for Manufacturing Engineering and Automation IPA in Stuttgart, Germany since September 2011. He is also Director of the University of Stuttgart's Institute of Industrial Manufacturing and Management (IFF). His scientific focus is on production organization, factory planning, energy-efficient production, surface engineering, automation and process engineering, and digital and biological transformation. Bauernhansl studied mechanical engineering at RWTH Aachen University. After completing his Ph.D. with honors in 2002, he embarked on his career with Freudenberg in 2003, advancing to become Director of the Technology Center at Freudenberg Sealing Technologies. Bauernhansl was responsible for the regions Europe, North and South America, optimizing the "global footprint" of the production network made up of over 50 production sites.

5th Conference on Production Systems and Logistics

Precision Assessment of Tactile On-Machine Inspection for Milling Operations

Jonas Krebs[1], Gregor Mueller[1], Lars Roedel[1], Jan Prochnau[2], Josip Florian Strutz[2] and Thomas Bauernhansl[1,3]

[1]*Fraunhofer Institute for Manufacturing Engineering and Automation, Stuttgart, Germany*
[2]*CERATIZIT Besigheim GmbH, Besigheim, Germany*
[3]*Institute of Industrial Manufacturing and Management, IFF, University of Stuttgart, Germany*

Abstract

The manufacturing industry faces customer demands for increased product quality and individuality to be economically successful. Established processes on the shop floor cannot overcome resulting challenges. Due to the increased quality requirements, potentially more products must be checked regarding their requirement fulfilment. In addition, customer individuality increases the number and rate of product releases. During product releases, the quality of the product is checked. Coordinate measuring machines are usually used for the quality assessment of milling processes. However, these are only suitable in the area of high quantities per batch due to downtimes of the milling machine while assessing product quality. On-machine inspection systems show particular strengths when a high proportion of the manufactured products have to be inspected and potentially reworked. These systems are criticized for their poor precision compared to coordinate measuring machines. This paper demonstrates the precision and repeatability of a tactile system in a field test at a tool manufacturer. Based on the test results, the tactile on-machine inspection system is compared with conventional coordinate measuring machines. Finally, the application area and its limits are identified for tactile on-machine inspection systems.

Keywords

on-machine inspection; quality assessment; tactile measurement; customized products; milling

1. Introduction

Current trends in the market for machining products indicate that products are becoming more customized to individual customers while, at the same time, there are increasing demands for product quality [1-3]. The market-driven customer individuality is reflected in mass personalization, which realizes customer-specific parts at comparable costs, even for batch sizes of 1 [4]. For economical production of batch size one not only the manufacturing process but also the quality assurance processes must ensure the necessary quality [5].

1.1 Initial situation

One essential quality assurance process is product release obtained for serial parts for the first manufactured part, confirming that the manufacturing system meets the product requirements [6]. After product release, quality inspection for the series are implemented in a defined sequence. These measures can range from inspecting every part of the series (100% inspection) to a small or complete waiver of samples. Based on the customer-specific product, each part must undergo inspection for the necessary product release, as with a high number of customer-specific features, each part is a new part [7]. The standard process in the industry for product release of milled parts comprises eight steps:

DOI: https://doi.org/10.15488/15263
ISSN: 2701-6277

1. Unclamping from the machine (machine waits)
2. Clamping in the coordinate measuring machine
3. Programming the inspection task (can be done pre-process in a digital environment)
4. Execution of the inspection program
5. Unclamping of the work piece
6. Interpretation of the inspection results
7. Possibly rework and start of step 1
8. Product release and release of the machine tool for the next order.

The introduction of tactile on-machine inspection offers the possibility of shortening the process chain and minimizing non-value-added activities [8]. A common criticism against using tactile measuring systems for quality assurance is the perceived lower precision compared to coordinate measuring machines [9]. However, this paper will demonstrate that tactile on-machine inspection can match the precision of conventional coordinate measuring machines.

1.2 Scope

To support this claim, experiments were conducted on a machine tool using the touch probe system for reproducible measurement. The repeatability within manufacturing tolerances and the use in a productive manufacturing system were tested.

The results of these experiments show that tactile on-machine inspection provides acceptable precision that meets the requirements of manufacturing tolerances. This allows for efficient quality inspection directly on the machine without additional measuring equipment, such as coordinate measuring machines. Integrating inspection into the manufacturing process can prevent non-value-added activities such as unclamping and measuring on separate measuring machines.

It is important to note that the precision of tactile on-machine inspection depends on various factors, such as machine stability, calibration of the touch probe system, and proper programming of the measurement tasks. Therefore, careful setup and regular verification are crucial to achieve optimal results.

Overall, this paper demonstrates that tactile on-machine inspection is a promising alternative to conventional quality inspection with coordinate measuring machines. It enables efficient and precise monitoring of manufacturing quality directly on the machine, leading to shortened lead times and a reduction in non-value-added activities.

2. State of the art

The following section discusses tactile touch systems for milling. During milling, chips are generated, and coolant is used. Both can reflect when using an optical measurement system. Therefore, a more robust system is necessary to withstand environmental influences [10-11]. The touch system uses mechanical force on the probe head and is thus better suited for the machining environment.

Measurement methods for quality assurance can be divided into two groups: in situ measurement methods that measure during the process (in situ or on-machine) and measurement methods that are outsourced from the process (ex situ). Both measurement methods use the same principles (e.g., tactile, optical, etc.) [12-13]. Due to the focus on tactile in situ measurements, the corresponding offline measurement method is also presented as a reference.

2.1 Coordinate measurement machines

Generally, tactile measurement outside the machine tool uses coordinate measuring machines (CMM). These machines typically consist of a tool holder, a probe, and kinematics for multiple axes. The general use and a brief description of operating CMM can be found in [14-16].

The advantage of CMMs is their explicit use for measurements, as no high forces occur during the measurement process. Consequently, the kinematics can be designed more precisely than machine tools and the CMM wears less. A CMM can measure in 1,5 µ range [17]

Criticism of tactile in-situ measurement is based on the fact that the touch system consisting of the probe and machine is not as precise as a coordinate measuring machine. This is because the machine tool must handle the high forces of machining, which comes at the expense of precision. In addition, the machine tool is subject to higher wear and tear due to machining and possible crashes during processing. The on-machine touch system consists of the probe inserted into the tool holder and the machine tool that realizes the movement of the probe. Both the probe and the machine tool are subject to tolerances, which add up during measurement in the machine [9]. With the increasing precision of machine tools, the tolerance range of the in-situ touch system decreases.

2.2 On-machine inspection

OMI stands for on-machine inspection, a method of measuring workpieces directly on the machine tool in the same clamping situation as they were manufactured. This offers several advantages, including the ability to immediately correct the work piece based on the measurement results without re-clamping or adjusting the machine. OMI also reduces handling times compared to coordinate measuring machines, although it may reduce the availability of machinery time for other value-adding activities [18-19].

The precision and reproducibility of OMI is within the range of the machine tolerances on the installed machine tool. However, reproducibility may decrease with increasing machine wear due to crashes or axis misalignment [20]. OMI is particularly useful for correction-intensive workpieces, as tool correction is based on the machining operation and the subsequent measurement operation rather than just tool wear, resulting in improved production quality.

3. Methodology

This scientific paper aims to demonstrate the suitability of tactile on-machine inspection in a production environment. The study consists of three experimental series conducted to evaluate the effectiveness of the tactile system.

In the first series, the tactile system's repeatability is examined by testing its performance on a manufactured contour. The focus is initially on the z-axis, followed by an assessment of repeatability in the x and y-axes. The distribution of test points is based on the product manufactured by the industrial company involved in the study. Specifically, the company produces drills with indexable inserts. The contour to be inspected is the seat for the indexable inserts, and eleven points are strategically distributed on the seat for inspection purposes. The first three points are located in the seat base and are exclusively tested in the z-direction. The remaining four points lie on a straight line defined by x and y coordinates and are approached at a constant z-height (Figure 1). For this series, one seat is manufactured and inspected three times to determine the repeatability of the tactile system in both 1D and 2D by analysing the collected measurement data.

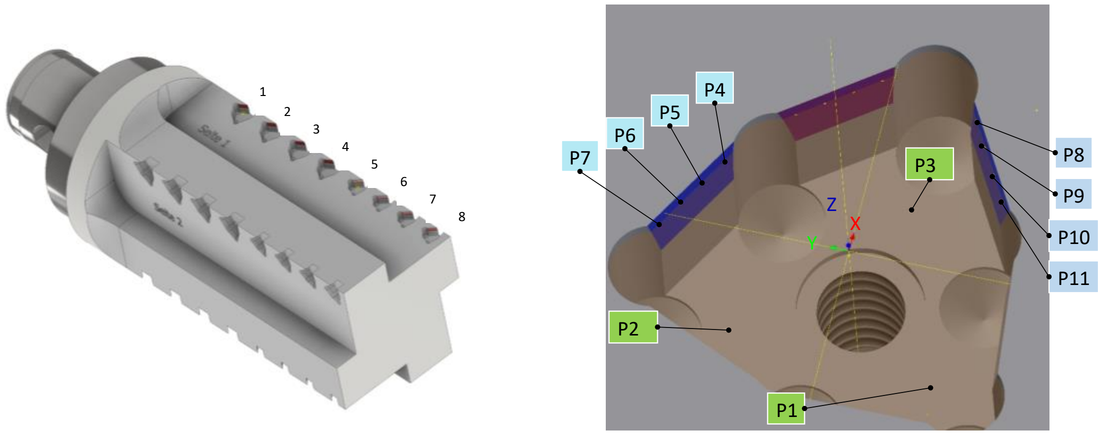


Figure 1: Test sample containing seats for indexable inserts (left) and digital model of seat for indexable inserts including inspection points (right)

The second experimental series focuses on the same geometry as the first series. However, instead of scanning a single manufactured geometry multiple times, the second series measures multiple indexable insert seats manufactured with the same machine parameters. To achieve this, the machine tool produces four seats with identical machine parameters that are shifted exclusively in the x-coordinate. This experimental setup allows an assessment of the interaction between manufacturing tolerances and the tolerance of the tactile system. By measuring multiple seats, the second series provides a more comprehensive evaluation of the system's performance and ability to handle variations in the manufacturing process. This analysis is crucial for understanding the system's limitations and identifying areas for improvement.

In this experiment, four manufactured seats will be inspected. However, the focus will be on points 4-11, which are expected to exhibit higher measurement uncertainty due to the two-axis approach. This series aims to examine the influence of a replicating manufacturing factor on the measurement results. To achieve this, eight points will be recorded for four different manufacturing operations in the experimental series.

Compared to the previous series, the third series introduces a variable manufacturing factor. Instead of producing four identical seats, the machine tool will produce seats of varying sizes. This will be accomplished by manufacturing an indexable insert seat with a negative tool setting. After each measurement, the tool setting will be adjusted to increase the radius. The intention is to observe the effect of the tool setting in the subsequent measurements. By analysing the measurement results, the sensitivity of the measurement process to manufacturing variations, such as rework due to tool wear, can be evaluated.

The three experimental series make it possible to evaluate the reproducibility of a repetitive inspection task (series 1), the precision of the machine in the interaction between manufacturing and inspection (series 2), and the sensitivity of the measurement system to tool setting (series 3). This research aims to provide valuable insights into the effectiveness and applicability of tactile OMI in a production setting.

4. Results

The experimental series were conducted at CERATIZIT Besigheim GmbH, a tool manufacturer, using a DMG CTX Beta turning and milling centre employed for special drilling tools. The milling centre operates daily to produce drills including the indexable insert seats. Equipped with a BLUM LC50 3D touch probe measurement values are provided to the machine control. The test sample consisted of hardened steel serving as the base material for the drills to be manufactured.

4.1 First series

In the first series of experiments, a geometry was repeatedly probed in one axis and afterwards in multiple axes. The measurement points for this series were outlined in the previous chapter. To ensure comparability between the experimental series, the smallest measured value for each point was set to zero, and the remaining measurement values for that point were adjusted accordingly. For the one-dimensional probing in the z-direction (P1-P3), a maximum deviation of three points from 1,2 µm was observed, indicating a high level of repeatability in a single axis (Figure 3).

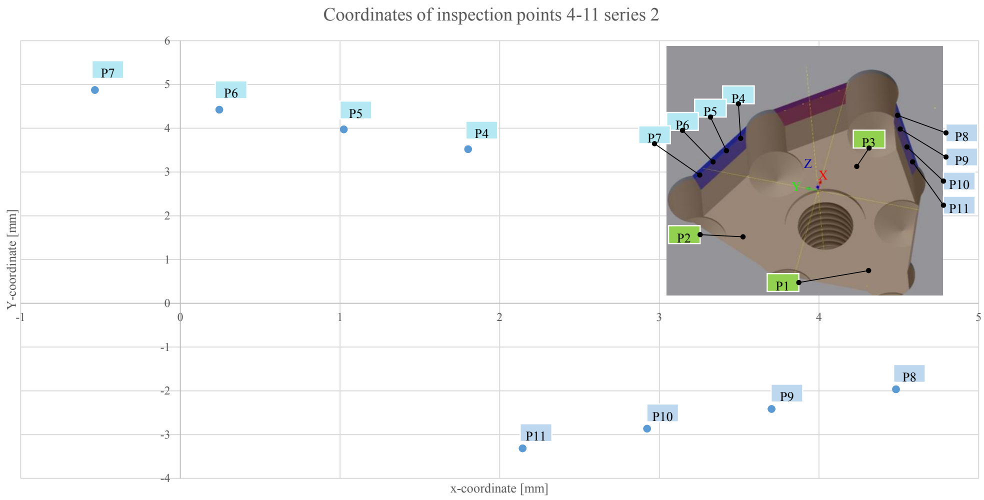
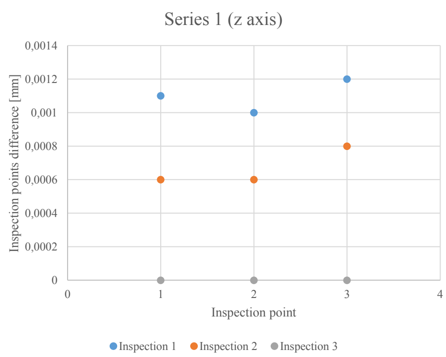


Figure 2: Distribution of inspection points

In the two-axis measurement approach, a total of eight points were utilized, four located on the contact surfaces of an indexable insert seat. The touch probe was used to probe the surface orthogonally in the X and Y directions, resulting in X and Y coordinates for each point (Figure 2). The calculation method mirrored that of the one-dimensional probing. The minimum values for each coordinate and point were recorded and subtracted from the corresponding measurement values. The assessment of the two-axis contribution involved calculating the hypotenuse of the X and Y deviations, representing the difference in both axes. The results demonstrated that the reproducibility of the measurements did not exceed 1 µm for all points, indicating the presence of a highly precise tactile system comprising the machine tool and the touch probe (Figure 3).

$$Inspection\ point\ difference\ two\ axis_i = \sqrt{(X_i - X_{min})^2 + (Y_i - Y_{min})^2)}$$



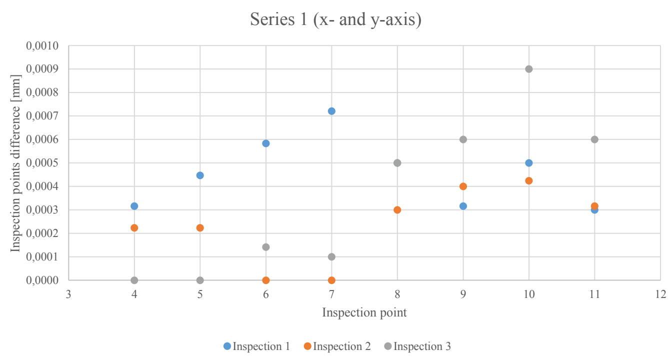


Figure 3: Inspection difference in series 1

4.2 Second series

In the second series of experiments, four indexable insert seats were manufactured on the test specimen. These seats were strategically positioned at different locations along the x-axis and produced consecutively with identical machine parameters. This setup allows for isolating the machine tool's kinematic influence during the machining process. Calculating the measurement value deviations for each point followed the same procedure as in the first series, as the same eight points were considered within the four manufactured seats.

As anticipated, the manufacturing influence resulted in larger variations among the points. The largest difference observed was 3.6 µm, although it appeared to be an outlier, as most of the measurement differences for each point fell within the range of 2 µm. When all the difference values for the eight points were analysed collectively, it was found that 50% of the differences ranged from 0.4 µm to 1.5 µm (Figure 4). This indicates that even in the presence of manufacturing influence, the tactile system exhibited high precision.

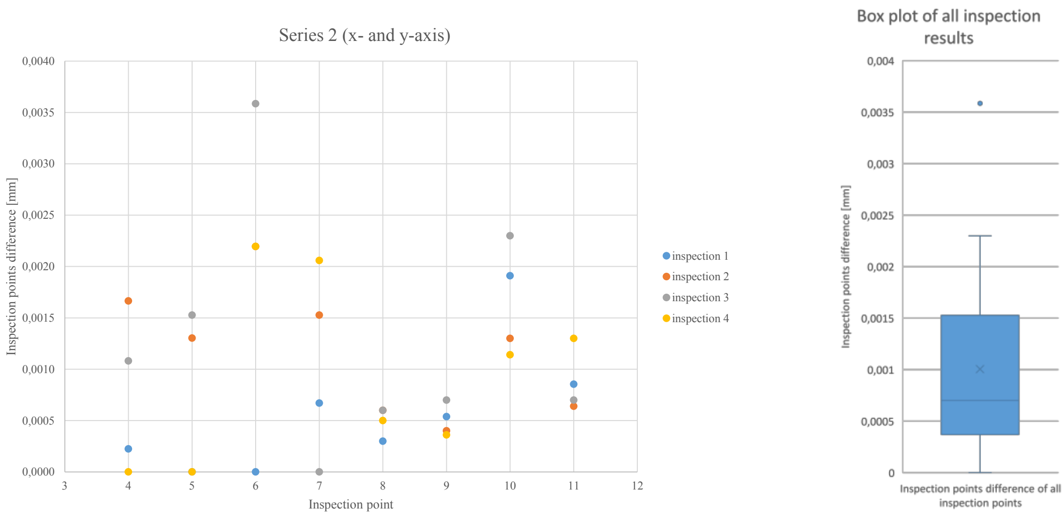


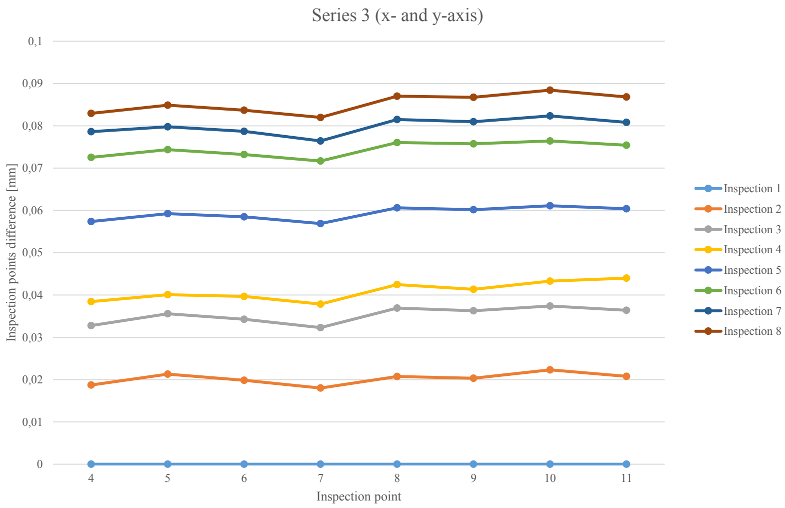
Figure 4: Inspection point difference in series 2 per point [left] and aggregated [right]

4.3 Third series

In the third series of experiments, the first seat was manufactured with a fine adjustment of -0.05 mm on the tool. This adjustment indicates that the tool was corrected by -0.05 mm on the radius, resulting in a contour that is 0.05 mm smaller than the ideal contour in an ideal system with no tool adjustment. Typically, fine adjustments are used to adjust tools based on the results of tool presetting and compensate for tool wear by making positive tool adjustments.

Within the experimental series, each seat was manufactured, measured, and then adjusted before repeating the process. Seven tool adjustments were made from the initial -0.05 mm, resulting in a cumulative adjustment of 0.085 mm to 0.035 mm. To analyse the results, the X and Y measurement values of the first measurement were subtracted from the corresponding measurement values, and the resulting vector was formed from the X and Y coordinates, as previously described. The tool adjustments are expected to be accurately reflected in the measurement results.

The results revealed a high sensitivity of the measurements to the tool adjustments. Each adjustment was clearly visible in the measurements, with the points fluctuating around the applied adjustment within the low µm range (Figure 5).



Inspection number	Tool radius adjustment [mm]	
1	-0,05	0,02
2	-0,03	0,015
3	-0,015	0,05
4	-0,01	0,02
5	0,01	0,015
6	0,025	0,005
7	0,03	0,005
8	0,035	

Figure 5: Inspection point difference in series 3 per point including tool adjustment

In summary, the tactile system demonstrated a reproducibility of 1 µm and a sensitivity to manufacturing operations within a few µm range. It is important to note that this analysis focused solely on 2D probing and the involvement of two machine axes. The sensitivity of the on-machine inspection solution is comparable to that of coordinate measuring machines and will be assessed for its suitability in further applications.

5. Critical assessment

The measurement precision of coordinate measuring machines is typically in the range of 1.5 µm, as described in the state of the art. However, the presented on-machine inspection solution showed a reproducibility difference of only 3,6 µm for the same manufacturing task with the same machine parameters. Most of the measurement values fluctuated within less than 2 µm and were sensitive to the manufacturing influence of the tool adjustment. Therefore, the on-machine inspection solution is a viable alternative to established coordinate measuring machines.

The high sensitivity to tool adjustments makes on-machine inspection suitable for quality monitoring and deriving necessary tool corrections. By transferring the measurement values to the machine control, there is the possibility of adaptive process control based on the measurement values.

It is important to note that the experiments did not involve probing in three dimensions. However, this consideration was not pursued since no increased uncertainty was observed between 1D and 2D probing. The results strongly depend on the equipment used in the experimental series. However, based on the results obtained, a comparable touch probe on a machine tool would provide sufficient quality for the intended use and sensitivity for quality assurance within the machine. This assumption is supported by the fact that the test machine is used for the daily production of drills.

6. Conclusion

This study demonstrated the comparability of the sensitivity between an on-machine inspection solution and a conventional coordinate measuring machine. The reproducibility of the on-machine measurements and their sensitivity to manufacturing influences were investigated through three experimental series conducted at a special tool manufacturer. The results revealed excellent reproducibility of the measurement outcomes within the chosen experimental setup. The on-machine inspection system accurately detected tool adjustments within a few µm, offering a competitive alternative to coordinate measuring machines and laying the groundwork for a self-regulating machine tool. Looking ahead, future considerations should focus on topics such as tool regulation based on on-machine inspection and the necessary work preparation, including the generation of measurement points. Addressing these aspects will unlock the full potential of using on-machine inspection for high-customized parts.

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] Y. Wang, H.-S. Ma, J.-H. Yang, and K.-S. Wang, “Industry 4.0: a way from mass customization to mass personalization production,” Adv. Manuf., vol. 5, no. 4, pp. 311–320, 2017.

[5] 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.

[6] J. Ensthaler, A. Füßler, and D. Nuissl, “Produktbeschreibung und Erstbemusterung,” in Juristische Aspekte des Qualitätsmanagements (Springer eBook Collection Business and Economics), J. Ensthaler, A. Füßler, and D. Nuissl, Eds., Berlin, Heidelberg, s.l.: Springer Berlin Heidelberg, pp. 123–130, 1997.

[7] S. Beckschulte, R. Kiesel, and R. H. Schmitt, “Manuelle Fehleraufnahme bei Mass Customization,” Zeitschrift für wirtschaftlichen Fabrikbetrieb, vol. 116, no. 4, pp. 188–192, 2021.

[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] D. Li, B. Wang, Z. Tong, L. Blunt, and X. Jiang, “On-machine surface measurement and applications for ultra-precision machining: a state-of-the-art review,” Int J Adv Manuf Technol, vol. 104, 1-4, pp. 831–847, 2019.

[10] M. Bulgaru, V. Bocăneț, and M. Muntean, “Research regarding tactile scanning versus optical scanning,” MATEC Web Conf., vol. 299, p. 4013, 2019.

[11] P. Lehmann, “Optical versus tactile geometry measurement: alternatives or counterparts,” in Optical Measurement Systems for Industrial Inspection III, Munich, Germany, W. Osten, M. Kujawinska, and K. Creath, Eds., pp. 183-196, 2003.

[12] T. J. Ko, J. W. Park, H. S. Kim, and S. H. Kim, “On-machine measurement using a noncontact sensor based on a CAD model,” Int J Adv Manuf Technol, vol. 32, 7-8, pp. 739–746, 2007.

[13] J. Schmidt, B. Thorenz, F. Schreiner, and F. Döpper, “Comparison of areal and profile surface measurement methods for evaluating surface properties of machined components,” Procedia CIRP, vol. 102, pp. 459–464, 2021.

[14] C. Butler, “An investigation into theperformance of probes on coordinate measuring machines,” Industrial Metrology, vol. 2, no. 1, pp. 59–70, 1991.

[15] W. Estler et al., “Error compensation for CMM touch trigger probes,” Precision Engineering, vol. 19, 2-3, pp. 85–97, 1996.

[16] P. C. Miguel, T. King, and Á. Abackerli, “A review on methods for probe performance verification,” Measurement, vol. 23, no. 1, pp. 15–33, 1998.

[17] A. Wozniak and M. Dobosz, "Factors influencing probing accuracy of a coordinate measuring machine," in IEEE Transactions on Instrumentation and Measurement, vol. 54, no. 6, pp. 2540-2548, 2005.

[18] N. Huang, S. Zhang, Q. Bi, and Y. Wang, “Identification of geometric errors of rotary axes on 5-axis machine tools by on-machine measurement,” Int J Adv Manuf Technol, vol. 84, 1-4, pp. 505–512, 2016.

[19] S. Li, L. Zeng, P. Feng, Y. Li, C. Xu, and Y. Ma, “Accurate compensation method for probe pre-travel errors in on-machine inspections,” Int J Adv Manuf Technol, vol. 103, 5-8, pp. 2401–2410, 2019.

[20] 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.

Biography

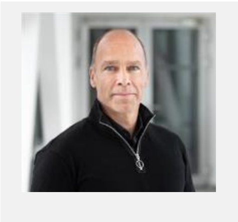
Jonas Krebs (*1995) is a research associate at the Fraunhofer Institute for Manufacturing Engineering and Automation IPA. He joined the Department Factory planning and production management in early 2021. He finished his Masters in production engineering at RWTH Aachen University with a background in 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.

Jan Prochnau (*1986) is employed as a project engineer in the production technology department at CERATIZIT Besigheim GmbH. After completing an industrial apprenticeship and working in production for several years, he moved to the administrative area of work preparation and production control in 2010. Since 2017 he has been responsible for the supervision and coordination of improvement projects and since 2022 for the machine procurement of the machining production at the CERATIZIT site in Besigheim.

Josip Florian Strutz (*1986) has been Head of Digitalization Production at Ceratizit since 2022 and is a PhD student at the University of Slavonski Brod, Croatia. From 2017 to 2022, he worked as a project engineer in the machine and equipment procurement department at Wilhelm Layher GmbH & Co. KG. Prior to that, he completed his Master's degree in Automotive Systems at the University of Applied Sciences in Esslingen, Germany.



Prof. Dr.-Ing. Thomas Bauernhansl (*1969) has been director of the Fraunhofer Institute for Manufacturing Engineering and Automation IPA in Stuttgart since September 2011 and at the same time director of the Institute of Industrial Manufacturing and Management IFF at the University of Stuttgart. His research focuses on digital and biological transformation, production organization, factory planning, automation, and robotics.

CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
CPSL 2023-2

5th Conference on Production Systems and Logistics

Transfer Learning Approaches In The Domain Of Radial-Axial Ring Rolling For Machine Learning Applications

Johannes Seitz[1], Tobias Moser[1], Simon Fahle[2], Christopher Prinz[1], Bernd Kuhlenkötter[1]

[1]*Chair of Production Systems, Ruhr-University Bochum, Bochum, Germany*
[2]*Westnetz GmbH, Dortmund, Germany*

Abstract

Due to increased data accessibility, data-centric approaches, such as machine learning, are getting more represented in the forming industry to improve resource efficiency and to optimise processes. Prior research shows, that a classification of the roundness of shaped rings, using machine learning algorithms, is applicable to radial-axial ring rolling. The accuracy of these predictions nowadays is still limited by the amount and quality of the data. Therefore, this paper will focus on how to make the best use of the limited amount of data, using transfer learning approaches. Since acquiring data for homogenised databases is time, energy and resource consuming, logged data gathered by the industry is often used in research. This paper takes both, industrial data from thyssenkrupp rothe erde Germany GmbH and a smaller dataset of an inhouse research plant, into account. Additionally, a synthetic dataset, created by generative adversarial networks, is considered. To accomplish an improvement of machine learning predictions using accessible data, three transfer learning approaches are investigated in order to extend existing models: (I) transferring from a radial-axial ring rolling mill to a different mill containing less available data with a ratio of 20:1, (II) learning from unlabelled data using an autoencoder and (III) training on synthetic data. The obtained improvements are further evaluated. Based on these results, future possible investigations are elaborated, in particular the consideration of transfer learning from the less complex cold ring rolling process.

Keywords

Radial-Axial Ring Rolling; Machine Learning; LSTM; Predictive Quality; Transfer Learning

1. Introduction

To cope with environmental and economical requirements, techniques to increase resource efficiency in the forming industry, are applied, such as material and process efficiency [1]. Especially the reduction of parts which either need to be reworked or are scrap, is of interest. In the hot forming process radial-axial ring rolling (RARR), there are still challenges to cope with this condition, since the establishment of a stable RARR process according to GUO ET YANG is difficult and depends on many influencing factors as for instance the ring growth behaviour [2]. Hence, several approaches have been conducted to obtain these improvements, including the use of machine learning (ML) algorithms. In RARR FAHLE ET AL. proved the applicability of ML in order to predict quality, through a classification task of the roundness of formed rings after each ring roll procedure [3]. Since ML algorithms are sensitive to the data quality and data amount, predictions are still limited. The conducted survey by FAHLE ET AL. demonstrates this issue: although all considered producing companies are storing data, just 50 % of these companies are analysing and using this data [4]. Additionally, in terms of using ML for quality predictions, it is necessary to

DOI: https://doi.org/10.15488/15303
ISSN: 2701-6277

connect process data with its target data. In terms of predictive quality in RARR, the target data is the corresponding measured quality parameter (label). To generate data for scientific applications, this procedure is consuming time and process energy. This is especially the case, if a dataset for ML applications is needed, since the performance is depending on the data amount.

Based on the difficulties concerning data gathering and availability, this paper contributes three approaches to increase the performance of ML algorithms with accessible data using transfer learning methods. Those models are varying in the utilised datasets and their approaches of transfer learning, so that each model represents a solution for a certain issue. Therefore, an overview of possible transfer learning use cases in RARR is presented. Moreover, the concept of transferring knowledge from the related cold ring rolling process to the RARR is introduced, hence the progress of the given transfer learning methods is motivating this further step.

2. Theoretical background and related work

2.1 Theoretical background

2.1.1 Radial-axial ring rolling

Radial-axial ring rolling (RARR) is a rotary hot forming process, to shape seamless rings in order to enlarge the ring diameter, reduce the thickness and decrease the height [5]. The forming is according to ALLWOOD ET AL. obtained by two opposite radial rolls and two conical axial rolls and their synchronous feed applied on a rotating ring (Figure 1). The final ring cross section can be rectangular, or if the tools have cavities, profiled [6]. Additionally, besides the RARR there are other ring rolling techniques available, such as cold ring rolling, where the preform is not preheated and just radial rolls are used [6,5]. In RARR several errors can take place, such as ring height deviation and non-circularity [7]. In conventional mills, data is logged during the forming process for each timestep (t_i) in a defined sampling rate, including process parameters such as forces or geometrical measurements.

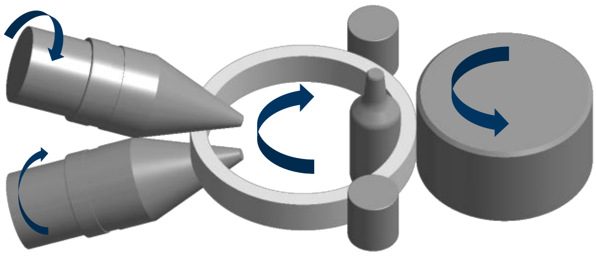


Figure 1: Radial-axial ring rolling scheme

2.1.2 Machine learning for time series predictions

In order to model time series, it is necessary to consider time dependency within the ML architecture. In the field of time series classification (TSC), where the whole timeseries is assigned to classes, multiple algorithms are according to FAWAZ ET AL. available to overcome this challenge. Those are including for instance nearest neighbour algorithms or deep learning approaches. Moreover, ensembles are available, combining different algorithms. [8] For the case of time series forecasting (TSF), where the course and future development of a time series is determined by a regression approach, statistics-based approaches and machine learning algorithms are available [9]. In terms of neural networks (NN), according to ORDÓÑEZ AND ROGGEN recurrent neural networks (RNN) can map this time dependency, trough the recurrent connection in each unit. Especially for long time scales the long short-term memory (LSTM) networks, an extension of RNNs, are usable, through a cell state, which is controlled by the activation of different gates (input, output and forget gate). [10]

2.1.3 Transfer learning

The concept of transfer learning is to improve ML models in one domain by transferring knowledge from another, but related, domain [11]. According to PAN AND YANG, it is necessary to define two spaces: the domains and the tasks. Those spaces are defined for the source and the target, whilst the source is the space providing knowledge to the target space. The domain is defined with a feature space X and its marginal probability distribution $P(X)$. The task is defined as a label space Y and an objective prediction function $f(\cdot)$. The objective prediction function is learned by the data, using training data which consist of pairs $\{x_i, y_i\}$. Therefore, the domain D and task T can be defined to:

$$D = \{X, P(X)\} \text{ and } T = \{Y, f(\cdot)\}. \tag{1}$$

Transfer learning is the case, if either the domain or the task is different between the source and the target. Within the source or target, the difference can appear in the spaces (X, Y), in the marginal probability distribution $P(X)$ or in the conditional probability distributions $P(Y|X)$ (unbalanced targets). Multiple approaches are available to obtain the knowledge transfer, such as instance transfer, feature-representation-transfer, parameter-transfer and relational-knowledge transfer. [12]

2.1 Related work

2.1.1 Machine Learning and data centric approaches in ring rolling

In the field of RARR, the CHAIR OF PRODUCTION SYSTEMS (RUHR-UNIVERSITY BOCHUM, GERMANY) recently conducted investigations in predictive quality solutions, based on ML approaches. The feasibility of a classification of the ring roundness with machine learning algorithms using process data, is shown by FAHLE ET AL. [3]. Moreover, FAHLE ET AL. introduced a model to obtain an early time series classification of the ring roundness during the process [13] and proposed methods to improve ML performances whilst using synthetic data and unsupervised learning algorithms on unlabelled data [14]. Additionally, a domain specific resample method for time scaling was provided [15]. MIRANDOLA ET AL. developed a ML model to predict the energy consumption in the RARR process using an gradient boosting approach and a multi-variable regression model [16,17]. In order to optimise the RARR process, LEE ET AL. used a combined enhanced extreme gradient boosting algorithm with a metaheuristic search algorithm [18]. Regarding quality determination with data mining methods, LAGAO classified process failures with a fuzzy logic approach [19] and GIORLEO ET AL. developed a regression model for the fishtail defect using finite element method (FEM) data [20].

2.1.2 Transfer learning

To the authors best knowledge, approaches of transfer learning have not been considered so far in RARR and in ring rolling processes. In other domains, this method has been successfully implemented in various applications [12], such as in image classifications [21] or Chemogenomics [22]. Transfer learning for image classification has been also used for classification tasks in strip rolling in order to use pre trained models [23–25]. Moreover, transfer learning has been implemented for fault diagnosis to cope with varying working conditions [26].

3. Models

In the following section, the developed transfer learning models are introduced and elaborated. The input dimension of the ML-models is set to three (amount of rolling experiments, number of timesteps, features). Since each experiment is representing one sequence, the models are limited for predictions for entire rolling time series. The focus of this work will be set on the transfer between two different mills with unequal data availability.

The models are created and trained on these datasets:

- Labelled dataset from thyssenkrupp rothe erde Germany GmbH, labels: roundness (classification) and outer diameter (regression), 1,300 experiments (TKRE)
- Labelled dataset generated by generative adversarial networks, labels: roundness (classification), 3,200 experiments (SD)
- Unlabelled dataset from thyssenkrupp rothe erde Germany GmbH, 2,400 experiments (TKRE-UL)
- Labelled dataset from an inhouse research plant of the Ruhr-University Bochum, labels: outer diameter (regression), 60 experiments (RUB).

3.1 Transferring between two different mills

To prove the applicability of the transfer from a larger database to a smaller database from a different mill, this approach is retraining a neural network model from the source space (TKRE) in the target space (RUB). This model is addressing a TSF approach. The transfer learning type is according to PAN AND YANG an inductive transfer learning approach with parameter transfer [12]. The source and target domains have the same features, but the marginal probability distribution is different since the mills are from a different type and the formed rings have different dimensions. Therefore, the domains are different but related. The source and target tasks are also different but related due to the different conditional probability distribution. The ML model is trained in the source space and reloaded for training in the target space. The initial weights of the network in the target space are taken from the source space and are retrained in the following training phases. Either all layers are retrained, or certain layers are locked and not trained.

The outer diameter (D_O), which is within the logged data, is regarded as the target in this approach. In usual cases, the outer diameter is measured continuously in conventional mills and is therefore itself not out of interest for ML predictions. Hence, this approach is addressed to prove the applicability of this method, based on this accessible target. The underlying prediction is a regression task, where the outer diameter (range: 0.3 - 1 m) is predicted for each timeseries using features from the logged data. In this first approach, just 50 % of the rolling process is considered, since this is the range where the source and target spaces are aligned concerning the rolling phases. The features are selected by their correlations in respect to the target and are *min max* scaled. Moreover, before the model training, the data is split in training, validation and test data. Within the source space, relevant processes are selected for model training according to the considered ring dimensions. The model architecture is an LSTM network to enable the mapping of the time dependency in the data. The evaluation of the performance of the model is done by the mean squared error metric. Eventually, the hyperparameters are optimised in respect to the best transfer characteristic, including the number of layers, nodes and dropout amount.

3.2 Transferring between an unlabelled and labelled dataset using an autoencoder

This model is using an autoencoder to achieve a system representation of the unlabelled TKRE-UL dataset and to use the encoder part as a pretrained model for the supervised learning within the TKRE dataset. The TKRE-UL dataset represents the source space and the TKRE dataset the target space. This transfer learning approach is according to PAN AND YANG the self-taught learning setting, which can be considered as a special case of inductive learning [12]. The autoencoder is first reducing the feature vector (encoder) and then reconstruct it back to the input (decoder) [27]. The model is therefore learning its own behaviour whilst reducing to the important feature information in the encoder part. The encoder weights are taken to retrain a model for a TSC for the determination of two roundness classes. The chosen autoencoder type is a sparse autoencoder. The network is realized, like in the first approach, with LSTM cells. Different hyperparameters are tested and evaluated, such as the minimum feature representation and the number of layers.

3.3 Transferring between a synthetic generated dataset and experimental data

The third approach consists of a synthetic data generation using generative adversarial networks (GANs) in the domain of RARR for TSC. It is investigated, if it is feasible to train a model within the synthetic data and to transfer its beneficials on experimental data. The target space is the TKRE dataset with a TSC problem and the source space is the synthetic dataset. In their work, FAHLE ET AL. used different GAN architectures for both, the univariate and multivariate time series, in the form of process data from RARR. Within the research work, unlabelled process data and also labelled data for the roundness were generated. [14] For this transfer learning approach, the labelled data is considered, and a ML model is trained on this dataset. The validation of the research results was built using the Train-Synthetic-Test-Real (TSTR) and Train-Real-Test-Synthetic (TRTS) metrics, thus a two-way view of the use of synthetic data [28].

3.4 Model Overview

The presented models are dealing with different available datasets and methodologies, so that different use cases are covered in this paper. An overview is given in Figure 2.

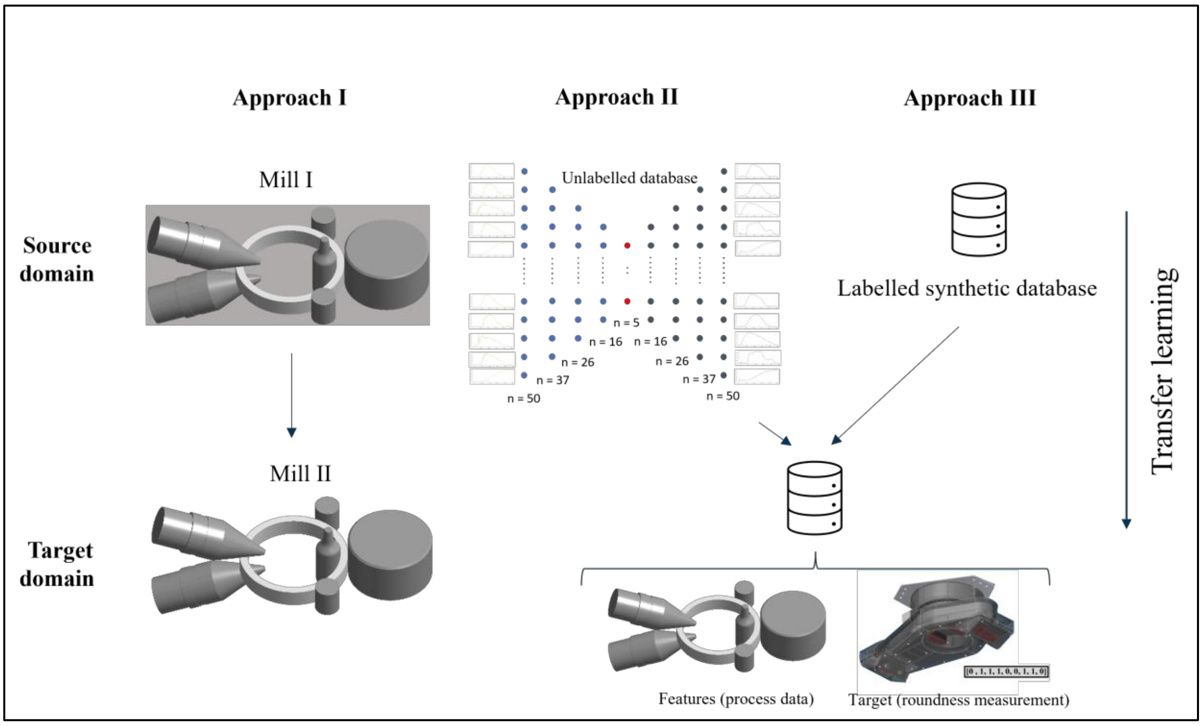


Figure 2: Transfer learning approaches for RARR

4. Experiments and results

This section is presenting the results of the three introduced models, with its focus in the approach of transferring between the two mills containing different sizes datasets. Moreover, the concept of the transfer between the cold ring rolling and RARR is elaborated.

4.1 Transferring between two different mills

The base model, trained in the source space (TKRE) to forecast the outer diameter, is tested with different layers and nodes in the LSTM-cell. The configurations and its mean squared errors (mse) are shown in Appendix 1. The lowest error is achieved by 3 layers and 7 nodes with a mse of $8.078*10^{-5}$ and is regarded as the baseline error. In comparison, the mse of the model trained on the smaller inhouse dataset (RUB) is greater and is equal to $1.349*10^{-4}$ (Appendix 2). The three baseline models with the lowest mse are used for transfer learning. In a first attempt, all layers are retrained, and then iterative layers are getting locked. The transfer learning results are shown in Appendix 3. The third baseline model (2 Layer and 7 nodes) with a retraining of all layers is leading to the best results, with a mse of $7.762*10^{-5}$. The achieved mse is in the magnitude of the source model and lower than the target model, trained within the RUB dataset. Therefore, it can be seen, that the transfer learning led to a significant improvement with a reduced mse by 42.5 %. As stated before, these models are covering the first 50 % of the rolling process. To extend the models for the entire process, a time scaling is needed to obtain an overlap of the rolling phases. For the entire rolling process, the mse in the target space is equal to $7.049*10^{-4}$ (3 layers and 7 nodes, Appendix 4). Hence, this difference is even greater compared to the difference for the first 50 %, the expected benefits of transfer learning are even greater.

Figure 3a shows the outer diameter over time out of the test dataset, with the predictions of the baseline model, the inhouse data model and the transfer learned model. Here, the transfer learned model is following the measured values best. In the validation data set, the results are showing as well better results (Figure 3b). These results are proving the transferability between two different RARR mills, with a significant improvement of prediction accuracies.

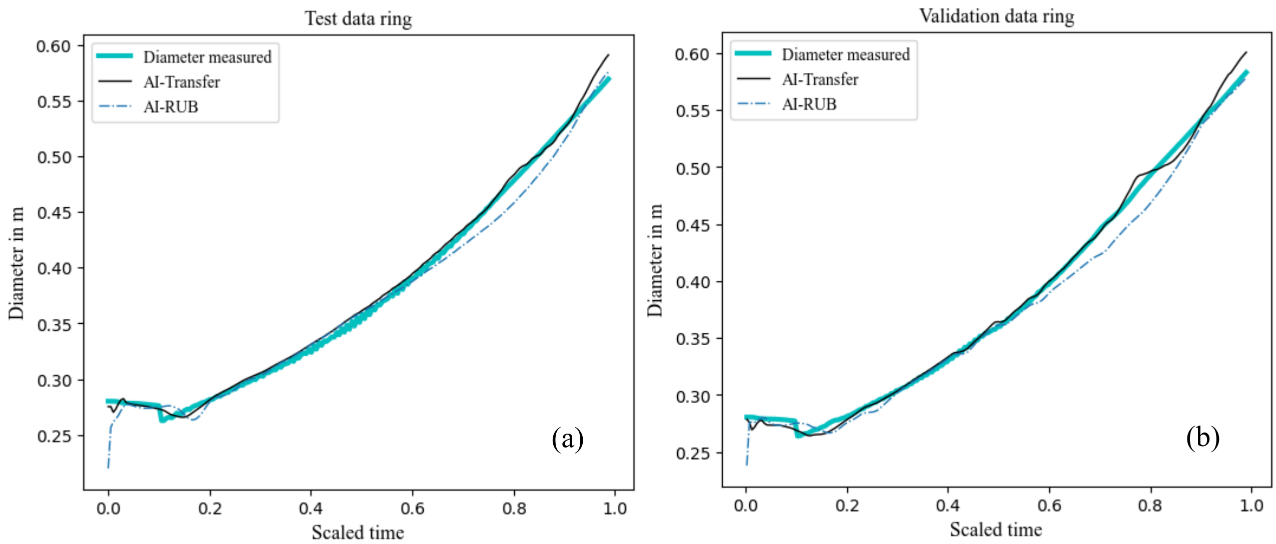
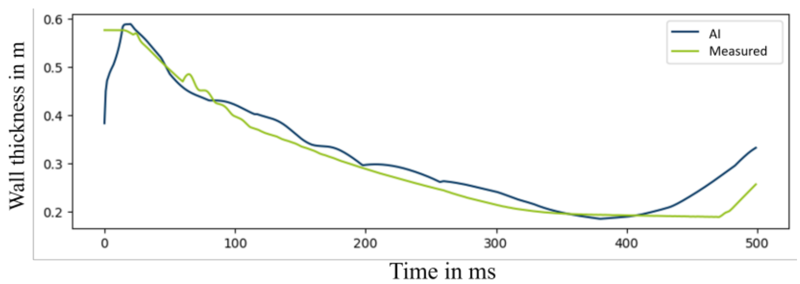


Figure 3: Excerpt of an instance rolling process of the test data (a) and the validation data (b) for the first 50 % of the process. The results of the two ML models are shown, as well the measured values (target)

4.2 Transferring between an unlabelled and labelled dataset using an autoencoder

Different hyperparameters for the sparse autoencoder are used to evaluate the performance regarding the feature representation. The final model with the best results is reducing the feature space from 50 features to 5 features within 5 layers. This configuration shows the best pest representation of the system after decoding it back to the input (Figure 4a).

(a)



(b)

Approach	Accuracy	Loss
Baseline	82,54 %	0.4335
Transfer learned	82,54 %	**0.4026**

Figure 4: Result of the autoencoder for the wall thickness (a) and TSC of the ring roundness (b)

Those layers were taken to conduct transfer learning to the TKRE-database, regarding the TSC of the roundness of the rings. To obtain this, a dense layer is added to the encoding part for a classification with this LSTM structure. The results are shown in Figure 4b. By comparing the results of the baseline approach (equal model without the pre training), the obtained accuracies are the same. Although, an improvement is seen by the loss (mse), which is 0.03 lower. This shows that the certainty of the forecast has improved with the transfer learned model, in comparison to the baseline approach.

4.3 Transferring between a synthetic generated dataset and experimental data

To validate if the synthetic data can be used for beneficial transfer knowledge, FAHLE ET AL. conducted a survey with nine process experts in radial-axial ring rolling. The results showed that several process experts were already unable to distinguish the synthetic from real process data. The evaluation of the results was based on the well-known inception score and the hype metric [29,30]. An instance of two rolling processes for the conducted evaluation is presented in Figure 5.

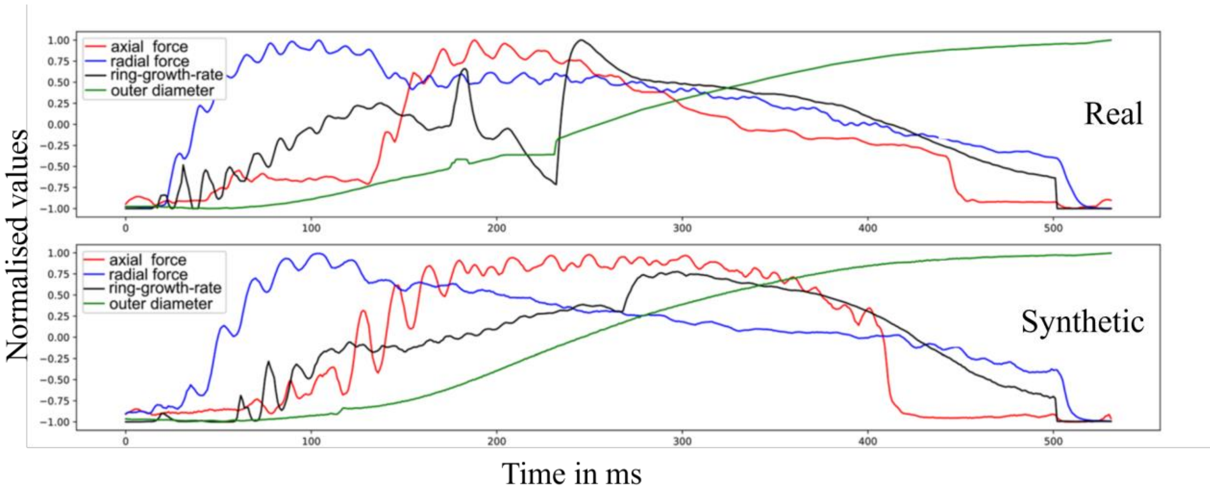


Figure 5: Instance rolling process for the evaluation of process experts [14]

Within the consideration of TRTS, especially promising results with a high accuracy of up to 97.4 percent could be achieved with the univariate use of the radial force. In addition, the basic usability of training a ML model was also demonstrated, with multivariate generated data and the TSTR metric. This is important for the productive usability, such as training exclusively on synthetic data and transfer learning it to real-world data since this data can be created in a few seconds with millions of copies. This model was able to achieve a significantly higher accuracy in the target space (TKRE dataset) than the random decision. [14] The exact improvement for the classification accuracy needs to be quantified in further investigations. In summary, the approach taken by FAHLE ET AL. to transfer synthetically produced data to real-world data is a promising approach and the basic feasibility of the approach has been demonstrated.

4.4 Concept of transfer Learning using cold ring rolling data

The DFG-project Nr. 499350001 (funded by the DFG-German Research Community) is currently expanding the given ideas of transfer learning further to a different process - the cold ring rolling. The cold ring rolling is a seamless ring forming technology at room temperature, containing only radial rolls and is forming smaller rings sizes than the RARR [5]. The shape of the ring is only constricted by its tool geometry and the radial feed. This process has two major advantages and is therefore considered: The dimensions of the shaped rings are smaller, and the process is carried out without pre heat treatment of the ring. This is reducing the consumed energy as well as the shaping- and preparation time. In a first step, the applicability of ML in cold ring rolling will be evaluated.

Due to the simplification of the regarded rolling process, it is possible to generate a database using an experimental setup, determined by a design of experiments (DoE) with the data amount needed for training ML algorithms. The scheduled scope is in the order of magnitude comparable to the utilised industry data in this paper. To meet the requirement of a balanced data set regarding its target values, the experimental database will be extended by synthetic data, mainly gathered by simulations. Those simulations are used for enriching the database, but also to address process controls reproducing errors, to homogenies the target classes. The synthetic data will be generated using these approaches: FEM, semi-analytical models and synthetic data generated by GANs shown in this paper. The FEM data will be generated using three approaches according to ALLWOOD ET AL.: models in pseudo-plane strain, partial ring models and full ring models [7]. Since FEM is time consuming (multiple hundred CPU hours), there is currently a semi-analytical model in development. The model is aiming to combine numerical algorithms and analytical approaches and is based on prior investigations of BROSIUS ET CWIEKALA, applying a semi-analytical model on the deep drawing process [31]. This complementary database, combining experimental and synthetic features, designed for ML-applications, is expected to perform more accurate compared to recent models in RARR. Therefore, it seems feasible to pre-train a ML model within this database and transfer it, similar shown to the transfer learning between the two RARR plants presented in this paper, to the radial-axial ring rolling data.

5. Conclusion and future work

In this work, three transfer learning approaches in the domain of radial-axial ring rolling were presented. It is addressing cases where no sufficient data amounts are available, or high accuracies are required. These approaches are transferring knowledge from these sources: a different mill, unlabelled data and from synthetic data generated by GANs to target spaces with less available data. The feasibility of the transfer from the synthetic data and the unlabelled data with an autoencoder is shown. The transfer using a pre-trained model through an autoencoder is not improving the accuracy but is reducing the loss and therefore the certainty of the prediction. The transfer from the synthetic data is showing promising results on univariate time series. Especially the transfer between two different machines, from the mill with the higher data amount to the minor one, showed significant improvements. The transfer learning lead here to a reduced mean squared error of 42.5 % compared to the model without transferring.

This work contributes approaches to implement transfer learning, if the accessible data amount is not sufficient, but related data from other machines or unlabelled data is available. Moreover, it shows the possibility of generating data by GANs, if no other data is available. These approaches can be considered in further scientific investigations, but also in industrial applications.

In further investigations, the proposed model for transferring between to different mills should be extended for the entire ring rolling process by aligning the rolling phases and can be applied to relevant process errors, such as ring climbing. Furthermore, it can be applied for time series classifications, like the ring roundness. Regarding the autoencoder and synthetic data approach with the generative adversarial networks, greater databases can be considered to improve given accuracies further. The present progress achieved by using transfer learning concepts, motivates even more extensive approaches, such as transferring from the less complex cold ring rolling to RARR. This question is currently considered in ongoing research (DFG Nr. 499350001).

Acknowledgements

The research results described here were largely developed in the DFG-project Nr. 499350001 (funded by the DFG-German Research Foundation). The authors would like to additionally thank Prof. Dr.-Ing. Alexander Brosius, as well as thyssenkrupp rothe erde Germany GmbH for their support.

Appendix

Appendix 1: Mean squared errors for given hyperparameter configurations for the prediction of the outer diameter within the TKRE dataset. The chosen baseline models with the lowest mse are highlighted

Layers	3 nodes	5 nodes	7 nodes
1	$1.788*10^{-4}$	$1.512*10^{-4}$	$1.184*10^{-4}$
2	$1.665*10^{-4}$	$1.457*10^{-4}$	**$1.074*10^{-4}$**
3	$1.408*10^{-4}$	**$1.065*10^{-4}$**	**$8.078*10^{-5}$**

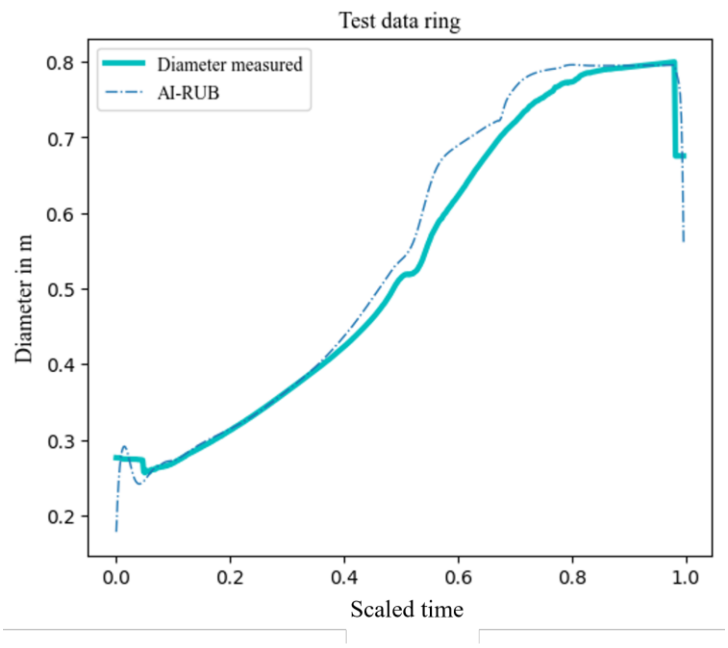
Appendix 2: Mean squared errors for given hyperparameter configurations for the prediction of the outer diameter within the RUB data set

Layers	3 nodes	5 nodes	7 nodes
1	$2.264*10^{-4}$	**$1.349*10^{-4}$**	$1.373*10^{-4}$
2	$3.647*10^{-4}$	$2.058*10^{-4}$	$1.362*10^{-4}$
3	$3.009*10^{-4}$	$1.617*10^{-4}$	$1.571*10^{-4}$

Appendix 3: Mean squared errors for transfer learned models. The retrain layer indicates the layer from which layer on weights are getting retrained

Retrain layer	2 layer 7 Nodes	2 layer 5 Nodes	3 layer 7 nodes
0	**$7.762*10^{-5}$**	$9.483*10^{-5}$	$7.871*10^{-5}$
1	$1.088*10^{-4}$	$2.006*10^{-4}$	$8.361*10^{-5}$
2	$8.087*10^{-4}$	$6.869*10^{-4}$	$1.437*10^{-4}$

Appendix 4: Excerpt of an instance rolling process of the test data for the entire ring rolling process



References

[1] Cullen, J., Allwood, J., Bambach, M., 2012. Mapping the global flow of steel: from steelmaking to end-use goods. Environmental science & technology 46 (24), pp. 13048–13055.

[2] Guo, L., Yang, H., 2011. Towards a steady forming condition for radial–axial ring rolling. In: International Journal of Mechanical Sciences 53 (4), pp. 286-299.

[3] Fahle, S., Glaser, T., Kuhlenkötter, B., 2021. Investigation of Machine Learning Models for a Time Series Classification Task in Radial–Axial Ring Rolling. in: Daehn, G., Cao, J., Kinsey, B., Tekkaya, E., Vivek, A., Yoshida, Y. (eds), Forming the Future. The Minerals, Metals & Materials Series 13, pp. 589–600.

[4] Fahle, S., Kuhlenkötter, B., 2020. A Framework for Data Integration and Analysis in Radial-Axial Ring Rolling. In: Nyhuis, P; Herberger, D; Hübner, M. (Eds.): Proceedings of the Conference on Production Systems and Logistics : CPSL 2020, pp. 127-136.

[5] Hua, L., Deng, J., Qian, D., 2015. Precision ring rolling technique and application in high-performance bearing manufacturing. In: 4th International Conference on New Forming Technology (ICNFT 2015), MATEC Web of Conferences 21.

[6] Allwood, J., Tekkaya, A., Stanistreet, T., 2005. The Development of Ring Rolling Technology. Steel research international 76 (2/3), pp. 111-120.

[7] Allwood, J., Tekkaya, A., Stanistreet, T., 2005. The Development of Ring Rolling Technology - Part 2: Investigation of Process Behaviour and Production Equipment. Steel research international 76 (7), pp. 491 - 507.

[8] Fawaz, H., Forestier, G., Weber, J., Idoumghar, L., Muller, P., 2019. Deep learning for time series classification: a review. In: Data Min Knowl Disc 33, pp. 917-963.

[9] Yan, W., 2012. Toward Automatic Time-Series Forecasting Using Neural Networks. In: IEEE TRANSACTIONS ON NEURAL NETWORKS AND LEARNING SYSTEMS 23 (7), pp. 1028-1039.

[10] Ordóñez, F., Roggen, D., 2016. Deep convolutional and LSTM recurrent neural networks for multimodal wearable activity recognition. Sensors 16 (1).

[11] Weiss, K., Khoshgoftaar, T., Wang, D., 2016. A survey of transfer learning. In: J Big Data 9 (3).

[12] Pan, S.J., Yang, Q., 2010. A Survey on Transfer Learning. In: IEEE Transactions on Knowledge and Data Engineering 22 (10), pp. 1345-1359.

[13] Fahle, S., Glaser, T., Kuhlenkötter, B. Investigation Of Suitable Methods For An Early Classification On Time Series In Radial-Axial Ring Rolling. In: Herberger, D; Hübner, M. (Eds.): Proceedings of the Conference on Production Systems and Logistics : CPSL 2021, pp. 97-107.

[14] Fahle, S., Glaser, T., Kneißler, A., Kuhlenkötter, B., 2022. Improving quality prediction in radial-axial ring rolling using a semi-supervised approach and generative adversarial networks for synthetic data generation. In: Prod. Eng. Res. Devel. 16, pp. 175–185.

[15] Fahle, S., Kneißler, A., Glaser, T., Kuhlenkötter, B., 2021. Research on Preprocessing Methods for Time Series Classification Using Machine Learning Models in the Domain of Radial-Axial Ring Rolling. In: Behrens, BA., Brosius, A., Hintze, W., Ihlenfeldt, S., Wulfsberg, J.P. (eds) Production at the leading edge of technology. WGP 2020. Lecture Notes in Production Engineering, pp. 487-496.

[16] Mirandola, I., Berti, G., Caracciolo, R., Lee, S., Kim, N., Quagliato, L., 2021. Machine Learning-Based Models for the Estimation of the Energy Consumption in Metal Forming Processes. In: Metals 2021 11 (5).

[17] Mirandola, I., Berti, G., Caracciolo, R., Lee, S., Kim, N., Quagliato, L., 2021. Multivariable regression and gradient boosting algorithms for energy prediction in the radial-axial ring rolling (rarr) process. In: ESAFORM 2021. 10.25518/esaform21.3775.

[18] Lee, S., Park, J., Kim, N., Lee, T., Quagliato, L., 2023. Extreme gradient boosting-inspired process optimization algorithm for manufacturing engineering applications. In: Materials & Design 226 (111625).

[19] Lagao, P., 2004. Einsatzpotenziale des Data Mining bei der Klassifikation komplexer Fertigungprozesse am Beispiel des Radial-Axial Ringwalzens. Zugl.: Bochum, Univ., Diss., 2004.

[20] Giorleo, L., Ceretti, L., Giardini, C., 2012. Investigation of the Fishtail Defect in Ring Rolling by a FEM Approach. In: Transactions of the North American Manufacturing Research Institution of SME 40, pp. 104-111.

[21] Zhu, Y., Chen, Y., Lu, Z., Pan, S., Xue, G.-R., Yu, Y., & Yang, Q., 2011. Heterogeneous Transfer Learning for Image Classification. In: Proceedings of the AAAI Conference on Artificial Intelligence 25 (1), pp. 1304-1309.

[22] Maral, B.C., Tan, M. Transfer Learning for Predicting Gene Regulatory Effects of Chemicals. In: Maglogiannis, I., Iliadis, L., Macintyre, J., Cortez, P. (eds) Artificial Intelligence Applications and Innovations. AIAI 2022. IFIP Advances in Information and Communication Technology 647, pp. 414-425.

[23] Bouguettaya, A., Mentouri, Z., Zarzour, H., 2023. Deep ensemble transfer learning-based approach for classifying hot-rolled steel strips surface defects. Int J Adv Manuf Technol 125 (11-12), pp. 5313–5322.

[24] Cohn, R., Holm, E., 2021. Unsupervised Machine Learning Via Transfer Learning and k-Means Clustering to Classify Materials Image Data. Integr Mater Manuf Innov 10 (2), pp. 231–244.

[25] Meng, L., Ding, J., Dong, Z., Li, X., Zhang, D., 2023. Crown Prediction of Hot-Rolled Silicon Steel Using Transfer Learning Network Fused with Whale Optimization Algorithm. steel research int., pp. 1-14.

[26] Peng, R., Zhang, X., Shi, P., 2023. Multi-Representation Domain Adaptation Network with Duplex Adversarial Learning for Hot-Rolling Mill Fault Diagnosis. Entropy 25 (1).

[27] Bengio, Y., Courville, A., Vincent, P., 2013. Representation Learning: A Review and New Perspectives. In: IEEE TRANSACTIONS ON PATTERN ANALYSIS AND MACHINE INTELLIGENCE 35 (8), pp. 1798-1828.

[28] Esteban, C., Hyland, S., Rätsch, G., 2017. Real-valued (Medical) Time Series Generation with Recurrent Conditional GANs, 13 pp.

[29] Salimans, T., Goodfellow, I., Zaremba, W., Cheung, V., Radford, A., Chen, X., 2016. Improved Techniques for Training GANs. https://arxiv.org/pdf/1606.03498.

[30] Zhou, S., Gordon, M., Krishna, R., Narcomey, A., Fei-Fei, L., Bernstein, M., 2019. HYPE: A Benchmark for Human eYe Perceptual Evaluation of Generative Models. https://arxiv.org/pdf/1904.01121.

[31] Brosius, A., Cwiekala, T., 2015. Fast Semi-analytical Approach for Deep Drawing Processes. In: Tekkaya, A. E; Homberg, W; Brosius, A. (eds): 60 Excellent Inventions in Metal.

Biography

Johannes Seitz (*1996) is a research associate at the chair of production systems at the Ruhr-University Bochum. He studied mechanical engineering at the Ruhr-University Bochum (B. Sc.) and the University Duisburg-Essen (M. Sc.). In his research he is using methods of machine learning and data mining for processes in the domain of forming technologies.

Tobias Moser (*1994) is a research associate at the chair of production system at the Ruhr-University of Bochum since 2021. He earned a bachelor's and master's degree in mechanical engineering at the Ruhr-Universität Bochum. His primary research topics are machine learning, time series and radial-axial ring rolling.

Simon Fahle (*1994) has been a member of the Chair of Production Systems (LPS) at Ruhr University Bochum. He completed a bachelor's and master's degree in mechanical engineering at Ruhr-University Bochum and received his doctorate in 2022. Currently, he is employed at the Westnetz GmbH.

Christopher Prinz (*1985) studied mechanical engineering at the Ruhr-University Bochum. After receiving his doctorate in 2018 on the topic of knowledge management in production, he was named Academic Councilor at the Chair of Production Systems (LPS). As part of the chair management, he is responsible for the strategic development of the chair and the initiation and controlling of research projects.

Bernd Kuhlenkötter (*1971) was responsible for product management and technology at ABB Robotics Germany until 2009. In 2009, Bernd Kuhlenkötter took over the professorship for "Industrial Robotics and Production Automation" at the Technical University of Dortmund. Univ. Prof. Dr.-Ing. Bernd Kuhlenkötter has held the professorship for "Production Systems" at the Ruhr University Bochum since 2015.

CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
CPSL 2023-2

5th Conference on Production Systems and Logistics

Towards A Holistic Cost Estimate Of Factory Planning Projects

Leonard Rieke[1], Luca Philipp[1], Peter Nyhuis[1]
[1]Institute of Production Systems and Logistics / Leibniz University Hannover / Germany

Abstract

As an interdisciplinary and complex task, factory planning lays the foundation for the economic efficiency of factories. Factory planning projects significantly influence the financial situation of production companies due to their high capital requirements and long lifetime. Today's inaccurate basis for decision-making in cost estimation leads to serious financial challenges in the future. Costs must be estimated with sufficient reliability to avoid misinvestments. There is currently a need for research for a holistic and systematic approach. This is partly due to the many requirements such an approach must meet. In this context, the paper aims to determine the requirements for a holistic approach to cost estimation in the early phase of factory planning projects. Based on a literature review, four key requirements for a holistic cost estimate could be identified and prepared for an approach. This includes the joint consideration of the interactions between spatial and process requirements. In addition, the early planning phase is challenging, in which little reliable information is available, but costs can still be sufficiently influenced. Furthermore, the operating costs during factory operation must be considered over and above the specific investment. With the help of various factors influencing factory design, scenarios should be generated and compared early to counter future opportunities and risks in the best possible way. These requirements can now be used for an approach to be developed that enables holistic cost estimates in the early phase of factory planning projects.

Keywords

Factory planning; Cost estimate; Early planning phase; Life cycle costs; Capital expenditures; Operating costs; Scenario design; Total Cost of Ownership

1. Introduction

Factory planning is crucial for the subsequent economic success of companies [1]. This is mainly because decisions within factory planning are often of strategic and long-term consequence [1,2]. Due to the highly dynamic business environment, ever shorter product life cycles and increasing customer requirements, the challenges for manufacturing companies are constantly increasing [3]. This also increases the challenges for factory planning. The realisation of factory planning projects, especially large-scale development and expansion planning projects, significantly impacts companies' liquidity due to the high capital requirements [1,4]. On the one hand, this is due to the considerable investments in production and process technology (process view) as well as in construction and building equipment (spatial view) [5]. On the other hand, operating costs, such as personnel and energy costs, influence the total costs and profitability of factories and their elements [2,6,7]. Due to the long life cycle of factories [8], the highest costs occur in terms of operating costs in the factory operation phase, despite high initial investments [9–11]. However, often only investments are used as a basis for decisions regarding project realisation, which can lead to erroneous cost estimates and misinvestments [12,13]. In this context, incorrect cost estimates and the associated wrong decisions can lead small and medium-sized enterprises (SMEs), in particular, into serious financial difficulties. This is also because SMEs lack the resources and necessary know-how, especially for investment controlling [14]. In Germany alone, with over 3000 building permits for factory and workshop buildings

DOI: https://doi.org/10.15488/15249
ISSN: 2701-6277

[15], approximately 130 billion euros were invested in new buildings and equipment in terms of machinery and devices in 2021 [16]. However, statistical evaluations show that cost targets are missed in factory planning projects in more than 70% of the cases [17]. For large infrastructure projects, studies indicate that even an average cost overrun of 37% can be expected [18]. At this point, it is essential to note that these studies are limited only to investments, usually from the construction point of view. The operating phase, which leads to a much higher share of costs due to operating costs, has not yet been considered here. Overall, incorrect decision-making principles in cost planning for the construction and operation of factories today lead to serious financial challenges in the future.

The points mentioned underline the relevance of an early, holistic cost estimate for planning projects. Therefore, this paper aims to review the current state of the art in this context, derive current research needs, and review relevant topics for and requirements of cost estimation to prepare for a holistic approach.

2. State of the art and need for research

Several sources underline the problem of finding an appropriate and practically applicable solution for cost estimates [19–22]. In practice, estimates are often based only on expert opinions and are therefore subjective and not reproducible [23,24]. The following, therefore, identifies the requirements necessary for a holistic and reproducible cost estimate. First of all, the relationship between process and building planning is often neglected [2]. This must be avoided since the central building requirements must be derived from the technical process [2,25]. As an interdisciplinary and complex task, factory planning and the associated cost estimation must consider the planning of production and logistics processes (process view) and other disciplines, such as building equipment and architectural planning (spatial view) (requirement 1). Furthermore, the foundation for a factory planning project's economic efficiency and functionality is already laid in the early planning phase [1,4]. The most significant share of the investment is determined at an early planning stage, so the most significant influence on costs can still be exerted there [8]. This approach comes, among other things, from product planning, where a large part of the costs is already determined at the beginning of product development [26]. This knowledge must also be transferred to cost estimation in factory planning (requirement 2). In previous work, the existing literature and approaches regarding cost estimation from an investment perspective (CAPEX) in the early planning phase have been discussed in detail [27,28]. However, life cycle costs comprise investments and operating costs [29]. Therefore, in addition to the investment view, operating costs (OPEX) must also be considered for a holistic cost estimation [6,28] (requirement 3). Each factory is unique and requires case-specific solutions [2,30]. Cost estimates are always subject to uncertainties [31]. The so-called scenario concept allows for opening up a space of possible futures and thinking through possible decisions' effects [32]. Transferring scenario management as an established strategy planning method to factory planning has proven very useful [33]. To obtain a valid basis for decision-making with a longer-term view of opportunities and risks within a cost estimate, it is therefore appropriate to compare different planning scenarios regarding content and related costs (requirement 4). In addition to the four derived requirements, a holistic cost estimate must meet general basic requirements. These include, among others, a high level of standardisation concerning existing approaches and a high degree of application focus for practical use.

Conducting a literature review provides the foundation for research work [34]. A systematic search procedure was conducted to identify relevant sources and existing approaches to holistic cost estimation. The search process focused on works that can be assigned to the context of the keywords factory planning, cost estimation, life cycle costs, total cost of ownership and early planning phase, and their links. Figure 1 shows the results of an intensive literature review of existing approaches and their analysis concerning the derived requirements (R1-R4). The basic literature [1,2,4,8,35] focuses predominantly on planning procedures and does not include holistic approaches to the associated cost estimation. According to WIENDAHL [2], the approaches analysed are subdivided according to the levels of detail in the factory. These can be assigned to the factory fields of technology, organisation and space and subdivided into the hierarchy levels of factory, section and workstation. The factory can only be considered and evaluated holistically if all levels up to the level factory are considered [2].

R4: *Consideration of different scenarios*
R3: *Consideration of CAPEX and OPEX*
R2: *Application in the early phase of planning*
R1: *Consideration of process and building*

	Source	building	process	early phase	CAPEX	OPEX	scenario design
factory	Brieke (2009)	◑	◑	○	●	◑	○
	Cevirgen et al. (2021)	●	○	●	●	○	◑
	Götze et al. (2013)	○	●	○	◑	◑	◑
	Heinemann et al. (2013)	◑	●	◑	◑	◑	○
	Hingst et al. (2023)	◑	●	○	◑	●	○
	Kovacic et al. (2016)	●	○	◑	●	●	◑
	Möller (2008)	◑	●	○	◑	◑	◑
	Nielsen et al. (2016)	◑	●	○	◑	◑	○
	Rieke et al. (2023)	●	◑	●	●	○	◑
section	Aurich et al. (2009)	○	●	○	●	●	○
	Dreier, Wehking (2016)	○	●	○	◑	●	○
	Heinemann et al. (2014)	◑	●	◑	●	●	◑
	Pohl (2014)	◑	●	○	●	◑	◑
station	Dehli (2020)	○	●	○	●	●	○
	Denkena et al. (2010)	○	●	○	●	●	◑
	Herrmann et al. (2011)	○	●	○	●	●	○
	Kampker et al. (2013)	○	●	◑	●	●	◑
	Lindner, Götze (2011)	○	●	○	●	●	○
	Mattes et al. (2012)	○	●	○	●	●	○
	Osten-Sacken (1999)	○	●	○	●	●	○

legend: ● focus ◑ partly covered ○ not covered

Figure 1: Analysis of existing approaches concerning the derived requirements [9,27,28,36–51]

Research and analysis of the literature show that single requirements are partially fulfilled, whereby approaches to the cost consideration exist due to the comparably simple object of consideration, in particular on the level of the workstation. At the factory level, approaches only take into account partial areas and do not consider interrelationships, such as between the spatial and process view or the investments and operating costs. Furthermore, only a few approaches consider different scenarios to generate planning alternatives and compare them with each other. Beyond the approaches considered, there are standards and guidelines [29,52–54] that only contemplate sub-areas from the building and factory planning and the cost view separately. The different approaches often concentrate only on small focus areas without considering holistic relationships and interactions. In summary, it can be said that with current approaches, methods and tools, a holistic cost estimation based on the derived requirements is not or only insufficiently possible. Own preliminary work in cost estimation, feasibility studies, life cycle considerations [27,28,36,37], and numerous consulting projects in companies underline the mentioned need for research.

The introduction of the problem definition, the consideration of existing approaches, and their discussion underline the research need for a holistic approach to the cost estimate of factory planning projects. In the following, the derived requirements and main focuses will be analysed, detailed and prepared as a basis for a holistic approach.

3. Requirements for a holistic approach to cost estimation

According to WIENDAHL [2], the principle of completeness before accuracy applies to cost estimation. A holistic cost estimate is required in the early phase to achieve this completeness. Figure 2 summarises the requirements for a holistic approach to cost estimation derived from past planning projects and the literature (Compare derivation of requirements and literature review in Chapter 2). *Capital expenditures* and *operating costs* must be considered jointly. These are determined in the factory primarily by the planning and designing of the *spatial and process view* and combined form the *life cycle costs*. Since one of the purposes of cost estimates is to minimise risk for companies, an estimate must be feasible at an *early planning stage*. The uncertainties associated with an early planning phase must be reduced as far as possible using a systematic procedure. In this context, every factory is unique [6]. Nevertheless, it is possible to identify general *factors that fundamentally influence* factory design and configurations. The specification of the influencing factors directly impacts the costs and leads to different *factory scenarios* depending on the configuration.

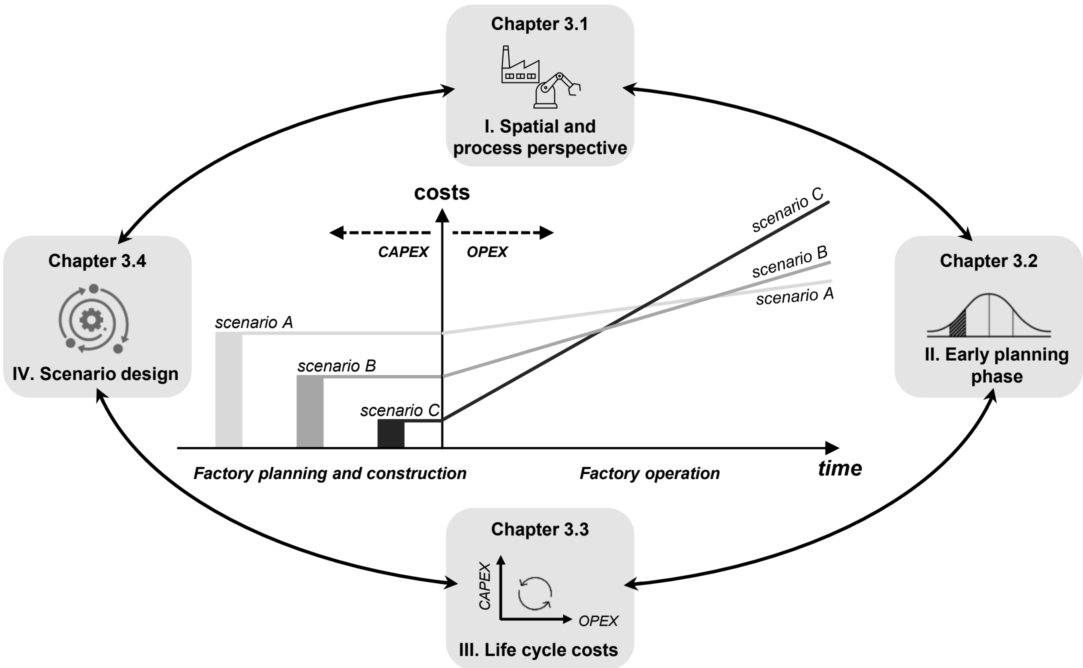


Figure 2: Overview of requirements for a holistic approach to cost estimation, own figure

Different scenarios during the planning and construction of investments lead to different specifications in the operating costs over the life cycle (example shown in Figure 2). In the following, the individual requirements will be scientifically specified and analysed to make them applicable to a holistic approach to cost estimation.

3.1 Synergetic cost estimate from spatial and process view

In order to systematise the interdisciplinary and complex planning tasks in the factory planning process, the planning procedure has been described by various authors [1,2,4,8] and summarised in the renowned guideline VDI 5200 [55]. Traditionally, in factory planning, the sequential planning phases are run through in a linear sequence, and the level of detail increases successively with advancing phases [2,55]. The interdisciplinary approach of synergetic factory planning has significantly contributed to VDI 5200 (Figure 3) [2]. This approach addresses the interdisciplinary character of factory planning. It combines the spatial view, i.e. the interior and exterior design of factories from the perspective of architectural and construction planning [56], with the process view, i.e. the design of the technological and logistical processes and the operating resources [2]. To develop a sustainable and successful factory concept, the requirements and the interactions from the process and spatial perspectives must be considered synergetically [2].

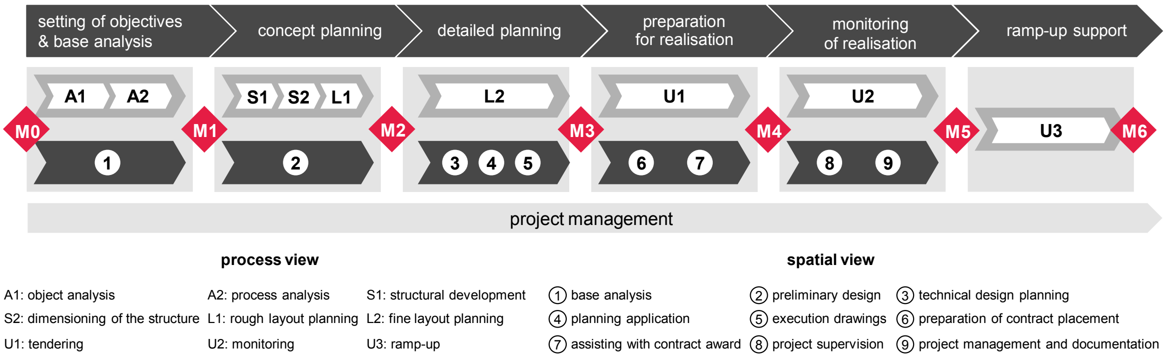


Figure 3: A process model of synergetic planning from a spatial and process perspective, adapted from [2]

Only by synchronising the building with the process is it possible to respond adequately to the rapid changes in the product and the technical equipment [57]. Future challenges require an even stronger focus on the interdisciplinary character of factory planning [58]. To reduce planning time and errors, process-side requirements (including equipment weights, equipment foundations, vibration sensitive areas) can be coordinated with the spatial specifications in a cooperative, efficient and early coordination process [2]. Increasing requirements from the process point of view also leads to increased costs in the building and the technical building equipment (e.g. through higher m² or m³ prices). Depending on the requirements, areas can be categorised, for example, into low, medium and high requirements with specific parameters. Depending on the category, different area parameters and building types lead to different cost characteristics based on comparative values (e.g. with the help of BKI [59]). Experience from past planning projects shows that inadequately combined consideration of costs leads to increased follow-up costs (e.g. reinforcements of the base plate, retrofits in the supporting structure and technical building equipment). For this reason, the synergy from a spatial and process view, e.g. following the process model of synergetic factory planning, must be considered in a holistic approach to cost estimation.

3.2 Consideration of the early planning phase

The foundations for the functionality and profitability of any factory planning project are set in the early phase [1,4]. Most investments are determined at an early planning stage, which is why the most significant influence on future project costs can also be exerted there [8]. The factory planner is faced with significant challenges in this process. On the one hand, the project scope and the associated costs are determined in the early phase [1,4]. On the other hand, the early phase is characterised by uncertainty, so information and data are often unreliable [23]. Costs are determined in an early planning stage but only occur in subsequent planning phases in which they can no longer be sufficiently influenced [60–62]. Figure 4 shows this dilemma and the determination of the early phase for the holistic approach to be developed.

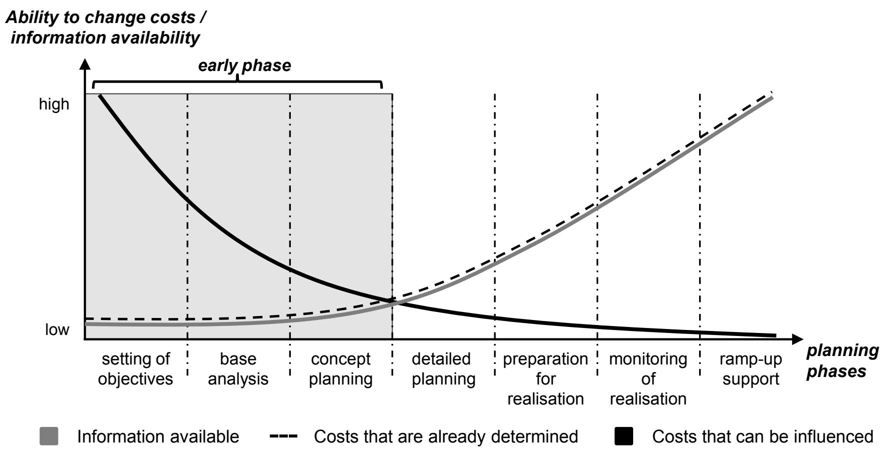


Figure 4: Cost occurrence and cost influence in the early planning phase, own figure adapted from [60–62]

As shown in Figure 4, in this paper, the early planning phase of factory planning is defined up to and including concept planning, in which the cost influence is still high. As the planning period and level of detail advance, the cost influence decreases, and costs can only be influenced and determined within the framework of the concept that has already been developed [2,55]. In practice, another aspect becomes relevant. Frequently, projects cannot even be released and started without a cost or budget estimate. The reasons presented, already underlined by own preliminary work [28,63], emphasise the necessity of a decision-making tool in the early planning phase.

3.3 Consideration of the life cycle costs of factories

In the basic literature, the stages of the factory planning process are seen as an investment process [1]. Capital expenditure is generally understood as the use of capital and, thus, the long-term commitment of financial resources to assets [64–66]. In addition to the often exclusive consideration of investments as decision support, so-called operating costs are incurred in the factory during the operating phase, often exceeding the investments after only a few years [2,67,68]. Due to the time component, investments and operating costs have a different impact on companies' value generation and cash flow. Thus, input data of the investment calculation are often associated with uncertainties and risks that must be included in the calculation [64,69]. In the case of real estate, capital expenditure accounts for only 20% of the life cycle costs, while operating costs account for 80% [70,71]. Even for machine tools, operating costs can cause 80% of the life cycle costs [13]. The remedy for decision support is the consideration of the life cycle of objects and their associated costs. The life cycle describes generally typical patterns of a system over time [12]. Life cycle costing (LCC) methods holistically consider life cycle costs over the life of objects and thus support the purchase of capital-intensive and capital goods with long lifetimes [72,73]. Despite different terms for life cycle costs, all definitions share that costs are summed up over the life cycle to show the trade-off between initial and follow-up costs [74]. The long lifetime and high investments underline the necessity of a life cycle consideration of factories [37,75]. The life cycle of the factory and its elements can be divided into higher-level phases of factory planning and construction, factory operation and factory reconfiguration and end of life [76]. The factory life cycle can be divided into different life cycles, such as the product, component or process life cycle [2,77]. The life cycle of a factory usually extends over 30 to 50 years, whereby the individual elements of the factory, such as machines, have a shorter life cycle [8,78]. Figure 5 shows the exemplary life cycle and the associated costs of the factory and its elements.

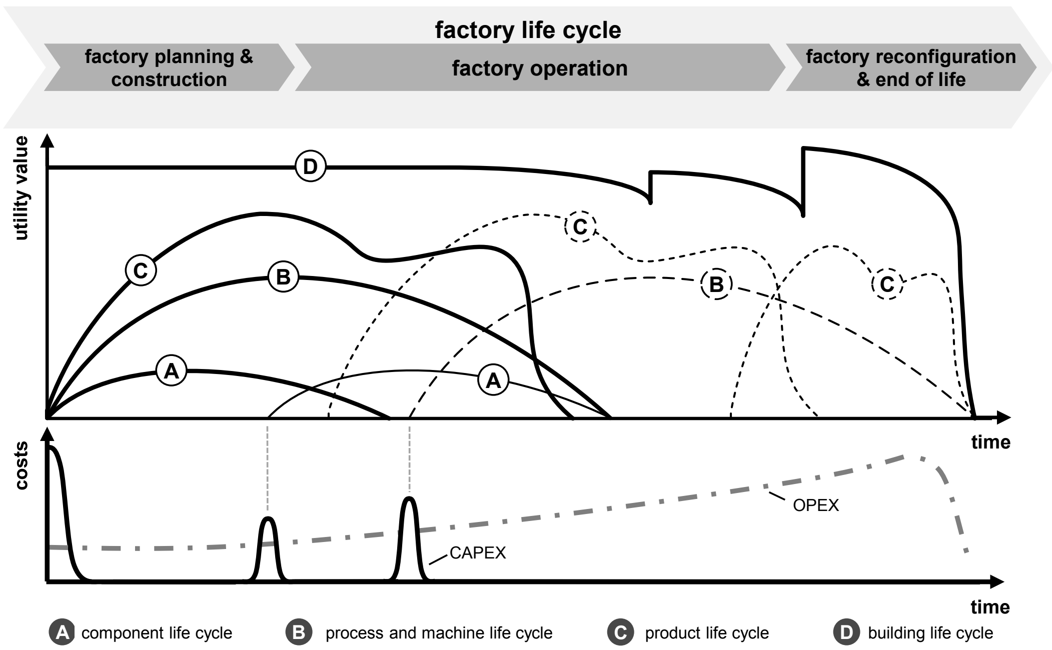


Figure 5: Exemplary life cycle and costs of factories and their elements, own figure adapted from [36,76,79]

The figure also outlines the costs underlying the life cycle as an example. These are represented by the two exemplary CAPEX peaks in Figure 5. After high initial investments, further follow-up investments become necessary depending on the lifetime of the components and machines. The investments are displayed simplified and independently of possible payment flows as fixed-step costs. The operating costs rise constantly in this case due to, for example, increasing energy, personnel or maintenance costs. Figure 5 underlines the relevance of the operating costs in the production life cycle costs due to the long lifetime. This also highlights the fact that the factory planning phase has a critical influence on life cycle costs [1,4]. Factory operation, with a duration of several decades, is the longest and, thus, the most crucial phase in the life cycle of factories [9,10]. This emphasises the trade-off between CAPEX and OPEX, which must be considered holistically in spatial and process view interaction. The objective of companies is to enable the production of a maximum outcome with the lowest possible operating costs [80]. However, the determining factors for this are already set in the planning stage, which is why an early lifecycle-oriented cost estimate is essential.

3.4 Consideration of influencing factors for scenario design

Each factory planning project is unique due to the different processes and products [2,35]. In addition to established procedural steps for factory planning, it is possible to identify generally applicable influencing factors on factory design. In this context, design or structure-relevant influencing factors are those factors that have a structural impact on the subsequent factory design and layout. Influencing factors can be divided into external and internal influences [2,80]. External influencing factors, such as increases in the price of materials or energy [81], can only be considered to a limited extent, so although they influence costs, they can only be insufficiently influenced by factory planning. Internal influencing factors are factors that directly impact the factory design. For example, these influencing factors can be derived from different factory types in the literature [35]. Examples are the degree of automation, product specifications (size, weight) or the number of variants [8,35]. At this point, the fuzzy logic method is an option for modelling the uncertainty [82], which is present due to the early planning phase. The subsequent impact of these influencing factors is often already determined in the early planning phase. It has a direct influence on the design of the factory and its life cycle costs. With the methodical aid of the factory objects as elements of the factory [83], Figure 6 shows a simplified relationship using the example of the influencing factor of the degree of automation and the factory object of means of transportation.

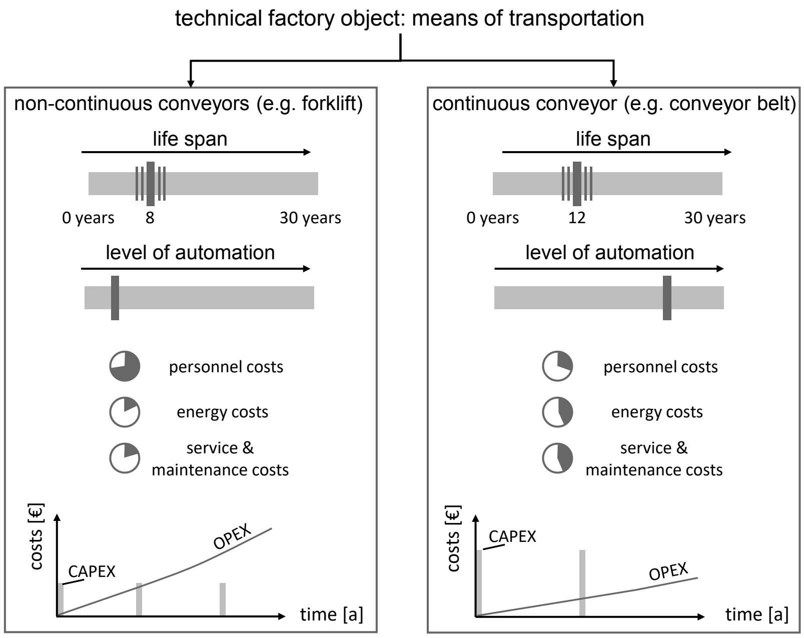


Figure 6: Exemplary configuration of the factory object means of transportation by the influencing factor degree of automation, own figure

Depending on product-side and process-side requirements, a decision can be made in a factory area in favour of a high degree of automation of the means of transportation, i.e. tending towards continuous conveyors, or a lower degree of automation, i.e. tending towards non-continuous conveyors. Although the superior group of continuous conveyors exhibits a higher potential for automation [84], it also requires considerably higher investments. The group of non-continuous conveyors [84] is characterised by a lower degree of automation and, thus, comparatively lower initial investment but higher operating costs. This is because the investment is generally higher for automated than manual systems [85]. The lifetime of the factory elements also influences the cost structure since, based on the lifetime, a supplementary or replacement investment becomes necessary in specific cycles over the life cycle. Overall, the degree of automation and the associated personnel requirements (in addition to, among other things, energy costs and maintenance costs) define a large part of the expected operating costs [86]. In the example shown in Figure 6, a simplified life cycle assessment concludes that a decision favouring a non-continuous conveyor is associated with lower initial investment but higher operating costs. A decision favouring a continuous conveyor based on life cycle costs depends on other factors, such as the product or the number of units. In general, the decision in favour of a particular configuration of a factory object also depends on the process requirements (see 3.1). For example, it may be the case that only certain factory sections, such as logistics, can be automated due to the complex process. Products with high complexity and low quantities could lead to only manual assembly over the life cycle being economical.

The consideration of different influencing factors enables different, future-oriented scenarios of factory design and the associated cost estimation over the life cycle as a basis for decision-making. The example above underlines the importance of considering influencing factors that configure the factory on a scenario basis via the factory elements and lead to different cost trends over the life cycle.

4. Conclusion and outlook

Factory planning projects are strategically important and capital-intensive projects with a long lifetime. Due to such projects' long-term and interdisciplinary character, the project cost estimate is essential. Incorrect cost estimates can lead to severe misinvestments. With current methods and tools, a holistic cost estimate is not or only insufficiently possible. Based on an intensive literature review, this paper identifies the research needs and requirements for a holistic approach to cost estimates for factory planning projects. Four essential requirements are identified and further analysed for a holistic approach. First, an approach must consider synergetic planning and costs from both a spatial and process view due to the interdependence of the two planning disciplines. Furthermore, the approach must be applicable in the early planning phase since costs can still be sufficiently influenced in this stage. In addition, in the context of a life cycle consideration, investments and operating costs must be estimated simultaneously due to their interactions. Finally, design-related influencing factors must be considered, which are essential in determining the factory design and, thus, the associated costs for scenario design. The methodically elaborated and detailed requirements are the basis for developing, in the next step, a holistic approach to cost estimates for factory planning projects in the early planning phase.

References

[1] Grundig, C.-G., 2018. Fabrikplanung: Planungssystematik - Methoden - Anwendungen, 6th ed. Hanser, München.

[2] 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.

[3] Lanza, G., Nyhuis, P., Fisel Johannes, Jacob, A., Nielsen, L., Schmidt, M., Stricker, N., 2018. Wandlungsfähige, menschzentrierte Strukturen in Fabriken und Netzwerken der Industrie 4.0. (acatech Studie). Herbert Utz Verlage, München.

[4] Kettner, H., Schmidt, J., Greim, H.-R., 2010. Leitfaden der systematischen Fabrikplanung: Mit zahlreichen Checklisten. Hanser, München.

[5] Dombrowski, U., Hennersdorf, S., Palluck, M., 2007. Die wirtschaftliche Bedeutung der Fabrikplanung am Standort Deutschland. Zeitschrift für wirtschaftlichen Fabrikbetrieb 102 (1-2), 14–18.

[6] Schenk, M. (Ed.), 2015. Produktion und Logistik Mit Zukunft: Digital Engineering and Operation. Springer Berlin / Heidelberg.

[7] Niemann, J., Westkämper, E., 2004. Investitionskosten versus Betriebskosten – Nicht Preisschild sondern Lebenslaufkosten entscheiden über den Produktnutzen. wt Werkstattstechnik online 94 (3), 43–47.

[8] Pawellek, G., 2014. Ganzheitliche Fabrikplanung: Grundlagen, Vorgehensweise, EDV-Unterstützung, 2nd ed. Springer Vieweg, Berlin, Heidelberg.

[9] Herrmann, C., Kara, S., Thiede, S., 2011. Dynamic life cycle costing based on lifetime prediction. International Journal of Sustainable Engineering 4 (3), 224–235.

[10] Gebler, M., Cerdas, J.F., Thiede, S., Herrmann, C., 2020. Life cycle assessment of an automotive factory: Identifying challenges for the decarbonisation of automotive production – A case study. Journal of Cleaner Production 270.

[11] Abele, E., Dervisopoulos, M., Kuhrke, B., 2009. Bedeutung und Anwendung von Lebenszyklusanalysen bei Werkzeugmaschinen, in: Schweiger, S. (Ed.), Lebenszykluskosten optimieren. Gabler, Wiesbaden, pp. 51–80.

[12] Herrmann, C., 2010. Ganzheitliches Life Cycle Management: Nachhaltigkeit und Lebenszyklusorientierung in Unternehmen. Springer Berlin Heidelberg, Berlin, Heidelberg.

[13] Mattes, K., Schröter, M., 2012. Kurzstudie Wirtschaftlichkeitsbewertung: Bewertung der wirtschaftlichen Potenziale von energieeffizienten Anlagen und Maschinen, Kurzstudie. Fraunhofer-Institut für System- und Innovationsforschung ISI.

[14] Rautenstrauch, T., Müller, C., 2006. Investitionscontrolling in kleinen und mittleren Unternehmen (KMU). Z Control Manag 50 (2), 100–105.

[15] Statistisches Bundesamt (Destatis), 2021. Bauen und Wohnen - Baugenehmigungen/Baufertigstellungen von Nichtwohngebäuden (Neubau).

[16] Statistisches Bundesamt (Destatis), 4. Vierteljahr 2022. Volkswirtschaftliche Gesamtrechnungen - Arbeitsunterlage Investitionen.

[17] Reinema, C., Pompe, A., Nyhuis, P., 2013. Agiles Projektmanagement. Zeitschrift für wirtschaftlichen Fabrikbetrieb 108 (3), 113–117.

[18] McKinsey&Company, 2017. The art of project leadership: Delivering the world´s largest projetcs.

[19] Bracht, U., Geckler, D., Wenzel, S., 2018. Digitale Fabrik: Methoden und Praxisbeispiele, 2nd ed. Springer Vieweg, Berlin.

[20] Rimpau, C., 2011. Wissensbasierte Risikobewertung in der Angebotskalkulation für hochgradig individualisierte Produkte. Herbert Utz Verlag, München.

[21] Niazi, A., Dai, J.S., Balabani, S., Seneviratne, L., 2006. Product Cost Estimation: Technique Classification and Methodology Review. Journal of Manufacturing Science and Engineering 128 (2), 563–575.

[22] Siemon, K.D., Speckhals, R., Siemon, A., 2021. Baukostenplanung und -steuerung: Bei Neu- und Umbauten, 7. Auflage ed. Springer Vieweg, Wiesbaden.

[23] Unzeitig, W., 2014. Methodik zur frühen Fabrikplanung bei Unsicherheiten. Dissertation, Graz.

[24] Souchoroukov, P., 2004. Improvement of cost estimating internal practice. Dissertation, Cranfield.

[25] Fiebig, C., 2004. Synchronisation von Fabrik- und Technologieplanung. Zugl.: Hannover, Univ., Diss., 2004. VDI-Verl., Düsseldorf.

[26] Ehrlenspiel, K., Kiewert, A., Mörtl, M., Lindemann, U., 2020. Kostengünstig Entwickeln und Konstruieren: Kostenmanagement bei der integrierten Produktentwicklung, 8. Auflage ed. Springer Vieweg, Berlin, Heidelberg.

[27] Cevirgen, C., Rieke, L., Bischoff, L.-M., Nyhuis, P., 2021. Investment Feasibility Study for Factory Planning Projects. Journal of Production Systems and Logistics 1.

[28] Rieke, L., Heinen, T., Cevirgen, C., Laßmann, F., Nyhuis, P. Development Of A Digital Planning Tool For Dimensioning And Investment Cost Calculation In An Early Factory Planning Phase. Herberger, D; Hübner, M; Stich, V. (Eds.): Proceedings of the Conference on Production Systems and Logistics: CPSL 2023 - 1. Hannover : publish-Ing., 2023, S. 229-238.

[29] VDMA, 2006. VDMA 34160 Prognosemodell für die Lebenszykluskosten von Maschinen und Anlagen.

[30] Wirth, S., Schenk, M., Müller, E., 2011. Fabrikarten, Fabriktypen und Entwicklungsetappen. Zeitschrift für wirtschaftlichen Fabrikbetrieb 106, 799–802.

[31] Cevirgen, C., Hook, J., Nyhuis, P., 2021. Investitionsentscheidungen unter Unsicherheit/Dimensioning changeable factories – Investment decisions under uncertainty. wt Werkstattstechnik online 111 (04), 227–231.

[32] Kosow, H., Gaßner, R., 2008. Methoden der Zukunfts- und Szenarioanalyse: Überblick, Bewertung und Auswahlkriterien. IZT, Berlin.

[33] Hernández Morales, R., 2003. Systematik der Wandlungsfähigkeit in der Fabrikplanung. Zugl.: Hannover, Univ., Diss., 2002. VDI-Verl., Düsseldorf.

[34] Baker, M.J., 2000. Writing a Literature Review. Mark. Rev. 1 (2), 219–247.

[35] Schenk, M., Wirth, S., Müller, E., 2014. Fabrikplanung und Fabrikbetrieb: Methoden für die wandlungsfähige, vernetzte und ressourceneffiziente Fabrik, 2nd ed. Springer Vieweg, Berlin, Heidelberg.

[36] 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.

[37] 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 15 (5).

[38] Brieke, M., 2009. Erweiterte Wirtschaftlichkeitsrechnung in der Fabrikplanung. Dissertation. PZH, Produktionstechnisches Zentrum, Garbsen.

[39] Götze, U.; Müller, E.; Meynerts, L.; Krones, M., 2013. Energy-Oriented Life Cycle Costing – An Approach for the Economic Evaluation of Energy Efficiency Measures in Factory Planning, Chemnitz.

[40] Heinemann, T., Thiede, S., Herrmann, C., Berning, B., Müller, K., Linzbach, J., 2013. Life cycle evaluation of factories: Approach, tool and case study. Proceedings 11th Global Conference on Sustainable Manufacturing, 479–484.

[41] Kovacic, I., Waltenbereger, L., Gourlis, G., 2016. Tool for life cycle analysis of facade-systems for industrial buildings. Journal of Cleaner Production 130, 260–272.

[42] Möller, N., 2008. Bestimmung der Wirtschaftlichkeit wandlungsfähiger Produktionssysteme. Zugl.: Diss., Techn. Univ., München, 2008. Herbert Utz Verlag, München.

[43] Aurich, J.C., Lauer, C., Faltin, M., Schweitzer, E., 2009. Abschätzung der Lebenszykluskosten neu entwickelter Fertigungsprozesse. Zeitschrift für wirtschaftlichen Fabrikbetrieb 104 (9), 720–724.

[44] Dreier, J., Wehking, K.-H., 2016. Lebenszykluskosten von elektrischen Antriebssystemen.

[45] Heinemann, T., Kaluza, A., Thiede, S., Ditterich, D., Linzbach, J., Herrmann, C., 2014. Life Cycle Evaluation of Factories: The Case of a Car Body Welding Line with Pneumatic Actuators, in: Advances in production management systems. Innovative and knowledge-based production management in global-local world. Springer, Amsterdam, pp. 546–554.

[46] Pohl, J., 2014. Adaption von Produktionsstrukturen unter Berücksichtigung von Lebenszyklen. Zugl.: München, Techn. Univ., Diss., 2013. Utz, München.

[47] Dehli, M., 2020. Lebenszykluskosten von Maschinen und Anlagen, in: , Energieeffizienz in Industrie, Dienstleistung und Gewerbe. Springer Vieweg, Wiesbaden, pp. 81–95.

[48] Denkena, B., Schürmeyer, J., Eikötter, M., 2010. Berücksichtigung temporärer Effekte von Lebenszykluskosten in der Technologiebewertung. Zeitschrift für wirtschaftlichen Fabrikbetrieb 105 (11), 959–963.

[49] Kampker, A., Burggräf, P., Wesch-Potente, C., Petersohn, G., Krunke, M., 2013. Life cycle oriented evaluation of flexibility in investment decisions for automated assembly systems. CIRP Journal of Manufacturing Science and Technology 6 (4), 274–280.

[50] Lindner, R., Götze, U., 2011. Lebenszykluskostenrechnung als Instrument der energiebezogenen wirtschaftlichen Bilanzierung und Bewertung von Werkzeugmaschinen, in: Neugebauer, R. (Ed.), Methoden der energetisch-wirtschaftlichen Bilanzierung und Bewertung in der Produktionstechnik. Methodenworkshop der Querschnittsarbeitsgruppe 1 "Energetisch-wirtschaftliche Bilanzierung“ des Spitzentechnologieclusters eniPROD; Tagungsband. Verl. Wiss. Scripten, Auerbach, Zwickau.

[51] Osten-Sacken, D., 1999. Lebenslauforientierte, ganzheitliche Erfolgsrechnung für Werkzeugmaschinen. Zugl.: Stuttgart, Univ., Diss., 1999. Jost-Jetter, Heimsheim.

[52] Deutsches Institut für Normung e.V., 2018. DIN 18960 - Nutzungskosten im Hochbau. Beuth-Verlag, Berlin.

[53] International Organization for Standardization, 2017. ISO 15686-5:2017. Buildings and constructed assets – Service life planning – Part 5: Life-cycle costing.

[54] Verein deutscher Ingenieure, 2005. Purchase, operating and maintenance of production equipment using Life Cycle Costing (LCC): VDI 2884.

[55] Verein deutscher Ingenieure, 2011. VDI-Richtlinie 5200: Fabrikplanung- Planungsvorgehen / VDI-Guideline 5200: Factory planning - Planning procedures.

[56] HOAI, 2013. HOAI - Honorarordnung für architekten und ingenieure / official scale of fees for services by architects and engineers, 6. Auflage ed. Springer Vieweg, Deutschland.

[57] ElMaraghy, H.A., 2009. Changeable and Reconfigurable Manufacturing Systems. Scholars Portal, London.

[58] Hilchner, R., 2012. Typenorientiertes Lösungsraum-Management in der Fabrikplanung. RWTH Aachen, Aachen.

[59] Baukosteninformationszentrum Deutscher Architektenkammern, 2020. BKI-Baukosten 2020 Neubau: Statistische Kostenkennwerte. BKI, Stuttgart.

[60] Gairola, A., 1981. Montagegerechtes Konstruieren ein Beitrag zur Konstruktionsmethodik, Dissertation.

[61] Zehbold, C., 1996. Lebenszykluskostenrechnung. Gabler, Wiesbaden.

[62] 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.

[63] Rieke, L., Cevirgen, C., Gloy, A., Nyhuis, P. Procedure Model for Dimensioning and Investment Cost Calculation in an Early Factory Planning Phase. Herberger, D; Hübner, M. (Eds.): Proceedings of the Conference on Production Systems and Logistics: CPSL 2022. Hannover : publish-Ing., 2022, S. 308-318.

[64] Becker, H.P., Peppmeier, A., 2022. Investition und Finanzierung: Grundlagen der betrieblichen Finanzwirtschaft, 9., vollständig aktualisierte und erweiterte Auflage ed. Springer Gabler, Wiesbaden.

[65] Thommen, J.-P., Achleitner, A.-K., Gilbert, D.U., Hachmeister, D., Jarchow, S., Kaiser, G., 2020. Grundlagen der Investition und Unternehmensbewertung, in: Thommen, J.-P., Achleitner, A.-K., Gilbert, D.U., Hachmeister, D., Jarchow, S., Kaiser, G. (Eds.), Allgemeine Betriebswirtschaftslehre. Gabler, Wiesbaden, pp. 375–381.

[66] Weber, W., Kabst, R., Baum, M., 2018. Einführung in die Betriebswirtschaftslehre, 10. Aufl. 2018 ed. Springer Gabler, Wiesbaden.

[67] Theis, F., 2011. Lebenszyklusorientierte Betriebskosten bei gebäudetechnischen Anlagen im deutschen Krankenhaussektor, 1. Aufl. ed. Gabler, Wiesbaden.

[68] Müller, D., 2020. Betriebswirtschaftslehre für Ingenieure, 3., wesentlich überarbeitete Auflage ed. Springer Gabler, Berlin, Heidelberg.

[69] Jonen, A., Harbrücker, U., 2019. Investitionsrechenverfahren in der Praxis: aktueller Stand und historische Entwicklung, 03/2019 - 1. Auflage ed., Mannheim.

[70] Steinmetz, F., Gürtler, V., 2008. Lebenszyklusmanagement/ PPP an Hochschulen: Ansätze im Hochschulbau. HIS Hannover.

[71] Rotermund, U., 2016. Aktueller Entwicklungsstatus Lebenszykluskostenberechnungen - fm benchmarking. FH Münster - University of Applied Sciences.

[72] Hauschild, M.Z., Rosenbaum, R.K., Olsen, S.I., 2018. Life cycle assessment: Theory and practice. Springer.

[73] Kneifel, J., Webb, D., 2020. Life Cycle Costing Manual for the Federal Energy Management Program. National Institute of Standards and Technology.

[74] Pelzeter, A., 2006. Lebenszykluskosten von Immobilien: Schriften zur Immobilienökonomie.

[75] Westkämper, E., Constantinescu, C., Hummel, V., 2006. New paradigm in manufacturing engineering: Factory life cycle, in: , Production Engineering. Research and Development, vol. 13, pp. 143–146.

[76] Wirth, S., Enderlein, H., Petermann, J., 2000. Kompetenznetze der Produktion. In: Vortragsband IBF-Fachtagung "Vernetzt planen und produzieren".

[77] Denkena, B., Harms, A., Jacobsen, J., Möhring, H.-C., Jungk, A., Noske, H., 2006. Lebenszyklus-orientierte Werkzeugmaschinenentwicklung. wt Werkstattstechnik online.

[78] Helbing, K., Mund, H., Reichel, M., 2018. Handbuch Fabrikprojektierung, 2., aktualisierte und ergänzte Auflage ed. Springer Vieweg, Berlin, Heidelberg.

[79] Dér, A., Hingst, L., Karl, A., Nyhuis, P., Herrmann, C., 2021. Factory life cycle evaluation through integrated analysis of factory elements. Procedia CIRP 98, 418–423.

[80] Burggräf, P. (Ed.), 2021. Fabrikplanung: Handbuch Produktion und Management 4, 2. Auflage 2021 ed. Springer Berlin, Berlin.

[81] Grömling, M., Haß, H.-J., 2009. Globale Megatrends und Perspektiven der deutschen Industrie. Dt. Inst.-Verl., Köln.

[82] Kahlert, J., 1995. Fuzzy Control Für Ingenieure: Analyse, Synthese und Optimierung Von Fuzzy-Regelungssystemen. Springer Fachmedien Wiesbaden GmbH, Wiesbaden.

[83] Heger, C.L., 2007. Bewertung der Wandlungsfähigkeit von Fabrikobjekten. Zugl.: Hannover, Univ., Diss., 2006. PZH, Produktionstechn. Zentrum, Garbsen.

[84] Martin, H., 2016. Transport- und Lagerlogistik: Systematik, Planung, Einsatz und Wirtschaftlichkeit, 10. Aufl. 2017 ed. Springer Vieweg, Wiesbaden.

[85] Lotter, B., Wiendahl, H.-P. (Eds.), 2006. Montage in der industriellen Produktion. Springer, Berlin.

[86] Hompel, M. ten, Schmidt, T., Dregger, J., 2018. Materialflusssysteme: Förder- und Lagertechnik, 4. Auflage 2018 ed. Springer Berlin Heidelberg, Berlin, Heidelberg.

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).

Luca Philipp (*1997) has been studying production and logistic (M.Sc.) at Leibniz University Hannover (LUH) since 2021. He has been a research assistant in the factory planning group at the Institute of Production Systems and Logistics (IFA) at Leibniz University Hannover since 2023. Previously, he studied mechanical engineering (B.Eng.) at the University of applied science Bielefeld.

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).

CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
CPSL 2023-2

5th Conference on Production Systems and Logistics

Assessing Risk Mitigation Preference Effect on Supplier Commitment and Procurement Performance in the Public Health Industry in South-Africa

Osayuwamen Omoruyi [1], Matthew Quayson[2]

[1]Department of Management Sciences, Sol Plaatje university , Kimberley, South Africa
[2]Department of Logistics and Supply Chain Management, Ho Technical University,Ghana

Abstract

The lack of a well-stated risk mitigation strategy has caused several challenges within the South African Public Health sector. Additionally, setting a risk mitigation strategy around mitigation preferences can be challenging for procurement personnel. As such, risk mitigation penalty clauses in the case of failure of the selected supplier are not agreed upon from the onset of the contract agreement. This research proposes risk-sharing versus risk-shifting contracts as risk mitigation/reduction strategies within the supplier relationship of the public health sector. We evaluate the effect of risk shifting and sharing mitigation preference on supplier commitment and supplier performance in the public health industry in South Africa using structural equation modelling. The results show that there is a significant relationship between supplier selection and risk sharing, risk sharing and supplier commitment, risk shifting and supplier commitment, and risk sharing and procurement performance. However, there was no significant relationship between supplier selection and risk shifting and risk shifting and procurement performance, which may be due the need to constantly evaluate supplier and manage risk collaboratively. These results imply that to build a win-win supply chain, public health sector procurement managers should balance risk sharing and shifting mitigation strategy in procurement instances where appropriate to improve on a higher level of procurement performance.

Keywords: risk sharing, risk shifting, supplier commitment, procurement performance, public health industry, preference effect

1. Introduction and problem statement

The preference for risk management during supplier selection is necessary to determine the level of commitment among supply chain and procurement personnel. Risk-associated challenges are inevitable in any contractual agreement, especially when selecting a supplier to manage a strategic function within a supply chain or an organisation [15]. Mitigating risk-associated challenges during the supplier selection and procurement process may require agreeing on whether the risk should be shared or transferred to the supplier or buyer. The risk mitigation preference may determine the level of supplier commitment and overall procurement performance [4]. Setting a risk mitigation strategy around mitigation preferences may be challenging for procurement personnel but will certainly help the buyer-supplier better prepare against the occurrence of environmental and market disruptive factors such as global economic risk factors, competitive factors, internet and information technology, and dynamic market environment that drives changes and decision-making capabilities of an organisation. Risk management is a process that mitigates risk, reduces costs, and effectively improves customer and consumer service within a supply chain. Supply chain

DOI: https://doi.org/10.15488/15266
ISSN: 2701-6277

management integrates, collaborates and coordinates all activities involved in material flows, sourcing, conversion, and physical distribution of the final product or service [22].

Within the public health sector of South Africa, the objective of supplier selection is to improve overall procurement performance. Public procurement in South Africa is defined as a 'function by which public sector organisations acquire goods, services, development, and construction projects from suppliers in the local and international market [7]. The supplier selection process follows a competitive bidding process, consisting of a request for an invitation to tender, actual tender calling, submission and receiving of tenders, opening of tenders, assessing tenders, and finally, awarding of tenders. The suitability of the selected supplier is rated against the supplier's price, quality, capabilities, and financial standing. However, risk mitigation preferences are not well emphasised during selection [32]. As such, risk mitigation penalty clauses in the event of failure on the part of the selected supplier are not agreed upon from the onset of the contract agreement. The lack of a well-stated risk mitigation strategy has caused several challenges within the South African Public Health sector. Examples include non-compliance with procurement legislation, policies and processes; a lack of accountability and transparency; a lack of procurement knowledge and skill, embedded ethical practises, fraud, and corruption, which further impact negatively on supplier commitment and overall procurement performance [7]. Therefore, the public sector goals of providing reliable and quality health services might be jeopardised [43]. Based on these challenges, this research proposed risk sharing versus risk shifting contracts as risk mitigation/reduction strategies within the supplier relationship of the public health sector. Therefore, the question is: What is the effect of risk mitigation preferences on supplier commitment and procurement performance in the public health industry in South Africa? The article aims to evaluate the effect of risk shifting and sharing mitigation preference on supplier commitment and procurement performance in the public health industry in South Africa [28]; [47]; [48]). The research is one of its kind because it aimed to model risk sharing and risk shifting mitigation preferences during supplier selection.

2. Literature review

2.1 Risk management and risk mitigation

Risk management aims to forecast potential threats to an organisation and devise strategies to deal with them. It involves identifying potential threats, weighing their likelihood and impact, and developing plans to deal with them. New risks must be constantly evaluated and accounted for, making risk management an ever-evolving process [35]. Possibilities and risks to a project are categorised by their likelihood of occurring and their potential impact [31]. The term "risk mitigation" refers to procedures designed to reduce the negative effects of potential dangers on a business. Risk mitigation, which includes risk reduction, is an effort to reduce the likelihood of unfavourable results from hazards to business continuity (BC).

Risk mitigation and risk management are related. One facet of risk management is "risk mitigation," and its implementation differs from business to business. This means consistently addressing the most pressing threats and concerns to keep a business safe. Common types of mitigation include controls, processes, and procedures that guide and direct an organization [24]. Again, they are linked, as one function of risk management is to seek out dangers and devise ways to minimise their impact. One of these tactics is known as "risk mitigation." As defined by [38], risk management is the process of recognising and responding to possible threats to an organisation, whereas risk mitigation is eliminating or significantly lowering those threats. The probability of a risk and the effort put towards reducing it are directly related. When implemented, risk mitigation plans reduce the likelihood of many risks occurring, especially those that originate within an organization [31]. The likelihood of severe losses is reduced when an organisation takes precautions against potential dangers.

2.2 Supplier selection and risk sharing

Supplier selection and risk management are two important aspects of supply chain management [3]. Supplier selection identifies suppliers that can provide the best value for a business [41]. Since the inception of supply chain theory, the idea that careful supplier selection is essential to building a formidable supply chain has been widely held. The significance stems from the gravity of the decision to purchase or make a procurement. The cost of procuring raw materials can account for up to 90% of an industrial company's revenue [20]. Quality, delivery timeliness, processing speed, and cost have traditionally been the primary metrics considered in selecting suppliers [35]. This demonstrates how supplier selection is based on several factors.

However, the original work on supplier selection has been extended by significant and recent research to include risk sharing [21] as an important consideration, especially for public private partnerships (PPP). To reduce exposure to risk, businesses and individuals can use risk sharing as a risk management method. Shared risks can reduce supply chain risks, which is why it is an integral part of supplier management.

Procurement entities are comfortable with suppliers willing to share risks to mitigate risks [45]. This protects them from quality problems, monetary losses, and interruptions in supply chain activities. By dividing risks with their suppliers, companies can ensure that manufacturing and shipping go smoothly and avoid costly loss of profits due to early risk detection. We posit that a procurement entity will select a supplier willing to share risks to minimise risk mutually. Therefore, we state the hypothesis that:

H1: *There is a direct association between supplier selection and risk sharing.*

2.3 Supplier selection and risk shifting

Choosing reliable suppliers is a crucial part of effective purchasing management because it impacts a company's ability to differentiate itself in the market. Typically, businesses choose their suppliers based on how well they are expected to perform with respect to product quality, cost, service, and reliability. Researchers [29] took a more nuanced approach and advocated communication skills and commitment to continuous improvement as essential supplier selection criteria. The selection of suppliers based on their technological and financial skills has become increasingly vital. The potential for variations in supplier selection criteria across industries was the subject of another line of enquiry. Supplier selection, according to proponents of the transaction cost economics theoretical perspective [51], is motivated by operational goals of minimising expenses and optimising profits through cost shifting. Therefore, if a company can shift some of the risks to its vendors, it can save money.

Risk shifting refers to the practise of transferring danger to another entity. Buying an insurance policy or hedging investment holdings are two examples of transferring risk. Risk shifting aims to mitigate the negative effects of a risk by placing that obligation on another party. The return on assets (RoA), a proxy for a company's profitability, has been proven to be correlated with its propensity to take risks in the future by [18]. Mutual funds that take on more risk underperform those that maintain a steady level of risk, according to research by [26], who conclude that agency problems may lead to risk shifting by fund managers. Outsourcing, buying insurance, hedging investment positions, forming partnerships with key suppliers to manage risk and ensure supply, testing supplier business continuity plans with information reviews, informal walk-throughs and joint exercises, and conducting risk analysis and scenario planning of disruptive events are some of the ways buyers can shift risk in procurement [6]. To reduce their exposure, purchasers should create a risk registry and continuously thoroughly monitor its contents, mapping and evaluating the value chains of all important items. Therefore, we hypothesise that:

H2: *There is a significant relationship between supplier selection and risk shifting.*

2.4 Risk sharing and supplier commitment

A critical decision for suppliers engaged in business-to-business (B2B) interactions is what contract terms offer buyers. The most common hands-off approach lists products at a set wholesale price. From the supplier's perspective, this is a simple contract to administer, requiring only setting one contract parameter and no monitoring of buyers' behaviour following the purchase, which shows weak commitment [6]. This is one of the early lessons in supply chain contracting and is a motivator for why "risk-sharing" contracts may be a useful alternative to supplier commitment. Risk-sharing contracts allow suppliers to absorb some of the cost of demand uncertainty facing buyers. Examples include buyback, revenue sharing, quantity flexibility, option contracts, and sales rebates.

However, risk sharing becomes more effective when there is a high level of supplier commitment [20]. The relationship between risk sharing and supplier commitment is that when suppliers are committed to a buyer, they are more likely to share risks with them. This is because they have something to gain from the project's or transaction's success and will be more willing to collaborate with the buyer to make it happen. Researcher [9] looked at how the risk and absorptive ability of a global supply chain partner affected an organisation's decision to commit to and share risk with that partner. For the study, the researchers polled 207 businesses to learn how they rated their offshore outsourcing and supply chain partners according to four criteria: risk sharing, absorptive capacity, commitment, and information sharing. They confirmed the hypothesised connections between an organisation's dedication and transparency in the supply chain and the perceived risk-sharing of its partners.

Many fields of study, from organisational psychology to strategic management and marketing to the study of social interaction, have focused on supplier commitment. Research shows that dedication improves results, whether the system is a group, an organisation, or a supply chain. Assuming that interactions can be measured, the social exchange theory (SET) states that cooperation between group members will result in net gains for the group as a whole (benefits minus costs). Researchers have adopted SET to study the supply chain, primarily emphasising the creation of connections between parties. According to [34], the antecedents of information sharing are trust, commitment, reciprocity, and power, and these relationships in the supply chain are developed because of the mutual advantages shared by its participants. Within these perspectives, we state the hypothesis that;

H3: There is a significant positive relationship between risk sharing and supplier commitment, such that risk sharing enhances suppliers' commitment

2.5 Risk shifting and supplier commitment

Risk shifting refers to transferring risk from one party to another. In a supply chain context, risk shifting can occur when a supplier shifts risk to a buyer by increasing prices or reducing quality. Supplier commitment refers to the extent to which a supplier is willing to invest in a relationship with a buyer [19]. Suppliers, such as price commitment and inventory commitment, can use several commitment strategies. Researchers [6] state that committing to a price reduces the incentive to stockpile and shift inventory responsibility to the manufacturer by reducing the quantity of orders. Buying an insurance policy, hedging financial positions, or a company switching from a defined-benefit pension to a defined-contribution plan such as a 401(k) are all examples of risk shifting. The hiring of a janitorial service to maintain a safe and clean workplace is another example of change in risk. These cleaning companies may be asked to sign a contract that shifts some of the responsibility and liability to them. In commercial real estate, the landlord may look for ways to shift some risks to renters. For example, many commercial space landlords insist that upscale boutique tenants sign leases and contracts. In addition to risk shifting, [25] discovered that audit liability insurance could help reduce risk by easing the dissemination of risk management expertise among audit firms. Therefore, we state the hypothesis that:

H4: *There is a positive relationship between risk change and supplier commitment.*

2.6 Risk sharing and procurement performance

Procurement performance refers to the degree to which buyers consistently achieve conformance to specifications and fitness for use. It illustrates how well and efficiently a company sources its goods and services. Metrics such as procurement cycle time, cost savings, supplier performance, and quality can be used to evaluate the effectiveness of a company's purchasing department [11]. Several companies use procurement performance management (PPM) to determine the value of procurement to the business.

When suppliers do not put in as much effort as possible to increase procurement performance, a phenomenon known as moral hazard exists in the supply chain connection [37]. Supply chain managers must overcome the formidable obstacle posed by moral hazard to ensure effective procurement. We believe that shared knowledge of the potential implications of procurement failure can be achieved through risk sharing between supply chain parties. Making informed decisions depends on having a common awareness of the risks associated with procurement. Implementing measures to mitigate the negative effects of procurement risk requires a common understanding of performance challenges. The possibility of moral hazard can be reduced and procurement performance can be improved if the supplier understands the costs and repercussions of procurement failure. Previous studies [2] have shown that the risk sharing mechanism can significantly contribute to the procurement performance of a firm by helping to resolve the competing goals of buyers and suppliers, improving the ability to predict and coordinate supply and demand, and more fairly allocating the costs associated with procurement risks. Social exchange academics have collected a body of work that, in contrast to the economic justification of transaction cost economics, gives a variety of social rationales for why exchange partners might continue to preserve a connection ([16]; [33]). From this theoretical vantage point, risk sharing between trading partners is attractive if it improves both parties' procurement results. We hypothesise that:

***H5.** The risk-sharing practise positively affects procurement performance.*

2.7 Risk shifting and procurement performance.

Procurement entities transfer risks to reduce their exposure to potential losses and ensure that they are not solely responsible for negative outcomes [18]. This improves procurement performance. Supply chain management is highly dependent on the efficiency with which risks are transferred and purchased. It is widely agreed that risk transfer is essential to effectively managing PPP projects. Proper and responsible use of resources, improved service, strengthened supplier and client relationships, greater appetite for innovation, greater customer service, and a data-driven culture that brings game-changing insights within reach of the firm can all result from the transfer of risks. However, there is a limit to how much risk the private sector can take on, and the government must keep some risk internal. The more powerful party typically bears the risk in a given situation [44].

Risk sharing in UK construction projects was the subject of a questionnaire study by [5]. They claim that the supplier is the best choice for managing project-specific risks and that the buyer should bear some risks while the two parties share others. Some evidence suggests that PFI deals provide better VFM for the private sector than for the taxpayer, and [49] are sceptical about the actual level of risk transfer in PPPs and believe that the private sector benefits. Therefore, we state the hypothesis that:

***H6:** There is a significant relationship between risk shifting and procurement performance.*

3. Research methodology

Following the research onion [40], the research methodology takes the positivism-deductive approach. The approach is chosen because the study is quantitative and based on the proposition that trends, procedures, and cause-and-effect issues are relevant to the execution of scientific research methods. Furthermore, research is based on a known knowledge of a given theory, practise, and sphere that aids in the deduction of hypotheses and is subjected to further empirical examination to allow a conclusion [30]. A non-probability-convenience sampling strategy is adopted because subjective decisions based on geographical proximity, respondent availability, easy accessibility, or willingness to participate are considered to decide which elements are included in the sample [23]. The sample frame of the public health industries located in Gauteng province was collected from the South African National Health Research Database (NHRD). Before anticipating the right sample size, a pilot study is carried out to predict an appropriate or exact sample size for the full-scale project and to improve various aspects of the study design. The target population consist of employees in the procurement department in public health industries located in the Gauteng province. The determination of the sample size is a scientific judgment made by the researcher, based on past studies [53]. Researchers [14] and [17] have examined the procurement performance in public health care sectors using sample sizes ranging between 150 and 300 elements. The sample size is also suitable for Smart PLS 3.0 data analysis. Of the 150 questionnaires distributed, 100 were valid and useful for research. A historical decision based on previous research in related fields and the suitability of the statistical package was used to determine the sample size for the investigation. The questionnaire comprises sections A to F, where section A contains the respondents' background, section B, supplier selection adapted from [46], sections C and D, detailed questions on risk mitigation strategies, which were adapted from [42], section E explains questions related to supplier commitment [1], and section F will comprise questions on procurement performance [46]. All sections except section A were measured on a 5-point Likert scale questions, anchored with 1= strongly disagree to 5= strongly agree. The Likert scaled type is useful because they are easy to construct and administer and participants find it easier to use [12]. Research ethics such as informed consent, voluntary participation, right to personal privacy and confidentiality, and protection from harm were considered essential during data collection.

4. Data analysis and discussions

The Social Sciences Statistical Package 25.0 (SPSS) enabled the descriptive statistics of the demographic data of the respondents. SMART-PLS version 3.0 for the structural equation modelling procedure was used to determine the relationship strengths of the research variables, as well as to assess the reliability and validity. For example, Cronbach's Alpha, rho A, and composite reliability were used to determine reliability, while extracted average variance (AVE) was used to assess the validity of the measurement variables. The T statistics and the P-value were used to test the significant level of the research variables.

4.1 Demographic information

There were more women (62%) than men (38%) in public health sector procurement functions, of which (64%) were between the ages of 26 and 37. About (98%) of the respondents were black, only (2%) were white and none were coloured or Indian. Of the 100 procurement personnel who participated in the research, (32%) percent were holders of senior certificates, while (38%) percent had diploma qualifications and (29%) percent had degrees.

Table 1: Descriptive and Internal consistency of constructs

Research constructs	Indicators	Descriptive statistics		Reliability statistics			Validity statistics			
		Mean ($\bar{x}$)	SD	Alpha (α)	*Rho*	CR	AVE	√AVE	Factor loadings	Item-total correlation
	SS1	3.717	0.779						0.795	0.738
	SS2	3.909	0.877						0.771	0.685
	SS3	3.788	0.913						0.845	0.801
	SS4	4.071	0.856						0.824	0.723
	SS5	3.848	0.869						0.827	0.764

Supplier selection	SS6	3.949	0.783	0.951	0.957	0.957	0.672	0.820	0.798	0.703
	SS7	3.980	0.910						0.857	0.801
	SS8	4.051	0.869						0.860	0.787
	SS9	4.040	0.875						0.854	0.770
	SS10	4.101	0.772						0.800	0.727
	SS11	4.182	0.796						0787	0.702
Risk sharing	RH1	3.960	0.803	0.898	0.916	0.919	0.618	0.786	0.721	0.679
	RH2	3.919	0.720						0.749	0.676
	RH3	4.000	0.765						0.767	0.677
	RH4	3.909	0.854						0.843	0.722
	RH5	3.990	0.772						0.830	0.728
	RH6	3.737	0.871						0.827	0.710
	RH7	3.990	0.732						0.757	0.690
Risk shifting	RS1	3.848	0.821	0.871	0.892	0.903	0.609	0.780	0.835	0.690
	RS2	3.859	0.739						0.737	0.569
	RS3	3.909	0.793						0.828	0.733
	RS4	3.828	0.682						0.703	0.619
	RS5	3.980	0.710						0.813	0.684
	RS6	3.960	0.724						0.641	0.576
	RS7	4.061	0.789						0.755	0.677
Supplier commitment	SC1	3.879	0.782	0.906	0.920	0.927	0.680	0.824	0.876	0.734
	SC2	4.162	0.598						0.804	0.668
	SC3	3.970	0.745						0.883	0.804
	SC4	4.111	0.584						0.794	0.704
	SC5	4.071	0.655						0.832	0.716
	SC6	4.131	0.580						0.751	0.698
Procurement performance	PP1	3.747	0.730	0.874	0.879	0.908	0.665	0.815	0.803	0.680
	PP2	3.869	0.774						0.850	0.677
	PP3	3.970	0.771						0.759	0.646
	PP4	3.838	0.735						0.827	0.632
	PP5	3.687	0.774						0.834	0.689

Note: Alpha (α) = Cronbach's alpha; Rho= Dillon-Goldstein's *rho*; CR=Composite reliability; AVE=Average variance extracted; 1= strongly disagree to 5= strongly agree.

In Table 1, Cronbach's alpha value (α), spearman's Rho-A, composite reliability value (CR), and item-to-total correlation value indicate internal consistency of the measurement variables for this research. This is because the above stated reliability coefficients are above the stipulated threshold of 0.7 and 0.5 respectively [40]. For example, Cronbach's alpha coefficient ranges from 0.871 to 0.951; spearman's Rho-A coefficient ranges from 0.879 to 0.957; Composite reliability coefficient ranges from 0.903 to 0.95 and item-to-total correlation coefficient ranges from 0.569 to 0.804 respectively. The results indicate that all measurement items adapted for this research are reliable.

As indicated in the descriptive statistics,

Table 2: Discriminant validity

Constructs	Procurement performance	Risk sharing	Risk shifting	Supplier selection	Supplier commitment
Procurement performance	**0,815**				
Risk sharing	0.497	**0.786**			
Risk shifting	0.119	0.119	**0,780**		
Supplier selection	0.378	0.547	**0.069**	**0.820**	
Supplier commitment	0.186	0.310	0.459	0.201	**0.824**
Note: Alpha (α) = Cronbach's alpha; Rho= Dillon-Goldstein's *rho*; CR=Composite reliability; AVE=Average variance extracted; 1= strongly disagree to 5= strongly agree.					

Factor loadings were used to assess whether the measurement items are highly loaded on their respective variable and should be at least greater than 0.5 (Martino et al., 2018). As shown in Table 1, all items were loaded highly with values ranging from (0.703 to 0.883). This stipulates an acceptable individual item convergent in the validity of all scale items. Discriminant validity was determined using the AVE and √AVE values. The value of AVE value should be greater than 0.5 and the intercorrelation matrix among the research variables should be less than the square root of the AVE ([27]; [30]). Table 2 shows that the inter-correlation values for all paired latent variables are less than √AVE (ranging from 0.780 to 0.824) and therefore assures the presence of discriminant validity for each construct.

4.2 Path model results

The proposed model for the research describes the relationship between the research variables. In addition to assessing the strength of the relationship among the research variables, the significance of the path coefficients was determined by bootstrapping analysis in addition to t-statistics for each of the path estimates. Figure 1 and Table 3 explain the statistical results of the Smart PLS for structural equation modelling.

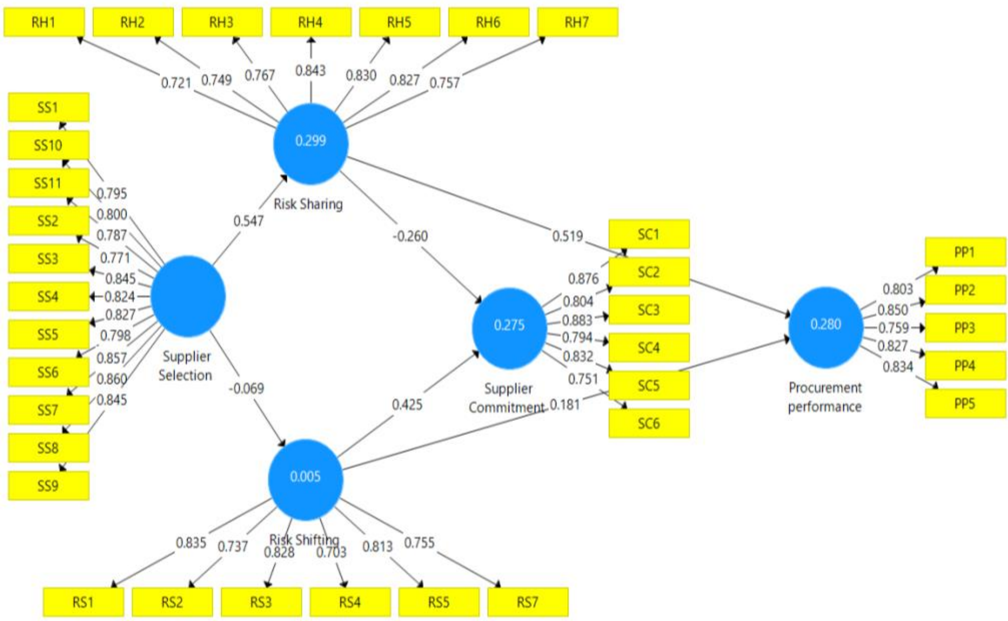


Figure 1: Path model relationship strength

Table 3: Results of structural equation model analysis and significant level

Proposed path relationship	Hypothesis	Path coefficient	T-statistics	P-value	Outcome
Supplier selection and risk sharing	H_1	0.547	6.060	0.000	Supported
Supplier selection and risk shifting	H_2	0.069	0.299	0.765	Rejected
Risk sharing and supplier commitment	H_3	0.260	3.461	0.000	Supported
Risk shifting and supplier commitment.	H_4	0.425	4.559	0.000	Supported
Risk sharing and procurement performance	H_5	0.519	6.210	0.000	Supported
Risk shifting and procurement performance	H_6	0.181	1.305	0.190	Rejected

Figure 1 and Table 3 present the six hypothesised relationships, the path coefficients, the t-statistics, and the accepted level. The value of the t-statistic indicates whether the relationship is significant or not. A significant relationship is expected to have a t statistic greater than 1.96 and a p-value of ≤0.05 to indicate whether the hypothesis is rejected and supported [27]. According to the statistical analysis, four of the six proposed hypotheses were statistically significant and accepted. Two hypotheses are rejected with a t-statistics of >0.5.

5. Discussion and Findings

The question that the research seeks to answer is: What is the effect of risk mitigation preferences on supplier commitment and procurement performance? The purpose of the article is to evaluate the effect of risk shifting and sharing mitigation preference on supplier commitment and supplier performance in the public health industry in South Africa. The measurement items for each variable presented in the proposed model have been statistically proven to be valid and reliable.

The proposed relationship between supplier selection and risk sharing (H1), is significant at (path estimate=0.547; p=0.000 <0.05 and the relationship effect of supplier selection and risk shifting (H2), is rejected at (path estimate=0.069; p=0.765 >0.05). The results indicate that procurement personnel in the public health industry in South Africa prefer the risk-sharing migration strategy to the risk shifting strategy in supplier selection. The risk sharing strategy is relational in the sense that it involves joint problem solving in a supply chain [52]. To build a win-win supply chain, risk sharing as a mitigation strategy is preferred than outsourcing or purchasing product liability insurance. The risk sharing mitigation strategy improves product quality in the long run through supplier development programmes, accurate / timely information sharing, participation of key suppliers in key decision making for effective cross-functional decision making, which ultimately mitigate risk and improve buyer-supplier commitment. The next section will discuss the risk mitigation strategy and the level of commitment among the supply chain members in determining the overall performance of the procurement.

The proposed relationship between risk sharing and supplier commitment (H3) is significant at (path estimate=0.260; p=0.000 <0.05). The proposed relationship effect of risk shift and supplier commitment (H4) is acceptable and significant at (path estimate=0.425; p=0.000 <0.05). These results indicate that although public health sector procurement personnel prefer risk sharing as appropriate risk mitigation strategy and management, they also embrace the fact that risk shifting further enhances supplier commitment [50]. This may be in the case where managing the quality of certain materials primarily becomes the responsibility of suppliers. In this sense, the public health sector may propose a high penalty resulting from defective supplies through a detailed description of suppliers' responsibilities to mitigate risk, reduce cost, and higher level of supplier commitment.

Procurement performance is one of the main reasons for supply chain collaboration. The proposed relationship between risk sharing and procurement performance (H5) is significant and supported in (path estimate=0.519; p=0.000 <0.05). The effect of the relationship between risk shift and procurement performance (H6) is rejected and insignificant in (path estimate=0.181; p=0.19 >0.05). Despite embracing risk shifting as a risk mitigation strategy to improve and manage supplier commitment, the South Africa's public health procurement personnel believe that a long-term coordinated relationship with their supplier is important to effectively manage risk. The result indicates that the public sector intends to maintain supplier relationship through the maximum effort of risk sharing mitigation strategy, and as such risk sharing influence on procurement performance statistically is highly significant.

6. Conclusion

The aim of the research, which is to evaluate the effect of risk shifting and sharing mitigation preference on supplier commitment and supplier performance in the public health industry in South Africa, has been scientifically proven. The risk mitigation strategy has become even more important in the business-relational environment, especially after the Covid-19 pandemic. The two important risk mitigation strategies presented in the research are important and their preference effect on supplier commitment and procurement performance and have been analysed and discussed.

7. Recommendation for future research

From the findings, it can be seen that the South African public health sector procurement gradually neglects the importance of risk shifting. This is because from the statistical results, more attention is focused on risk sharing as a better option to mitigate risk in the buyer-supplier relationship of the public health sector. Therefore, it is recommended that the public health sector procurement balances risk sharing and shifting mitigation strategy in procurement instances, where appropriate, to improve on a higher level of procurement performance.

The research did not investigate the level of impact of supplier commitment on procurement performance, but only focused on the effect of preference for risk mitigation on supply commitment and procurement performance. It is recommended that future researchers investigate to what extent the supplier's level of commitment enhances procurement performance within the public sector. In other words, the commitment of a supplier does not guarantee the procurement performance to the purchasing organisation and the overall supply chain performance. Other factors such as quality, delivery, flexibility, and social and environmental sustainability may play a significant role.

References

[1] Abdul-Muhmin, A.G. 2005. Instrumental and interpersonal determinants of relationship satisfaction and commitment in industrial markets. Journal of Business Research, 58:619- 628.

[2] Abednego, M. P. and Ogunlana, S. O. (2006) 'Good project governance for proper risk allocation in public-private partnerships in Indonesia', International Journal of Project Management. doi: 10.1016/j.ijproman.2006.07.010.

[3] Ada, N. 2022. Sustainable Supplier Selection in Agri-Food Supply Chain Management. International Journal of Mathematical, Engineering &Management Sciences, 7(1), 115-130. https://doi.org/10.33889/IJMEMS.2022.7.1.008 115-130.

[4] Afifa, Y. N., & Santoso, I. (2022). Proactive risk mitigation strategies and building strategic resilience in the food supply chain: a review. In Food Research. https://doi.org/10.26656/fr.2017.6(2).257.

[5] Akintoye, Edwards, and Hardcastle (2005). Critical success factors for PPP/PFI projects in the UK construction industry', Construction Management and Economics, 23(5), pp. 459–471. doi: 10.1080/01446190500041537.

[6] Alikhani, R., Torabi, S. A., & Altay, N. (2019). Strategic supplier selection under sustainability and risk criteria. International Journal of Production Economics. https://doi.org/10.1016/j.ijpe.2018.11.018

[7] Ambe, I. M., & Badenhorst-Weiss, J. A. (2012). Procurement challenges in the South African public sector. Journal of Transport and Supply Chain Management. https://doi.org/10.4102/jtscm.v6i1.63

[8] Ameyaw, C., Mensah, S., & Osei-tutu, E. (2012). Public procurement in Ghana: The implementation challenges to the Public Procurement Law 2003 (Act 663). International Journal of Construction Supply Chain Management. https://doi.org/10.14424/ijcscm201012-55-65

[9] Arnold, V., Benford, T., Hampton, C. & Sutton, S. (2010) 'Competing pressures of risk and absorptive capacity potential on commitment and information sharing in global supply chains', European Journal of Information Systems, 19(2), pp. 134–152. doi: 10.1057/ejis.2009.49.

[10] Aslam, H., Wanke, P., Khalid, A., Roubaud, D., Waseem, M., Chiappetta Jabbour, C. J., Grebinevych, O., & Lopes de Sousa Jabbour, A. B. (2022). A scenario-based experimental study of buyer supplier relationship commitment in the context of a psychological contract breach: Implications for supply chain management. International Journal of Production Economics. https://doi.org/10.1016/j.ijpe.2022.108503

[11] Bienhaus, F. & Haddud, A. (2018). Procurement 4.0: factors influencing the digitisation of procurement and supply chains', Business Process Management Journal, 24(4), pp. 965–984. doi: 10.1108/BPMJ-06-2017-0139

[12] Bradley, N. (2013). Marketing Research: Tools and Techniques. Koks i Khimiya.

[13] Bryman, A., Bell, E., Hirschsohn, P., Santos, A. dos, Toit, J. du, & Masenge, A. (2014). Research Methodology: Business and Management Contexts. Oxford University Press.

[14] Budak, J & Rajh, E.2014. The Public Procurement System: A Business Sector Perspective. The Institute of Economics, 1-80.

[15] Chai, J., & Ngai, E. W. T. (2020). Decision-making techniques in supplier selection: Recent accomplishments and what lies ahead. In Expert Systems with Applications. https://doi.org/10.1016/j.eswa.2019.112903

[16] Chao, C-M., Yu, C-T., Cheng, B.W. & Chuang, P.C. 2013. Trust And Commitment In Relationships Among Medical Equipment Suppliers: Transaction Cost And Social Exchange Theories. Social Behavior & Personality, 41(7), 1057-1070. http://dx.doi.org/10.2224/sbp.2013.41.7.1057.

[17] Chegugu, N. R. & Yusuf, K. G. 2017. Effect of electronic procurement practices on organizational performance in public hospitals in the county government of Uasin Gishu, Kenya. International Academic Journal of Procurement and Supply Chain Management, 2(3):16-32.

[18] Chen, Z., Strebulaev, I. A., Xing, Y., & Zhang, X. (2021). Strategic risk shifting and the idiosyncratic volatility puzzle: An empirical investigation. Management Science, 67(5), 2751–2772. https://doi.org/10.1287/mnsc.2020.3593

[19] Chiu, J-Z. & Hsieh, C.C. 2022. Exploring the Influence of Supply Chain Relationship Commitment and Loyalty in F&B Industry. Advances in Management & Applied Economics, 12 (2), 1-20 ISSN: 1792-7544 (print version), 1792-7552(online) https://doi.org/10.47260/amae/1221.

[20] Collier, Z. A. & Sarkis, J. (2021) The zero trust supply chain: Managing supply chain risk in the absence of trust. International Journal of Production Research, 59(11), pp. 3430–3445. doi: 10.1080/00207543.2021.1884311.

[21] Deneckere, R., de Palma, A., & Leruth, L. (2019). Risk sharing in procurement. International Journal of Industrial Organization, 65, 173–220. https://doi.org/10.1016/j.ijindorg.2019.01.002

[22] Dohale, V., Ambilkar, P., Gunasekaran, A., & Verma, P. (2022). Supply chain risk mitigation strategies during COVID-19: exploratory cases of "make-to-order" handloom saree apparel industries. International Journal of Physical Distribution and Logistics Management. https://doi.org/10.1108/IJPDLM-12-2020-0450

[23] Etikan, I. (2016). Comparison of convenience sampling and purposive sampling. American Journal of Theoretical and Applied Statistics, 5(1), 1–4. https://doi.org/10.11648/j.ajtas.20160501.11

[24] Fadun, O.S. 2013. Risk Management and Risk Management Failure: Lessons for Business Enterprises. International Journal of Academic Research in Business & Social Sciences,3(2), 225-239.ISSN: 2222-6990.

[25] Frank, M., Maksymov, E., Peecher, M. & Reffett, A. (2021) 'Beyond Risk Shifting: The Knowledge-Transferring Role of Audit Liability Insurers*', Contemporary Accounting Research. doi: 10.1111/1911-3846.12670.

[26] Gärling. T., Fang, D., Holmen, M. & Michaelsen, P. (2020). Financial risk-taking related to individual risk preference, social comparison and competition. Review of Behavioral Finance, 13(2), 125-140. doi: 10.1108/RBF-11-2019-0153

[27] Garson, G. D. (2016). Partial Least Squares: Regression & Structural Equation Models. In Multi-Label Dimensionality Reduction.

[28] Ghadge, A., Dani, S., Ojha, R., & Caldwell, N. (2017). Using risk sharing contracts for supply chain risk mitigation: A buyer-supplier power and dependence perspective. Computers and Industrial Engineering. https://doi.org/10.1016/j.cie.2016.11.034

[29] Ghadimi, P., Ghassemi Toosi, F. & Heavey, C. (2018) A multi-agent systems approach for sustainable supplier selection and order allocation in a partnership supply chain. European Journal of Operational Research. doi: 10.1016/j.ejor.2017.07.014.

[30] Henseler, J., Ringle, C. M. & Sarstedt, M. 2015. A new criterion for assessing discriminant validity in variance based structural equation modelling. Journal of the Academy of Marketing Science, 43:115-135. [https://doi.org/10.1007/s11747-014-0403-8].

[31] Hohenstein, N-O. 2022. Supply chain risk management in the COVID-19 pandemic: strategies and empirical lessons for improving global logistics service providers' performance. The International Journal of Logistics Management, 33(4), 1336-1365. DOI 10.1108/IJLM-02-2021-0109.

[32] Klaaren, J., & Watermeyer, R. (2022). Reforming procurement standards in order to effectively deliver public infrastructure: Rethinking the regulatory environment in post-pandemic South Africa. South African Journal of Economic and Management Sciences. https://doi.org/10.4102/sajems.v25i1.4465

[33] Li, S., Zhou, Q., Huo, B & Zhan, X. 2022. Environmental uncertainty, relationship commitment, andinformati on sharing: the social exchange theory and transaction cost economics perspectives. International Journal of Logistics: Research & Applications. https://doi.org/10.1080/13675567.2022.2141699.

[34] Manfredi, E. & Capik, P. (2022) A case of trust-building in the supply chain: Emerging economies perspective, Strategic Change. doi: 10.1002/jsc.2488.

[35] Munir, M., Sadiq, J.M.S., Ali, K.C. & Sami, F. (2020) Supply chain risk management and operational performance: The enabling role of supply chain integration. International Journal of Production Economics, 227(March 2019), p. 107667. doi: 10.1016/j.ijpe.2020.107667.

[36] Pamucar, D., Torkayesh, A.E. & Biswas, S.. 2022. Supplier selection in healthcare supply chain management during the COVID-19 pandemic: a novel fuzzy rough decision-making approach. Annals of Operations Research, 977-1019. 328:977–1019. https://doi.org/10.1007/s10479-022-04529-2

[37] Parker, D.W., Dressel, U., Chevers, D. & Zeppetella, L. (2018), Agency theory perspective on public-private-partnerships: international development project. International Journal of Productivity and Performance Management, 67(2), 239-259. https://doi.org/10.1108/IJPPM-09-2016-0191

[38] Rahman, M. S. and Adnan, T. M. (2020). Risk management and risk management performance measurement in the construction projects of Finland. Journal of Project Management. doi: 10.5267/j.jpm.2020.5.001.

[39] Saunders, M., Lewis, P., & Thornhill, A. (2015). Research Methods for Business Students (5th Edition). In Prentice Hall (5th Editio).

[40] Shamsudin, M.F, Ali, A.M, Ali, A.M, & Shabi, K.S. 2019. Exploratory study of students' decision for enrolment at Universiti Kuala Lumpur business school campus. Humanities & Social Sciences,7(2): 526-530.

[41] Shang, Z., Yang, X., Barnes, D. & Wu, C. 2022. Supplier selection in sustainable supply chains: Using the integrated BWM, fuzzy Shannon entropy, and fuzzy MULTIMOORA methods. Expert Systems With Applications, 195, 1-16. https://doi.org/10.1016/j.eswa.2022.116567.

[42] Sharma, S. K., & Bhat, A. (2014). Supply chain risk management dimensions in indian automobile industry: A cluster analysis approach. Benchmarking. https://doi.org/10.1108/BIJ-02-2013-0023

[43] Sibevei, A., Azar, A., Zandieh, M., Khalili, S. M., & Yazdani, M. (2022). Developing a Risk Reduction Support System for Health System in Iran: A Case Study in Blood Supply Chain Management. International Journal of Environmental Research and Public Health, 19(4). https://doi.org/10.3390/ijerph19042139

[44] Siemieniako, D., Makkonen, H. & Mitręga, M. 2023. Buying center-selling center interaction as a driver for power dynamics in buyer-supplier relationships. Industrial Marketing Management, 114, 94-109. https://doi.org/10.1016/j.indmarman.2023.08.007

[45] Suhonen, N., Tammi, T., Saastamoinen, J., Pesu, J., Turtiainen, M., & Okkonen, L. (2019). Incentives and risk-sharing in public procurement of innovations: Towards contracting strategy framework. Journal of Public Procurement. https://doi.org/10.1108/JOPP-06-2019-029

[46] Tawfik, M., Mady, T. T., & Mady, S. T. (2014). Procurement performance and manufacturer-supplier relationships: A multivariate analysis in Kuwaiti manufacturing companies. Journal of Business and Industrial Marketing. https://doi.org/10.1108/JBIM-01-2012-0005

[47] Um, J., & Han, N. (2021). Understanding the relationships between global supply chain risk and supply chain resilience: the role of mitigating strategies. Supply Chain Management. https://doi.org/10.1108/SCM-06-2020-0248

[48] Wakolbinger, T., & Cruz, J. M. (2011). Supply chain disruption risk management through strategic information acquisition and sharing and risk-sharing contracts. International Journal of Production Research. https://doi.org/10.1080/00207543.2010.501550

[49] Wang, Y. and Zhao, Z. J. (2018). Performance of Public–Private Partnerships and the Influence of Contractual Arrangements. Public Performance and Management Review. doi: 10.1080/15309576.2017.1400989.

[50] Whipple, J. M., & Roh, J. (2010). Agency theory and quality fade in buyer-supplier relationships. The International Journal of Logistics Management. https://doi.org/10.1108/09574091011089781

[51] Williamson, O. E. (1989) Chapter 3 Transaction cost economics. Handbook of Industrial Organization, 1, pp. 135–182. doi: 10.1016/S1573-448X (89)01006-X.

[52] Yoon, J., Talluri, S., Yildiz, H., & Ho, W. (2018). Models for supplier selection and risk mitigation: a holistic approach. International Journal of Production Research. https://doi.org/10.1080/00207543.2017.1403056.

[53] Zikmund, W.G., Babin, B.J., Carr, J.C. & Griffin, M. 2013. Business research methods. 9th ed. South-Western: Cengage Learning.

Biography

Dr. Osayuwame Omoruyi is a senior lecturer and researcher in Logistics, Operation, and Supply Chain Management since 2010. She is currently the Research Chair in the School of Economic and Management Sciences, Sol Plaatje University. Professionally affiliated with the Chartered Institute of Logistics and Transport (CILTSA) and has been a chartered member since 2019.

Dr. Matthew Quayson received his Ph.D. degree in Management Science and Engineering (supply chain option) from the University of Electronic Science and Technology of China, Chengdu, China. His research focuses on using multi criteria decision techniques to address issues relating to technology applications for sustainable supply chain management in emerging economies.

5th Conference on Production Systems and Logistics

Method For Creating A Control Cabinet Model With Realistic Wires

Stefanie Bartelt[1], Matthias Bartelt[2], Bernd Kuhlenkötter[1]

[1]*Chair of Production Systems, Ruhr University Bochum, Bochum, Germany*
[2]*SCHUBS GmbH, Hameln, Germany*

Abstract

During the assembly of a control cabinet, a major time-consuming step is the wiring of the included components. Hence, automating this step will noticeably reduce production costs. According to the planning, wires are routed through wire ducts and connected to components. While a comprehensive digital twin can be computed for the included components, this twin is missing a proper modelling of the connecting wires. For these, only a rough route through the wire ducts is given. However, a physically plausible model is an important prerequisite to perform reliable path planning for automated assembly. The paper addresses this need for accurate wire path computation during automated cabinet assembly and introduces a method to compute realistic wire paths through the wire ducts. Different models with and without a fixed wire length are presented and compared. An evolutionary algorithm optimizes the corresponding variables of the models. As described, both approaches yield valid paths, although the fixed length model appears to be able to compute more realistic paths.

Keywords

Control Cabinet Assembly; Wire Modeling; Path Planning; Simulation; Automated Assembly

1. Introduction

Control cabinets are very common in industry. They contain several components, e.g., programmable logic controllers, power devices, or terminal blocks. The kind of components correspond to the functions that the control cabinet must fulfill. Therefore, there is a high variance in the design of control cabinets. Furthermore, the components are connected by wire that are routed through wire ducts. Typically, there are about 300 to 400 components and about 500 wires in a cabinet. The production of a cabinet starts with the definition of functions and the selection of required components. Using an appropriate software, the physical design of the cabinet is created, and the components are connected as required. With this planning, the assembly of the cabinet can be done. [1] gives a detailed overview on the setup and assembly procedure. However, most assembly steps are carried out manually because effects such as poor data quality, low lot size, or a lack of component design suitable for automation hinder automation. The components are usually not designed for an automated assembly. This causes a high level of complexity regarding the required technology. Especially the wiring, which consists of assembly and routing, is complex in terms of automation [2]. Furthermore, there is no holistic digital model of the control cabinet in a system-neutral exchange format that can be used is the software tools. As a result, important information to automate the process steps are missing and an appropriate solution is both time-consuming and cost intensive. However, solutions for automating the manufacturing process must be cost-effective, which is a challenging task, particularly for make-to-order production. There are two promising approaches to increase the automation level – reduction of complexity and a comprehensive data model.

DOI: https://doi.org/10.15488/15281
ISSN: 2701-6277

The reduction of complexity refers to the shape and connections of the components. Nowadays, both shapes and connectors are not designed for automation. Additionally, there is a high variance among manufacturers, which obstructs automated assembly. In terms of connections, there are already good variants, such as push-in technology [3]. Nevertheless, optimizing components is the responsibility of the manufacturers.

The second approach is the creation of a comprehensive data model of the control cabinet. Especially for individual projects, it is important that the data model can be derived solely from the planning tool. Furthermore, the model must provide information in a system-neutral format to support the development of automated manufacturing steps. Currently, the information that can be derived from the design is a descriptive 3D model of the cabinet including the position, size, and hierarchical structure. Additionally, wiring information can be derived in a second step. The wiring information can include the connected components, the wire ducts for the routing, and information to the wire like color or cross section. Even if the accessible information provides a good model, important supplementary information is still missing for more complex tasks, such as the calculation of the degree of filling of wire ducts, the distribution probability of wires within the ducts, or the automation of assembly steps.

The paper focuses on the latter approach and presents a method to create a comprehensive data model. It is structured as follows. The next section gives an overview of the accessible information as well as a general method to enrich the model with further information. By combining different sources, the basis of a digital twin for a control cabinet is created. Both the data model as well as the data sources providing relevant content to the model are discussed. As the chapter reveals, a realistic model for the wires in the control cabinet is missing. Section 3 elaborates on this issue and presents an approach for a proper modeling. Section 4 discusses the results and ends with a conclusion of the presented work.

2. Control cabinet model

As discussed above, a comprehensive data model of the control cabinet supports the optimization of the manufacturing process. The generation of the model should be accomplished with as little effort as possible, and the creation process should be automated as much as possible. This is particularly important for control cabinets that are only manufactured once.

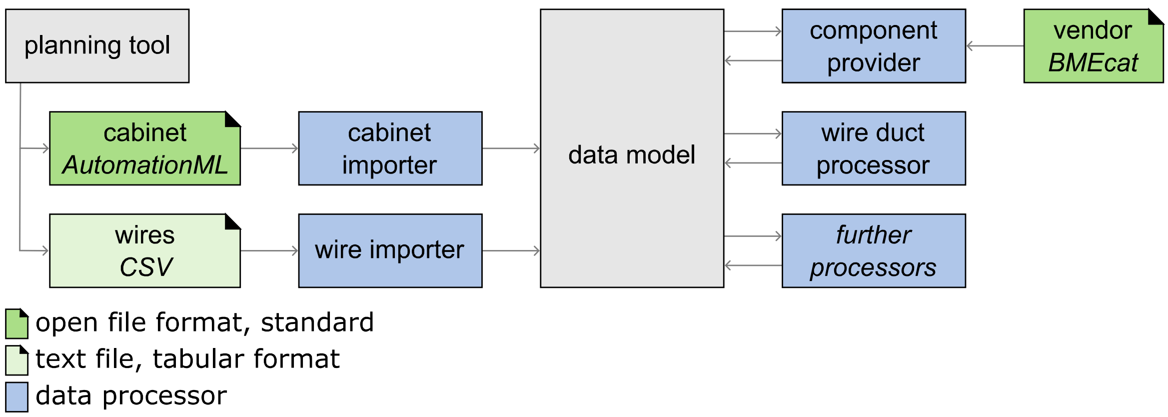


Figure 1: Concept for the creation and enrichment of the data model. The arrows indicate the flow of information.

In general, the effort to create the model can be divided into two tasks. The first task is to create all cabinet-specific information, which varies for each cabinet. The second task is the creation of component-specific information. This information is static for each component and must only be created once. Furthermore, it is possible to enrich the model by applying different algorithms or rules. Figure 1 depicts the corresponding concept to create a data model. All data sources are connected to the model via appropriate processors, while the planning tool is the only provider for cabinet-specific information.

2.1 Data sources

In general, the planning tool might provide a sufficient detailed set of cabinet-related as well as component-related information to build the data model. Nevertheless, there are several reasons, why the provided information is insufficient. For instance, the user may have planned the cabinet only partially, or the export of the tool lacks important details. Although the completeness of the exported data depends on the software used, it is most likely that more sources are required to achieve a holistic data model. While the planning tool must provide all information related to the specific setup of the cabinet, component-related information may can be acquired from other sources, i.e., the manufacturer of the components. Furthermore, there might be some information that is neither provided by the planning tool nor by the manufacturer in a machine-readable way. A further issue in collecting data are the data formats of the corresponding sources. Although there exist many standards for data exchange [4], proprietary data formats are still common.

Although proprietary data might be added to the model, e.g., by implementing adapters that transform the proprietary information to an appropriate exchange format as described in [5]. Nevertheless, standardized open file formats are preferred to achieve a vendor-independent solution. An open exchange format, which has a growing importance, is the AutomationML format [6]. Besides the exchange of arbitrary data, it offers the possibility to exchange component specific information in a standardized way, as described in [7]. As shown in Figure 1, further product-specific information can be added to the model by using the BMEcat format [8]. In addition, other data formats can be easily integrated by implementing appropriate processors as described in the next section.

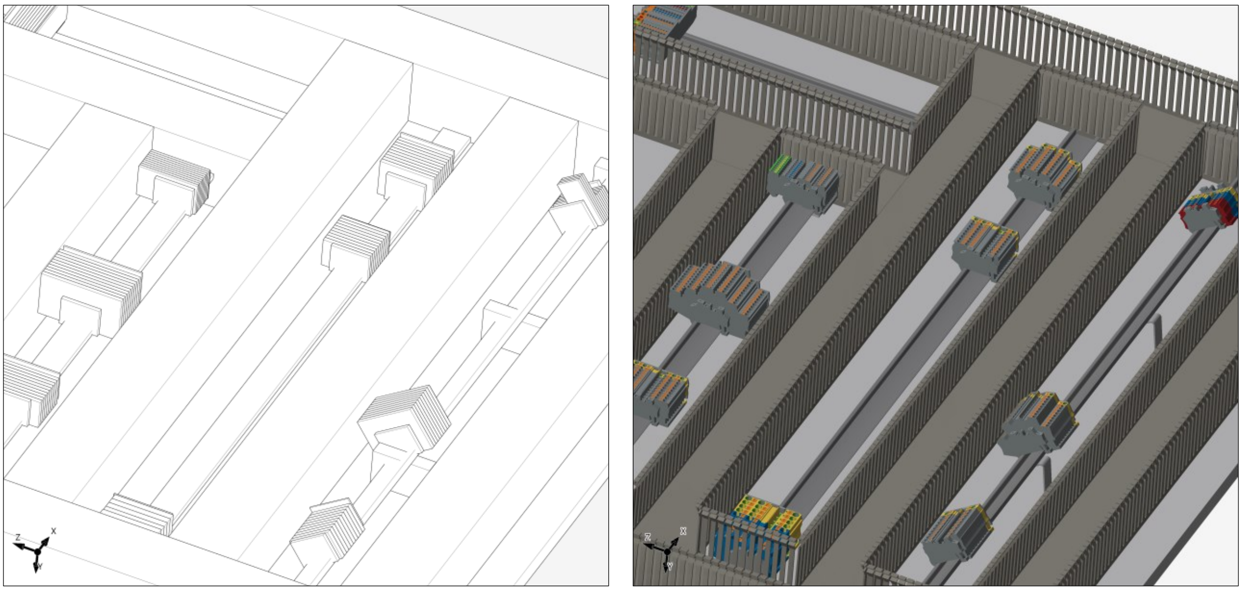
The planning tool generates two files. The first one exports the cabinet as AutomationML document. This document contains a list of components as well as the hierarchical structure of the cabinet. Each component has a unique identifier that refers to the type of the component, i.e., if a certain component is assembled multiple times, all have the same identifier. Furthermore, a component has information about its local transformation, a physical extent, and meta-information. The latter one includes, for instance, the manufacturer name, or the component's function. The second file generated by the planning tool is a document including wiring information. Although it is exported in an open file format, the export is tool specific and must by handled by a specialized data processor.

Further components-specific data is added via the BMEcat format. This data comprises the geometrical representation and attachment points that define where other components may be attached. For example, wires are mounted between two attachment points, or components can be assembled onto a DIN rail.

2.2 Data processors

Data processors can directly interact with the data model. They can access the stored information and they can add further information to the data model. With this, information provided by data sources is included, but a processor can also compute information that is not provided by any source. By successively running different processors, a holistic data model is achieved. In [9], a set of data processors are presented to compute the main cabinet model via a combination of several successive processors. They were required, because the planning tool only provides proprietary data as well as a small subset of the required information in a spreadsheet format. By applying different rules, missing information to build the model were computed. However, the model is consistent with the design only if the rules applied were followed in the planning. This results in additional requirements for the planning, making it more time-consuming. With the presented approach, these processors are not required anymore, which simplifies the planning process and enables the automatic generation of a consistent model.

As depicted in Figure 1, there are four processors right now: Two of them, the cabinet and wire importer, are importing data into the model. By processing the data provided by the planning tool, corresponding components are created in the cabinet model. Figure 2 (a) depicts the state of the model after running both processors. As shown, all components are placed correctly, but only their extent is defined and no real geometrical representation. Furthermore, wires cannot be connected, as there is no information about attachments. The component provider processor increases this detail level of the model by implementing a local database with component-specific information. This database is filled by importing BMEcat files or manually, if no appropriate files are provided by the manufacturer. By traversing all created components, each component is enriched by its geometrical information and by further information, especially attachment points for wires. The wire duct processor improves the detail level without using external data. This processor searches for all wire ducts and creates breakouts at positions where other wire ducts are adjacent.



(a) (b)

Figure 2: Visualization of the model after importing the information provided by the planning tool (a) and after enrichment by subsequent processors (b).

Figure 2 (b) depicts the model after running all four processors. Not shown in the picture are the specified wires. For these, only the components that the cable connects as well as the wire ducts through which the cable is to be routed are defined. The integration of the wires into the model is discussed in the next section.

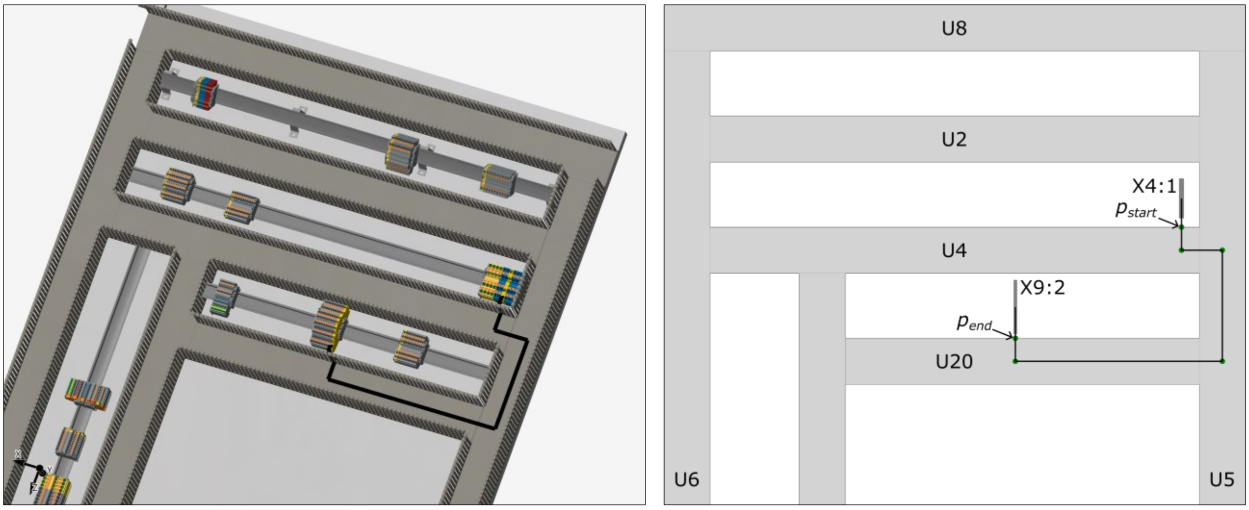
3. Modeling wires

This section discusses wire modeling methods. Figure 3 depicts an example of a routed wire. The data model specifies that the wire connects the components with item designation X1:4 and X9:2. Furthermore, it is specified that the length of the wire is 834 mm and that the wire should pass wire ducts U4, U5, and U20. For manual assembly, this information is sufficient. Nevertheless, to automate processes, a more detailed routing is required. For this, there are some boundary conditions that must be satisfied:

- Both start and end point are fixed. For routing, these points are placed at the feedthroughs to the wire ducts. These can be assumed to behave like a fixed point, and they are referred in the following as p_{start} and p_{end}.
- The length l of the wire between p_{start} and p_{end} is determined by the planning process. The wire is produced using this length before assembly. Hence, the wire length is constant for the path calculation.
- The wire between p_{start} and p_{end} must stay within any of the given wire ducts.

Paths that meet these conditions are referred to as valid. Paths that sufficiently match the physical properties of the wire are referred to as realistic.

The problem of finding a proper route for the wire correlates to the path planning for mobile systems. To solve the path finding problem for mobile systems, various algorithms have been developed [10–12]. However, path planning algorithms focus on finding the optimized path, e.g., the shortest one, and it is not possible to force a fixed length as required for the given problem. Of course, one can search a path and skip it if the length does not match the given length, but with this, the algorithms do not converge anymore, and a solution cannot be found. Another approach that is often used in simulation is an impulse-based model. The wire is approximated by small rigid segments that are connected by joints. For each simulation step, constant forces are assumed in the multi-body system (although these forces may be different in other time steps). By summing up forces, impulses can be computed that changes the velocities and angular moments of the single segment [13]. Further on, three different approaches are presented.



(a) (b)

Figure 3: Example of a routed wire from component X4:1 to component X9:2. The shown route is received by a linear routing as described in section 3.1.

3.1 Linear routing

The linear routing is a very simple algorithm. Starting at p_{start}, a linear path to the center of the wire duct with minimal length is created. From the end point, another linear path to the next duct with the same method is created. These steps are performed until the routing is complete. Finally, the end of the path is connected to p_{end}. Figure 3 shows the result of the routing. Although the algorithm is quite fast, it is not guaranteed that the wire length will match the specified length.

3.2 Minimal energy approach

The second approach to route is to compute the energy of the wire and minimize the energy. To find a global minimum, algorithms such as randomized minimization by Monte Carlo simulation, gradient descent method, or heuristic algorithms (cf. e.g. [14]) can be used. For the given problem, the wire with specified length l is considered as a sequence of n linear segments. To simplify the computation, all segments are assumed to be in the same plane. Each segment has a nominal length of $l_0 = l/n$. The first and last segment are connected to p_{start} and p_{end} respectively. The rotation of a segment i relative to its precursor is described by an angle α_i. Furthermore, there are angles between the first/last segment and the wire duct. With this, the bending energy E_B of a wire is

$$E_B = \sum_{i=0}^{n} \tfrac{1}{2} k_B \cdot \alpha_i^2. \quad (1)$$

k_B is the moment of direction. It depends on type of wire and is assumed to be constant. The requirement that the wires must be inside the wire ducts is achieved with an additional energy E_W. If a segment is within any wire duct, this energy is 0. Otherwise, a large value is set to move the segment into a wire duct. To find a global minimum, an evolutionary algorithms, e.g. as described in [15], is implemented. Thereby, the wire segments are assumed to be a straight line, and they can move freely as far as they are not. With this, any bending of the wire will create a force in the opposite direction.

In the following, two different models to compute a realistic wire path are presented. An evolutionary algorithm is implemented to find parameters resulting in minimal energy. For this, a population of wires is created with an initial path. This path is referred as initialized path. The path as computed by the linear routing is referred as planned path. It will be used to optimize the initial population. The population evolves into a new epoch by computing a set of best wires. With this set, new wires are computed until the initial size of the population is reached. The algorithm is implemented in C# and includes as dedicated processor in the data model as described in the previous section.

The first model does not force a certain length of the wire. It rather assumes a string between two successive joints. This results into a new energy E_L with

$$E_L = \sum_{i=1}^{n} \tfrac{1}{2} k_L \cdot (l_i - l_0)^2. \tag{2}$$

k_L is the (virtual) spring constant. The initial population of 100 contains wires with arbitrary segments. In each epoch, 70% of the wires with lowest energy survive. Until the population reaches the initial size, an offspring is generated with two parents by selecting an arbitrary value p with $1 \leq p \leq n+1$. Segments 1 to $p-1$ are taken from the first parent, and segments from p to n are taken from the second. $p = 0$ is a copy of the second parent, and $p = n+1$ is a copy of the first parent. Both parents are determined via a roulette wheel selection from the last population. For this selection, the energy of the wire is anti-proportional to the probability to be selected.

In a next step, wires are mutated with a probability of 0.1. If a wire mutates, an arbitrary segment is selected. Furthermore, m subsequent segments are selected. m is normal distributed with a standard deviation of 2.0.

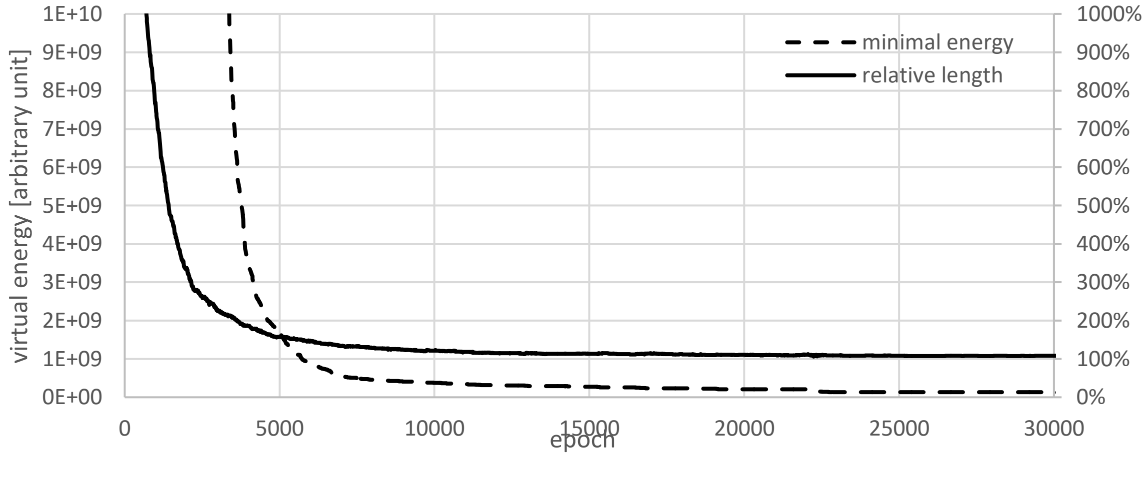
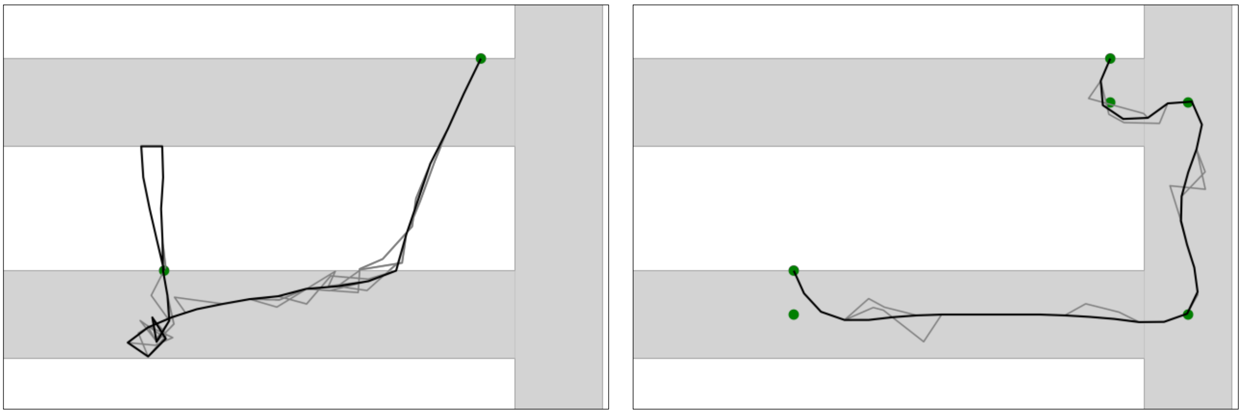


Figure 4: Minimal energy of the population (dotted line) and the corresponding wire length (solid line). The length of the wire is given as relative length compared to the planned length.

In each epoch, the wire with the lowest energy is selected as best approach. For this wire, also the length is computed. Figure 4 depicts the energy as well as the length over 30 000 epochs. As shown, the algorithm converges. Also, the length is about the specified length. However, there are several local minima, and it is not ensured that the algorithm converges to a valid wire. Figure 5 (a) shows the corresponding computed path. Although a local minimum is reached, the wire is obviously not valid. Additionally, it was found that loops in a wire are very likely to remain. To improve the results, the wires are not generated randomly, but they are created along the planned. Due to this initialization, similar results are obtained even with different starting conditions. Figure 5 (b) presents the resulting wire. Although valid solutions are computed, these solutions are very similar to the initialized path.

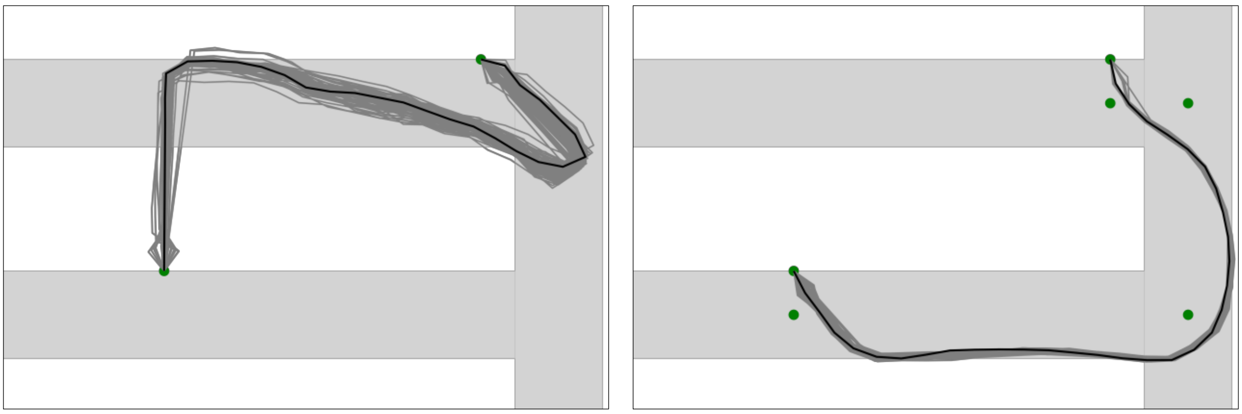


(a) (b)

Figure 5: Result with a randomly initialized set of wires (a) and when initializing the set along the planned path (b). The black wire indicates the wire with the lowest energy, while the other wires are drawn gray. However, most wires are similar and not visible in the figure.

The second model implements a fixed length. For this, segments with constant length l_0 are connected. Due to the fixed end points, the segments are not arbitrary, but each segment must be chosen in such way that subsequent segments can reach the end point. 50 wires are generated from the start to the end point and 50 wires are generated vice versa to improve the routing. The combination of two wires to a new offspring must also be changed to meet the fixed segment length. As before, segments are combined from both parents. However, the segments of the second parent are used, but they must be adjusted so that the wire reaches the end point.

Like the recombination, the mutation must be changed accordingly. An arbitrary segment is changed randomly. Either all subsequent or all preceding segments are then changed only to the extent that the end point is still reached. Figure 6 (a) depicts the result of the computation. Like the first model, the model converges but does not yield a valid solution. To improve the results, the intermediate points of the given planned path are used. With this, random sub-paths are created between two consecutive points. The sub-paths are combined to the wire, whereby the algorithm ensures that the number of segments are the same for all wires. As before, the paths are generated in both directions, from start to end point and from end to start point. Figure 6 (b) presents the resulting wire.



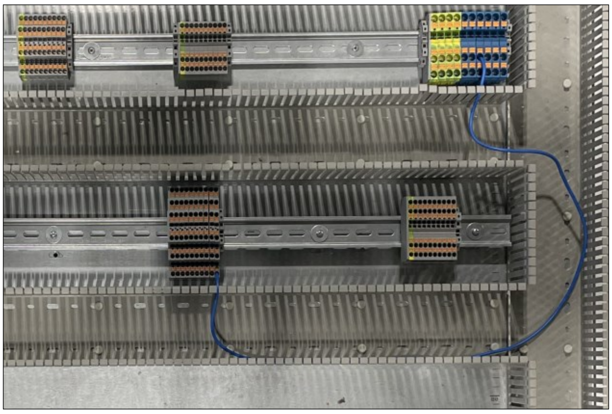
(a) (b)

Figure 6: Result with a randomly initialized set of wires (a) and when initializing the set along the intermediate points of the planned path (b).

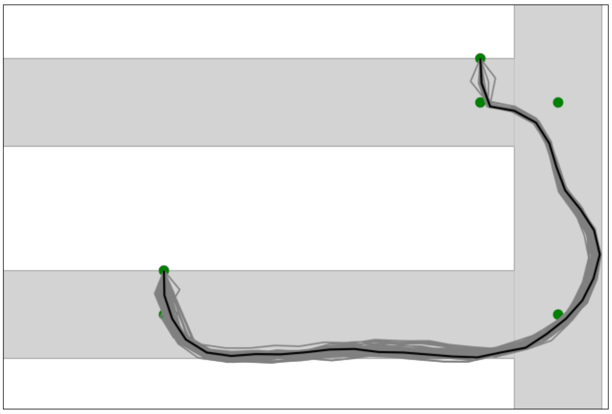
Wires are assumed to be unbent before assembly. However, the bending energy E_B can be modified to

$$E_B = \sum_{i=0}^{n} k_B \cdot \left(\alpha_i - \alpha_{0,\mathrm{i}}\right)^2. \tag{3}$$

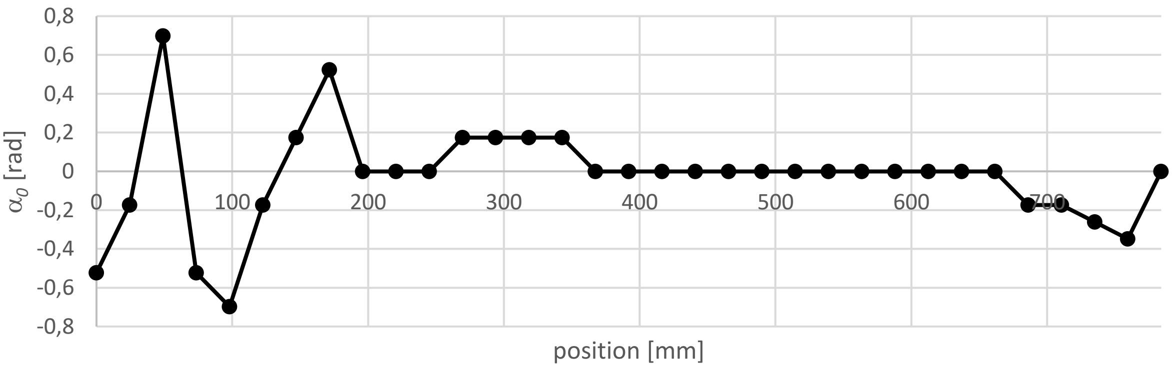
The parameters $\alpha_{0,i}$ indicate a preferred direction of the wire at the corresponding position. Although the parameters need not be equal in general, it is assumed that a constant value $\alpha_{0,i} = \alpha_0$ can be achieved via a suitable wire pusher mechanism. With this, bends in the wire can be included in the calculation. As a result, is should be possible to find parameters $\alpha_{0,i}$ that leads to a computed wire matching a real wire. Figure 7 (a) shows the real mounting plate that corresponds to the configuration shown in Figure 3. The length of the wire matches to the length of the wire used for the computations. Based on this image, parameters $\alpha_{0,i}$ are changed stepwise by 5°. For the computation of the path, the fixed-length model with initialization along the planned path is used. For each parameter set, the result is compared to the real image. However, this comparison is made only visual, i.e., there is no measure applied. Figure 7 (b) shows the best-found combination. The corresponding parameters are given in Figure 7 (c).



(a)



(b)



(c)

Figure 7: Photo of the real setup (a) and the result of computation (b) that is using the pre-bend angles α_0. The used values for the angles are shown in (c).

3.3 Physics simulation

The third approach to compute a wire model is the usage of a physics engine. The wire is modeled as kinematic chain with small segments with a length of 2 mm. The initial shape of the wire is set to the linear routed path that is computed as described in section 3.1. The physical computation is done by the BEPUphysics v2 library [16]. Figure 8 shows the resulting wire. Although the shape of the wire is fine, it is quite difficult to achieve a proper design of the wire. Especially defining physical properties such as the stiffness of the wire is complicated. Depending on the selected parameters, instabilities are very likely to occur, resulting in invalid wires.

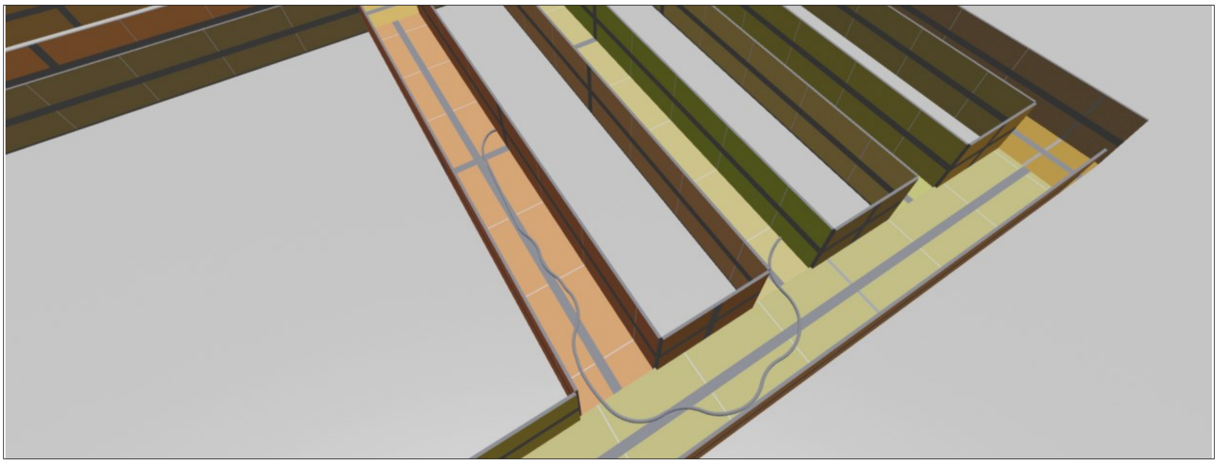


Figure 8: Simulation of the wire using a physics engine.

4. Conclusion and future work

In the paper, an approach to combine different data sources to build a comprehensive model of a control cabinet was presented. The resulting model is an important prerequisite, for example, to generate a digital twin that can be used to realize path planning for automatic wiring. After combining external data sources, data processors are utilized, particularly to compute proper wire models. For the latter, three different methods were implemented. The linear routed path is a fast and robust algorithm. The resulting path does not match a real wire, but it might be sufficient for simple tasks. The minimal energy and the physic engine approach can compute realistic wires. In comparison with a real assembled wire, pre-bend parameters can be determined that result in a good match to the real wire. Nevertheless, currently only a single wire is considered. An extension of the algorithm from the calculation of wires in the plane to a computation in three dimensions, as well as the treatment of multiple wires, will be done in subsequent works. The utilization of a physics engine is suitable for a dynamic simulation. Although multiple wires can be simulated together, their behavior in terms of stiffness is not realistic right now.

In future work, real assembled wires will be digitized, and a corresponding path will be computed. With this, a measure can be defined, and the deviation of the model with the real wire can be computed. By mounting the wire several time, the variance of the assembly process will be analyzed. Additionally, parameters $\alpha_{0,i}$ can be computed automatically by minimizing the deviation to the real wire. As soon as the assembly process is automated with a wire pusher, the assumption that $\alpha_{0,i}$ is influenced by the wire reel and the pusher mechanism can be validated. The findings will be used to improve the presented models.

With respect to a future simulation of the assembly, the models will be examined for their suitability. In this context, also further models, e.g., an impulse based approach, will be implemented and compared to the presented ones.

Acknowledgements

This Project is supported by the Federal Ministry for Economic Affairs and Climate Action (BMWK) on the basis of a decision by the German Bundestag (funding number: KK5055201MS0).

References

[1] Spies, S., Bartelt, M., Hypki, A., Kuhlenkötter, B., 2019. Robot Automation in Control Cabinet Assembly, in: COMA'19 Proceedings, pp. 272–277.

[2] Busi, M., Cirillo, A., Gregorio, D. de, Indovini, M., Maria, G. de, Melchiorri, C., Natale, C., Palli, G., Pirozzi, S., 2017. The WIRES Experiment: Tools and Strategies for Robotized Switchgear Cabling. Procedia Manufacturing 11, 355–363.

[3] Edelmann, M., 2021. How to make wiring more efficient from start to finish: Push-in technology Whitepaper.

[4] Khan, A.A., Abonyi, J., 2022. Information sharing in supply chains – Interoperability in an era of circular economy. Cleaner Logistics and Supply Chain 5, 100074.

[5] Winkler, D., Biffl, S., Bergsmann, J., 2019. Software Quality: The Complexity and Challenges of Software Engineering and Software Quality in the Cloud. Springer International Publishing, Cham.

[6] Lüder, A., Schmidt, N., 2020. AutomationML in a Nutshell, in: Hompel, M. ten, Vogel-Heuser, B., Bauernhansl, T. (Eds.), Handbuch Industrie 4.0. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 1–48.

[7] AutomationML consortium, 2020. Whitepaper AutomationML: Part 6: AutomationML Component.

[8] ETIM International, 2019. Guideline for suppliers to provide product data according to BMEcat Version 2005. http://www.etim.at/fileadmin/user_upload/ETIM_BMEcat_Guideline_V4-0-2_changes.pdf. Accessed 4 March 2023.

[9] Spies, S., Bartelt, M., Kuhlenkötter, B., 2019. Wiring of Control Cabinets using a Distributed Control within a Robot-Based Production Cell, in: 2019 19th International Conference on Advanced Robotics (ICAR). 2019 19th International Conference on Advanced Robotics (ICAR), Belo Horizonte, Brazil. 02.12.2019 - 06.12.2019. IEEE, pp. 332–337.

[10] Campbell, S., O'Mahony, N., Carvalho, A., Krpalkova, L., Riordan, D., Walsh, J., 2020. Path Planning Techniques for Mobile Robots A Review, in: 2020 6th International Conference on Mechatronics and Robotics Engineering (ICMRE). 2020 6th International Conference on Mechatronics and Robotics Engineering (ICMRE), Barcelona, Spain. 12.02.2020 - 15.02.2020. IEEE, pp. 12–16.

[11] Injarapu, A.S.H.H.V., Gawre, S.K., 2017. A survey of autonomous mobile robot path planning approaches, in: 2017 International Conference on Recent Innovations in Signal processing and Embedded Systems (RISE). 2017 International Conference on Recent Innovations in Signal processing and Embedded Systems (RISE), Bhopal. 27.10.2017 - 29.10.2017. IEEE, pp. 624–628.

[12] Karur, K., Sharma, N., Dharmatti, C., Siegel, J.E., 2021. A Survey of Path Planning Algorithms for Mobile Robots. Vehicles 3 (3), 448–468.

[13] Schotte, W., Ovtcharova, J., 2006. Improved impulse-based simulation of cables for virtual assembly environments, in: , International PACE Forum Collaborative Visualization.

[14] Gautam, B., 2021. Energy Minimization, in: Trindade Maia, R., Maciel de Moraes Filho, R., Campos, M. (Eds.), Homology Molecular Modeling - Perspectives and Applications. IntechOpen.

[15] Yu, X., Gen, M., 2010. Introduction to evolutionary algorithms. Springer, London, 418 pp.

[16] Bepu Entertainment LLC. BEPUphysics. https://www.bepuentertainment.com/. Accessed 2 August 2023.

Biography

Stefanie Bartelt (*1991) is a researcher at the Chair of Production Systems at Ruhr University Bochum. She conducts research in the field of industrial robotics and is currently working on a project for the automated handling and quality control of bendable components for the wiring of control cabinets.

Matthias Bartelt (*1978) is head of research and development at SCHUBS GmbH. He is working in the field of control cabinet manufacturing. Thereby, he develops solutions to optimize assembly processes and to achieve consistent use of data from the planning phase up to the delivery of the cabinet.

Bernd Kuhlenkötter (*1971) is Professor and head of the Chair of Production Systems (LPS) at Ruhr University Bochum. His research focuses on the planning, simulation and implementation of production systems and smart product-service systems. Prof. Kuhlenkötter is, among others, a member of the Scientific Society for Production Engineering (WGP) and the Scientific Society for Assembly, Handling and Industrial Robotics (MHI) as well as scientific director of the Research Center for the Engineering of Smart Product-Service Systems (ZESS).

CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
CPSL 2023-2

5th Conference on Production Systems and Logistics

Action Management – Status, Requirements And Implementation Strategies For SMEs

Jens Kiefer, Tara Rauch, Valesca Zeller

University of Applied Sciences Ulm, Germany

Abstract

Due to its great importance for a successful planning, control and improvement of business processes, action management is long established as essential management process in most companies. However, there is often a strikingly large gap between claim and actual implementation of action management. While internal and external requirements for action management are continuously increasing, its actual implementation – especially in small and medium-sized enterprises (SMEs) – is already often quite incomplete today.

First, this paper introduces in the topic field of action management as part of modern management systems. In its analysis part, the paper presents the current implementation status of action management in companies focusing on SMEs and portrays software-technical implementation possibilities. Taking into account the resulting fields of action, possible strategies to implement action management in SMEs' business processes in a more profitable way are presented. In the sense of a socio-technical overall system, not only methodical issues but also information-technical and organizational aspects are discussed. By means of a developed prototype and taking into account a concrete use case from industry, the characteristics, procedure, potentials and current limits of the proposed solution are critically evaluated and recommendations for action are illustrated. Finally, the paper ends with a summary, a discussion and an outlook towards future trends.

Keywords

Process Management; Action Management; Planning and Control; Implementation Strategies; SMEs

1. Action Management as part of integrated management systems

Action management has long become an important management topic in companies around the world. In all areas and departments of a company there are many actions to be taken every day – both at a strategic and at an operational level – and its number is constantly rising due to increasing internal and external requirements. In this context, the effective and efficient planning and implementation of actions are mayor goals that all companies try to achieve with an expedient, systematic and seamless action management.

The great importance of actions is described in many sources and standards, foremost in ISO 9000:2015. According to [1] an action is defined as an "activity to achieve something". In this context, actions can be subdivided into "actions related to nonconformities" and "actions on a product or a service". Actions related to nonconformities can be preventive actions, corrective actions or corrections, actions on a product or a service are reworks, repairs or scraps. What all actions have in common is their novelty and uniqueness.

According to [2] and [3] "action management" describes the process of a company or an organization how to plan, implement, monitor, control and report actions to solve problems or challenges or to achieve specific

DOI: https://doi.org/10.15488/15292
ISSN: 2701-6277

goals. The two key criteria for a successful action management are its effective and efficient implementation, both from a methodical, information-technical and organizational point of view.

In analogy to the PDCA cycle (PDCA: plan-do-check-act) the process of action management consists of four phases: plan actions (P), implement actions (D), check effectiveness (C) and ensure results (A). In the first phase “plan actions”, all relevant actions are defined and described and one responsible person per action is assigned. In order not to get bogged down in all the arising actions, setting the right priorities is of crucial importance. The second phase “implement actions” contains the implementation as well as the monitoring and control of the defined actions. The next step is to check the effectiveness of the implemented actions using defined criteria and a comparison between target plan and actual state is carried out. The last phase “ensure results” includes the orderly completion of actions as well as their documentation and reporting. The central document that is relevant for all phases of action management process is the action plan [4].

To meet the constantly increasing internal and external requirements and objectives in a reliable and systematic way, companies mostly have established topic-specific management systems. According to [5] a management system describes the way how companies organize their structures and processes to act systematically, ensure smooth processes and achieve their objectives. These objectives can relate to a number of different topics such as product and process quality, operational efficiency, environmental performance and many more. Management systems like quality management systems, environment management systems or even sustainability management systems [6] follow the so-called “High Level Structure” (HLS) that is defined in the respective ISO standards like ISO 9001 (quality), ISO 14001 (environment) or ISO 26001 (sustainability) [7]. Due to its central character, action management is part of all relevant management systems (Figure 1).

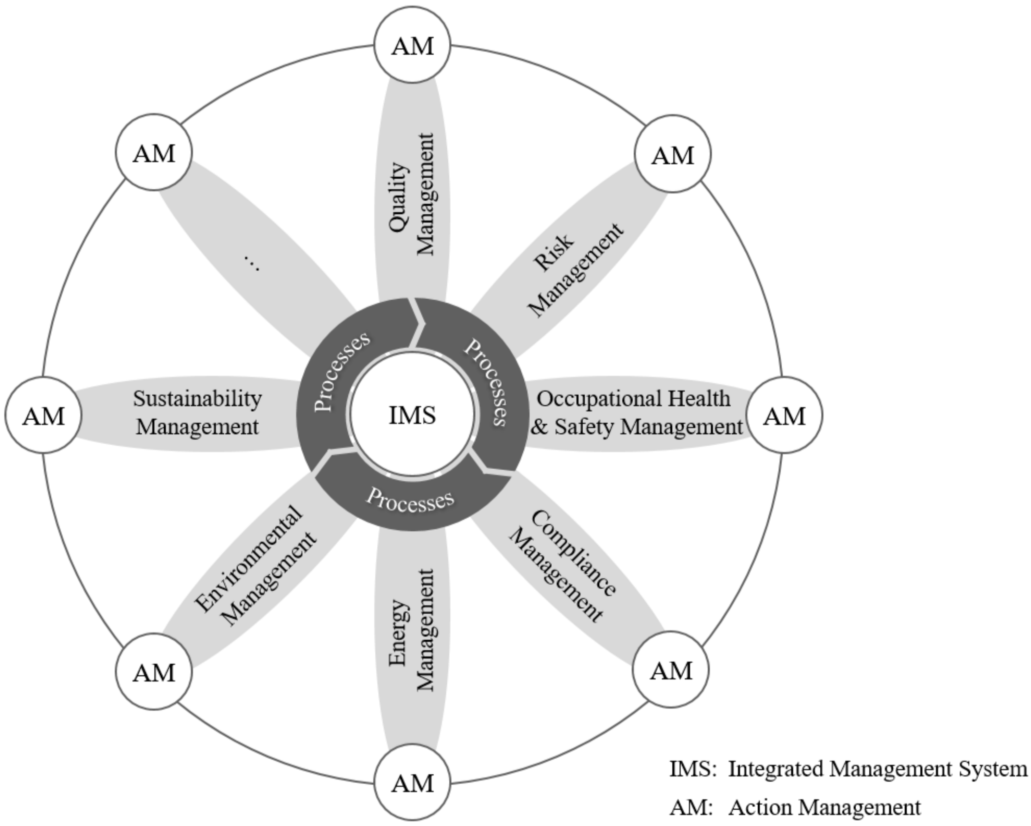


Figure 1: Action management in the context of an integrated management system

As illustrated in Figure 1 and as described in [8], an integrated management system (IMS) combines various management systems into a single, overall comprehensive and harmonized management system. This integrative approach provides a valuable overview of all relevant business processes and enables a consistent planning and control of them. Moreover, an IMS increases the transparency, effectiveness and efficiency of all business structures and processes by creating valuable synergies. The ultimate goal of an IMS is the increase and the systematic continuous improvement of the corporate performance.

2. Implementation status of action management in SMEs

2.1 Sources for actions in companies

Due to the huge number of internal and external requirements and the high number of departments, teams and projects in companies, there is a huge and constantly increasing number of sources for actions. Sources for actions can be subdivided into department-specific sources such as FMEA’s, simulation studies, quality circles or customer complaints and general (cross-sectoral) sources like meetings, audits, reviews, ideas, risk evaluations or data analyses. Actions arise along the entire product life cycle, they arise both from day-to-day operations (e.g. meetings), from projects and from strategic processes (e.g. risk analyses) and they can vary in complexity, scope and duration. The enormous variety and quantity of actions make it necessary to prioritize them absolutely clearly. Some actions are quite simple and can be implemented rather quickly, while others are very complex and require long-term planning and implementation.

2.2 Software solutions for action management

As portrayed in Figure 2, there are three “software classes” to realize action management in companies.

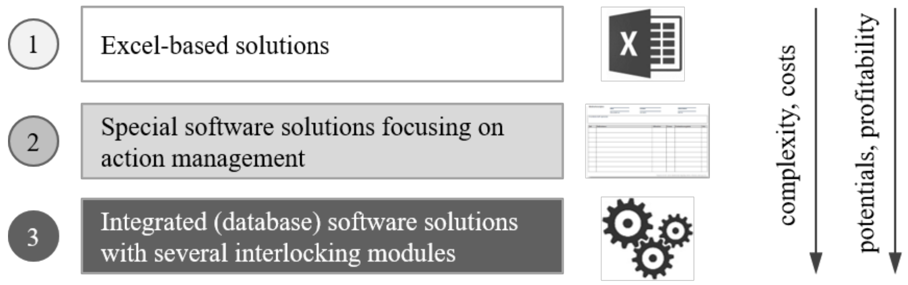


Figure 2: Classes of software solutions for action management

Due to their numerous advantages and future-oriented potentials, the software group of “integrated (database) software solutions with several interlocking modules” is considered in more detail below. In the context of action management, the two software groups of CAQ/ QMS (CAQ: Computer-Aided Quality Assurance, QMS: Quality Management System) software and IMS software are exemplary presented.

CAQ/ QMS software support companies to assure and improve the quality of their products, processes and services. Based on a central data backbone, different aspects of quality management like the definition and implementation of quality goals using specific QM methods and tools (QM: quality management) can be realized in an effective and efficient way. Moreover, CAQ/ QMS software enable companies to meet different customer- and standard-based QM requirements (such as according to ISO 9001). Nevertheless, focusing on SMEs, CAQ/ QMS software also have some drawbacks, foremost their complexity and the associated costs [9]. These two critical aspects refer not only to the purchase and maintenance of the software, but also to the training of the employees or to the information-technical integration of the software into the existing software environment of the company. Moreover, according to the knowledge of many change management projects, the great software complexity often leads to a lower user acceptance, which is a critical aspect to successfully introduce the new software in operational practice [10]. Companies need an appropriate IT strategy to answer the difficult question what topics and goals should be realized by what kind of software solutions or by what software modules. This situation is aggravated by the fact that you can realize different functions and topics by using different IT solutions [11]. For example, the implementation of action management can be realized either using respective modules of CAQ/ QMS or IMS software.

As shown in Figure 1, IMS software supports the integration of multiple management systems such as quality management and environmental management. It enables all management processes to be managed in a profitable way resulting in increasing quality, cost and time issues and it supports the fulfilment of requirements for various certifications (e.g. according to ISO 9001) by using one integrated IT platform. Apart from all these potentials, there are also some drawbacks using this kind of software similar to the use of CAQ/ QMS software solutions such as its complexity as well as quite high purchase, maintenance and integration costs.

As described above, all integrated software solutions like CAQ/ QMS software or IMS software have special foci and individual advantages and drawbacks. Therefore, the software selection should be aligned with the corporate strategy and the individual company requirements.

2.3 Implementation status in SMEs

The current situation in SMEs shows that there is often no systematic and seamless process to identify the causes of actions, to prioritize and implement the actions or to evaluate the recommendation for action in a consistent way. The assessment of the need for actions rarely takes strategies and goals into account, which often leads to insufficient effectiveness. There is often no systematic planning of the required resources and everyone (or every department) manages 'its actions' in different IT tools (e.g. Excel) using different standards and methods. Action prioritization is often done without a methodical basis, which not rarely leads to unnecessary discussions, chaos or even more important problems (e.g. if risk-related actions were incorrectly evaluated). As a result, there are often redundant works and poorly targeted actions with low effectiveness and efficiency. Counterproductive actions can cause additional efforts and lead to confusion. Due to missing transparency and incomplete monitoring and control methods, actions sometimes 'disappear', the tracking of actions is often not really comprehensible and a systematic CIP (CIP: continuous improvement process) is just rarely executed [12].

2.4 Requirements for the implementation of action management in SMEs

This section introduces the requirements for the implementation of action management in SMEs, which serve as common thread both for the evaluation of the implementation concepts (chapter 3) and the developed prototype (chapter 4).

The requirements for the implementation of action management in SMEs can be subdivided into three main groups: technical, economic and organizational requirements. All relevant criteria were gained and clustered by interviews of experts in the context of action management and by literature surveys such as [12].

The most important technical requirement is surely the fulfilment of all needed functions to plan, implement, monitor, control and report actions (e.g. use of an appropriate action plan). SMEs must ensure that their sensitive data (e.g. customer or internal data) is protected from unauthorized access and misuse. To support the SME's business processes, reliability is another important factor. Flexibility and a simple software customization (adaptations, extensions) is needed, as the SMEs' circumstances and needs may change over time. To realize a seamless, efficient and cross-sectoral dataflow, the used software should have appropriate workflow functions and it should be able to be smoothly integrated into the existing IT landscape (e.g. via appropriate interfaces) without causing too much efforts.

Due to the limitations of financial and human resources, economic requirements are also of great importance for SMEs. These requirements mainly refer to acquisition, training and ongoing operating costs.

Regarding organizational issues, a simple and intuitive usability as base for a sustainable user acceptance is a key requirement. In order to plan, monitor and control the actions, transparency, simple and efficient reporting possibilities and an adaptable authorization concept is very important. An authorization concept ensure that only authorized users or user groups can access and manipulate the respective actions to make changes.

Apart from the information-technical integration of the software solution, a low-effort introduction of the new software in the organization in the sense of a smooth change management is also of great importance.

3. Implementation concepts of action management in SMEs

3.1 Implementation concepts

In general, there are several possibilities and concepts to implement action management in operational practice. As shown in Figure 3, in this chapter three different implementation concepts are presented: 'use of decentrally organized, area-specific software solutions' (concept 1), 'use of a centrally organized, simple software solution" (concept 2) and 'use of a centrally organized, integrated software solution' (concept 3).

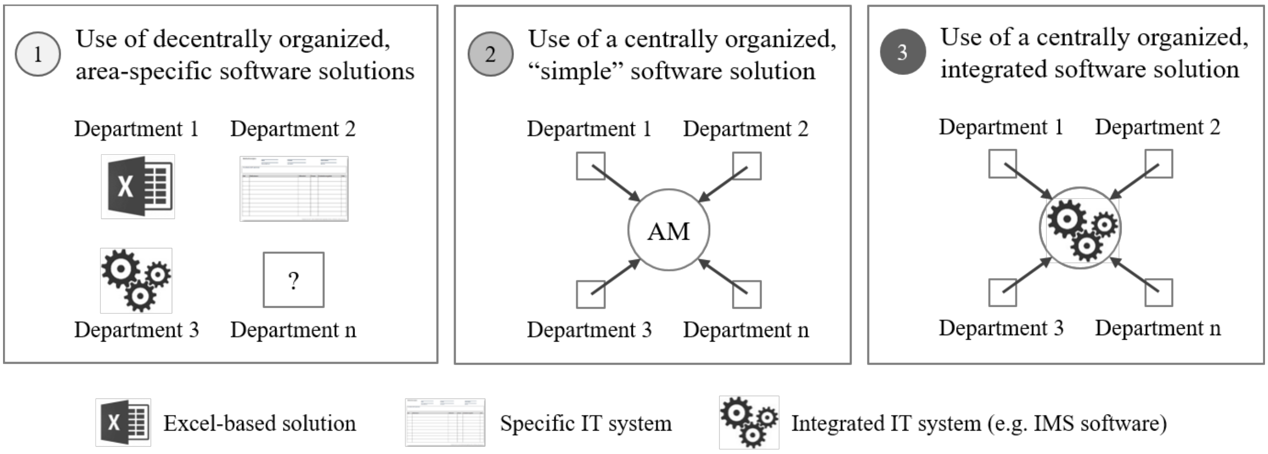


Figure 3: Implementation concepts for action management

In the context of concept 1, each department (e.g. production planning) decides for itself which software (e.g. Excel, special software) is best suited for action management, what enables better alignment with the needs of the business unit. The big advantage of using Excel as tool for action management is that it fundamentally works, every employee is familiar with it and there are no additional costs for the company. However, if action management is decentrally organized, there is no consistent, cross-sectoral procedure how to plan and implement actions. While department 'A' uses its specific software and procedure, department 'B' probably uses different ones. Therefore, it is hardly possible to realize an automated cross-sectoral workflow, there is no transparency about the whole action management process and there is also no possibility to get a central overview about all actions of the company, which lead to a significant loss in process effectivity.

From information-technical point of view, concept 2 could be exemplary realized by using MS SharePoint. Many companies already use such a centrally organized, 'simple' software like MS SharePoint, which saves additional costs. It offers a good and easy way to centrally store data and make it accessible to all employees in the company. Using a central software also makes it easier for IT administrators to make adaptations and upgrades, which simplifies monitoring and maintenance efforts. However, also such a 'simple' software solution like MS SharePoint can be quite complex and requires a certain level of IT knowledge to configure and customize it with regard to the needs of action management. To realize a seamless data flow, the central software solution has to be integrated in the existing IT environment (e.g. via links or via data interfaces).

The general advantages and disadvantages of using a centrally organized, integrated software solution like an IMS software was already discussed in chapter 2.2. By using a central data backbone, it is quite easy to import and export data to and from other IT tools, there is a consistent data management, automated workflows can be realized and a variety of reports and analyses are available. Apart from high acquisition and maintenance costs (e.g. to integrate this software into the existing IT environment), a further drawback is the dependence on the software vendor and low flexibility to adapt the software to the specific companies' needs.

3.2 Evaluation of the implementation concepts

To compare and evaluate the implementation concepts in an objective way, a cost-benefit analysis using the requirements from chapter 2.4 is used. The weighting of these criteria were done by experts using the method 'pairwise comparison' [13], the scoring is scaled from 1-5 points (5: best possible fulfilment) and KO criteria are defined. The cost-benefit analysis illustrates that the best implementation concept for action management in SMEs is the use of a centrally organized, simple software solution according to concept 2 (Table 1).

Table 1: Evaluation results of the implementation concepts using a cost-benefit analysis

criteria	KO	weighting	concept 1		concept 2		concept 3	
			points	value	points	value	points	value
technical		40		105		165		170
functions (e.g. action plan)	x	10	4	40	5	50	5	50
data security/ reliablity	x	10	3	30	4	40	4	40
flexibility/ adaptability		5	4	20	5	25	3	15
(cross-sectoral) workflow		5	1	5	4	20	5	25
integration	x	10	1	10	3	30	4	40
economic		30		135		135		70
acquisition costs	x	15	5	75	5	75	2	30
training costs		5	4	20	4	20	2	10
ongoing maintenance costs	x	10	4	40	4	40	3	30
organizational		30		106		128		120
simple usability	x	8	5	40	5	40	4	32
transparency		4	1	4	4	16	4	16
reporting		4	2	8	4	16	5	20
authorization concept	x	8	3	24	4	32	5	40
software introduction		6	5	30	4	24	2	12
total		100		346		428		360
ranking			3		1		2	

4. Information-technical implementation

4.1 Software-technical prototype

In general, there are several appropriate software solutions to realize the recommended implementation concept presented in chapter 3. One popular and widespread software that meets all these imposed requirements is MS SharePoint, which is used for developing the software-technical prototype.

As shown in Figure 4, the classification criteria for a defined action are for example its title, priority, status, topic and trigger. The 'action title' should be succinct to make the action clear to the relevant persons. The 'action priority' specifies the importance and urgency of the action; it can be exemplary carried out by using the Eisenhower principle [14]. The 'action owner' has to select the 'action status' ('open', 'in progress' or 'completed') and in the input field 'topic', an already existing topic can be chosen or a new one can be manually added. The action field 'trigger' describes the cause for the action. To make it as simple as possible, there are several preconfigured options such as 'audit deviation' or 'suggestion for improvement'. Further classification aspects, which are also realized in the developed prototype, are the associated 'management system' (e.g. 'quality management' or 'sustainability management'), a 'short description' of the action, the 'due date' when the action should be completed, the 'action owner' who is responsible for the implementation of the action and the 'effectiveness assessor'. If the verification is successful, the assessor confirms that status and the action gets the status 'completed'. To reduce the effort of data entry, not all input fields are declared as mandatory fields (marked with '*' in Figure 4). In order to pass the entire process of action management in a most profitable way, there is a defined workflow behind the whole procedure.

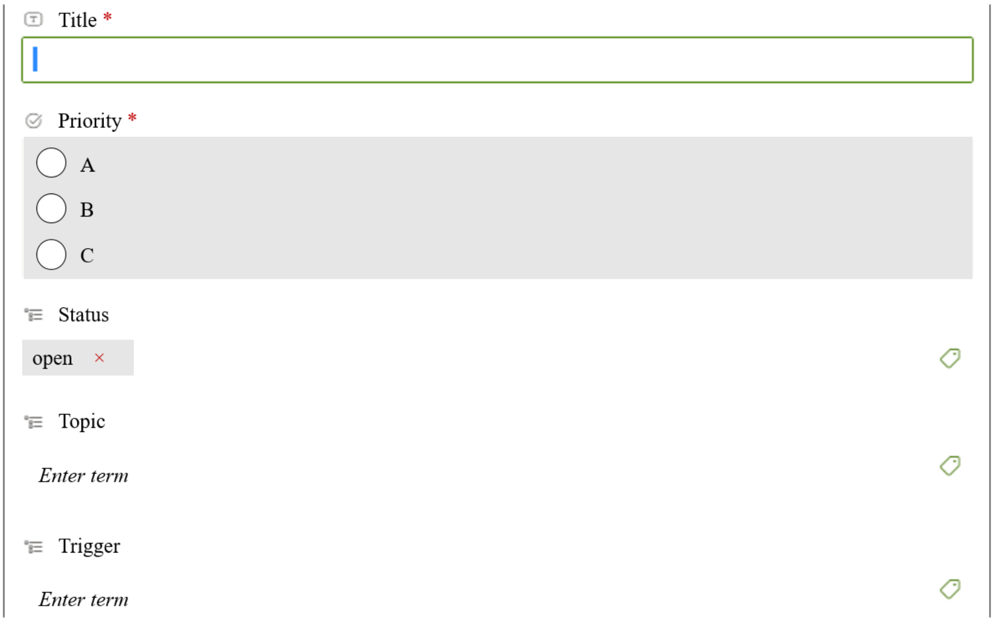


Figure 4: Extract of the software-technical prototype for action management using MS SharePoint

If the actions are created using the described procedure, there is the simple possibility to get a central and compact overview about all actions. Figure 5 exemplary shows such an overview about all available actions considering a special, preconfigured authorization role according to the defined authorization concept.

Actions

Title	Status	Priority	Topic	Management system	Due date
specify means of work	in progress	A	means of work	environment	31.03.2023
assess new packaging materials	in progress	A	packaging	sustainability	31.03.2023
check documents	open	B	documentation	quality	31.03.2023
introduce FMEA method	in progress	A	QM method	quality	30.04.2023
train employees	open	A	hazard	quality	30.04.2023
perform hazard assessment	open	A	training	information security	15.05.2023

Figure 5: Overview about all available actions in MS SharePoint

4.2 Evaluation of the software-technical prototype

As portrayed in Table 2, the developed prototype meets most of the technical, economic and organizational criteria in a quite good way. It impresses with its simple usability, its transparency, with a well established authorization concept and simple possibilities to introduce the software into operational practice. All basic functions of action management such as the seamless use and processing of an action plan are implemented and the requirements for the topics of data security, data reliability, flexibility and adaptability are mostly or even fully met. The use of seamless, cross-sectional workflows is fundamentally possible, even though there are some 'cosmetic' limitations (e.g. visualization possibilities). MS SharePoint can be easily integrated into existing IT environments and into defined processes without having too much effort (e.g. via defined links). So, the gaps between the used IT systems can be easily bridged. The possibilities of generating reports or graphical dashboards out of MS SharePoint are currently quite limited. However, for these purposes, there are technical possibilities to connect MS SharePoint to appropriate IT systems (e.g. to Power BI).

Table 2: Evaluation results of the developed prototype

criteria	KO	degree of fulfilment
technical		
functions (e.g. action plan)	x	●
data security/ reliablity	x	◕
flexibility/ adaptability		◕
(cross-sectoral) workflow		◕
integration	x	◕
economic		
acquisition costs	x	●
training costs		◕
ongoing maintenance costs	x	●
organizational		
simple usability	x	●
transparency		●
reporting		◔
authorization concept	x	◕
software introduction		◕

● Requirement fully met
◕ Requirement mostly met
◑ Requirement partly met
◔ Requirement met below average
○ Requirement not met

5. Summary, discussion and outlook

As presented in chapter 3, the most appropriate concept for action management in SMEs currently tends to be the use of a centrally organized, simple software solution like MS SharePoint. While the use of integrated software solutions like IMS software has great benefits in large industries, due to economic reasons its use is usually not (yet) worthwhile in SMEs. With respect to the pure need of action management, the technical possibilities of MS SharePoint are similar to the functionalities offered by powerful IMS software solutions.

However, the profitable implementation of action management is just one of various challenges that companies have to face. Further challenges like the profitable integrated implementation of different management systems like quality management, risk management or sustainability management have to be mastered – also within SMEs. In future, the objective will be less and less the development of very effective local solutions (like action management), but more about finding the most profitable overall solution from technical, economic and organizational point of view. And exactly that is the great strength of integrated software solutions.

It surely depends on the strategies, objectives, framework conditions and the risk appetite of each SME, but due to their great multifaceted potentials, integrated software solutions will certainly play an increasingly important role in future. Some meaningful advantages and potentials of such software solutions will be:

- Higher effectivity and efficiency using standards and AI (AI: Artificial Intelligence) algorithms [15]
- Simple realization of seamless, cross-sectoral workflows
- Simple and uniform visualization, analyses and reporting possibilities
- Simple information-technical integration due to standardized system interfaces
- Decreasing acquisition and ongoing costs due to tailored SME solutions
- Simple usability due to one uniform and user-focused software interface

The rapid developments in the fields of digitalization and AI will certainly contribute to the fact that the use of integrated software solutions like IMS software is becoming more and more profitable at an ever faster pace – also for SMEs. Apart from the development of all these (information-)technical potentials, the biggest challenges for SME will certainly be the smooth organizational introduction of these powerful software solutions aiming to a sustainable acceptance of their users. In this context, the topic of change management will be of great significance [16].

References

[1] DIN EN ISO 9001, 2015. Quality management systems – Fundamentals and vocabulary (ISO 9000:2015).

[2] Alwert, K., Will, M., 2014. Leitfaden Maßnahmen managen. Fraunhofer-Institut für Produktionsanlagen und Konstruktionstechnik IPK.

[3] Cockburn, T., 2009. Action Management: Strategies, Implementation, and Outcomes, SSRN Electronic Journal.

[4] Schaefer, J., 2018. "The action plan" – A planning-focused exercise, in: Proceedings of the Strategic Religious Peacebuilding conference, Washington.

[5] DQS Homepage, 2023. https://www.iso.org/management-system-standards.html, last accessed 2023/03/22.

[6] El-Haggar, S., Samaha, A., 2019. Sustainability Management System. Roadmap for Global Sustainability – Rise of the Green Communities, Springer, pp. 49-58.

[7] ISO Homepage, 2023. https://www.iso.org/management-system-standards.html, last accessed 2023/03/22.

[8] Koubek, A., Pölz, W., 2014. Integrierte Managementsysteme – Von komplexen Anforderungen zu zielgerichteten Lösungen, Carl Hanser Verlag München.

[9] Nguyen Duc, A., 2017. The Impact of Software Complexity on Cost and Quality – A Comparative Analysis Between Open Source and Proprietary Software, International Journal on Software Engineering and Application, vol. 8 (2), pp. 17-31.

[10] Nienhuis, J., 2014. Using Change Management to Improve CRM User Acceptance, School of Management and Governance & Electrical Engineering, Mathematics and Computer Science, University of Twente.

[11] Burr, H., Vielhaber, M., Deubel, T., Weber, C., Haasis, S., 2004. CAx/EDM-integration – enabler for methodological benefits in the design process, Proceedings of the 8th International Design Conference – DESIGN 2004, Dubrovnik, Croatia, pp. 833-840.

[12] Kölsch, R., 2012. Maßnahmenmanagement, DGQ Meeting, Karlsruhe, Germany.

[13] Ramik, J., 2020. Pairwise Comparisons Method – Theory and Applications in Decision Making. Springer; 1st ed. 2020 Edition, ISBN-13: 978-3030398903.

[14] Covey, S., 2012. Focus – Achieving Your Highest Priorities, Audio book.

[15] Kiefer, J., Ollinger, L., Precht, M., Beer, K., 2023. Potentials, limits and challenges of using data science methods to improve quality processes in manufacturing industry, Proceedings of the 17th Multi Conference on Computer Science and Information Systems, Porto, Portugal, pp. 269-276.

[16] Kotter, J. P., 2012. Leading Change, Harvard Business Review Press, ISBN: 978-1422186435.

Biography

Jens Kiefer (*1978) studied production engineering at the Saarland University. After finishing his PhD thesis in 2007, he had been working in different positions at Daimler in the fields of production planning, lean management and digitalization. Since 2013, Prof. Dr.-Ing. Jens Kiefer has worked for the University of Applied Sciences in Ulm. His teaching, research and consulting areas are quality management, process management, digitalization and integrated management systems.

Tara Rauch (*2000) studied production engineering at the University of Applied Sciences in Ulm. She wrote her bachelor thesis at Loacker AG/S.p.A., an Italian confectionery manufacturer based in South Tyrol, in the topic field of action management. Since March 2023, Tara Rauch has done a trainee program at Loacker in the field of procurement.

Valesca Zeller (*1995) studied industrial engineering at the University of Applied Sciences in Neu-Ulm. After finishing her B. Eng thesis in 2023, she started to work at Liebherr in the department of industrial engineering. Before studying, she completed an apprenticeship as a technical product designer at Electrolux. Valesca Zeller has held different positions in the fields of digitalization, production planning and lean management.

CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
CPSL 2023-2

5th Conference on Production Systems and Logistics

Enhanced Planning Of Production Plants: A Case-Based Reasoning Driven Approach

Daniel Syniawa[1], Robert Egel[1], Jan Schachtsiek[1], Alfred Hypki[1], Bernd Kuhlenkötter[1]

[1]*Ruhr-University Bochum, Chair of Production Systems, Industriestraße 38c, 44894 Bochum, Germany*

Abstract

Advanced industrial developments lead to increasingly customized products and shortened product life cycles. In the context of production systems, this necessitates faster engineering of suitable production resources and layouts to cope with the increasing product variety. Current engineering processes rely mainly on adapting already realized solutions and leveraging past experiences to address new project challenges. However, the knowledge about efficient planning processes is often tied to individual employees. These experiences cannot be utilized consistently, particularly in employee departure or absence due to illness. To counteract this problem, companies attempt to digitize and store knowledge in various ways. Nevertheless, the company-wide and person-independent retrieval of crucial information is still difficult or impossible. Influencing factors are, among others, non-standardized information models and forms of description. In response to these challenges, this paper introduces an approach for the standardized modeling and cross-company provision of experiences in production plant planning. Based on the paradigms of case-based reasoning and vendor-neutral data modeling using AutomationML, a system for selecting production resources and planning related layouts is demonstrated. By determining the similarity of new product structures, whose production facilities have yet to be engineered, with products whose production facilities are already realized, suitable existing solutions regarding production resources and their placement can be submitted explicitly to a planning expert. The approach is exemplified by a scenario of engineering an assembly system for electrolysis stacks. For this purpose, the similarity determination is performed using the Hamming similarity. Thus, it can be shown that case-based reasoning, which is already successfully used in other domains, has a significant potential to accelerate the subprocesses of production plant planning.

Keywords

Production plant planning; Case-based reasoning; Expert system; AutomationML; Knowledge management

1. Introduction

The manufacturing industry is influenced by significant changes related to current and future product structures and production systems. In particular, increasingly shorter product life cycles and the rising demand for individually customized products fundamentally influence engineering processes [1]. Consequently, this trend also affects the planning of suitable production plants. In the context of shorter development times, systems with increasing complexity – regarding the used resources, sensors, and software – must be newly designed or redesigned more frequently. Therefore, it is necessary to accelerate related engineering processes and support plant planners in crucial design decisions. The typical industrial approach of selecting appropriate production resources and defining their arrangement in an overall layout is primarily done in manual or semi-automated processes extending across departmental or company structures [2]. Previously developed or utilized production systems and related experiences are reused or adapted to meet new specific challenges. This can contribute to minimizing additional effort, risk, and in

DOI: https://doi.org/10.15488/15304
ISSN: 2701-6277

consequence costs. However, experiences and solutions from the past are often not accessible to everyone within the process chain. This is because relevant information is usually found in non-standardized directory structures and diverse data models. Further information is often not described or accessible in digital form, resulting in a massive loss of company-specific knowledge as an outcome of employee departure. As a result of the above depicted interrelationships, numerous approaches are researched to preserve knowledge or experiences throughout all company structures and make them available for specific use independently for individual stakeholders.

This paper demonstrates how the described issues in the field of production plant planning potentially be addressed by applying the paradigms of case-based reasoning (CBR) in combination with vendor-neutral standardized information modeling using AutomationML (AML). Based on this, planners can be provided with relevant experiences from past developments focusing on the processes of production resource selection and the planning of associated layout structures. This contribution is organized as follows. Section 2 gives an overview of already researched or existing approaches for efficiently planning production resources. Furthermore, the basic principles and related research concerning CBR are presented. Afterward, section 3 describes the application of a CBR cycle in the field of production plant planning. Using an example from the assembly of electrolysis stacks in combination with a developed tool for similarity determination of product structures, a possible application scenario of the shown approach is presented in section 4. Finally, section 5 draws conclusion and gives an outlook on future research.

2. State of the art

Various solutions have been developed to address the challenges in production plant planning. The following presents related research in production engineering focusing on selecting appropriate production resources and arranging them afterward. This will be extended by summarizing relevant works in the context of CBR.

2.1 Production plant planning

A variety of research work focuses on the effective selection of appropriate resources based on a matchmaking between production requirements and capabilities of production facilities. For example, in [3] and [4] requirements are extracted from product structures and the determined combination of requirements and production facilities is integrated into external planning tools or web services. In [5], a comparison between the mentioned elements is also done, but the implementation is pursued using an approach based on reinforcement learning. *Zimmermann et al.* present an advanced approach that includes not only a tool for selecting production facilities but also a concept for the optimized combination of individual resources into an overall system [6]. Furthermore, *Kathrein et al.* focus on the selection using organized resource catalogs and the description of product, process, and resource in a suitable data model [7]. In the context of additive manufacturing, [8] demonstrates a knowledge-based framework that focuses on securing expert knowledge to accelerate planning processes. Another group of research works focus on simulation-based planning of production layouts [9,10] or are using modern technologies such as augmented or virtual reality for planning tasks [11,12]. A template-based planning process for modular production facilities is shown in [13]. Furthermore, [14] depicts a methodology for automatically creating initial production layouts and [15] presents a web platform for the configuration of automated production systems based on engineering information described manufacturer-independent in AML. In the context of layout planning various approaches and algorithms are getting explored to solve arrangement challenges. In this field, heuristic methods and increasingly AI-supported systems are mainly used [16]. Nevertheless, these solutions do not have the goal of creating complex production plants with a variety of different production resources, but rather to determine an arrangement of production units in order to optimize a specific objective function, for example regarding to costs or transportation times between these units.

2.2 Case-based reasoning

CBR is an artificial intelligence paradigm based on the principle of similarity-based problem solving, where comparable problems require analogous solutions [17]. The fundamental methodological foundation of CBR can be explicitly described as "solving a problem by remembering a previous similar situation and by reusing information and knowledge of that situation" [18]. Rather than generating solutions through rule-based algorithmic manipulation, CBR retrieves relevant cases from a knowledge base and adapts them to the current problem context. The paradigm is based on the following two main principles: first, the premise that similar problems can effectively be resolved by comparable solutions, and second, the recognition that the types of problems encountered by an agent inherently tend to recur [17,19]. The primary research focuses on the efficient application of CBR in health science [20] and law [21], but also on different types of engineering activities. In the following, already investigated issues and research results concerning the application of CBR in engineering are summarized.

Various related works explore the potential applications of CBR for the detection, diagnosis, and resolution of faults or defects within the production. In [22], an approach for error diagnosis in the context of automated production systems and related logistics combining CBR with model-based reasoning, is presented. For the generation of the needed topological system model, AML, which is similar to the work of the present paper, is utilized. A comparable focus was set by *Khosravani et al.* [23], which use CBR to achieve error detection within the production of injection-molded drippers. Based on a similarity comparison between a newly appearing fault and past ones, suitable countermeasures are determined, contributing to reducing downtime in production. In [24], a system for the planning and efficient execution of maintenance work using CBR is presented. Further research work focuses on specific design challenges or planning of manufacturing processes. Thus, a system is presented that combines CBR with common product design methods, such as TRIZ, to support product developers [25]. Similarly in the context of product design, [26] depicts a CBR-based framework in the field of low-carbon product design that aims to address the conflict between product functionality and low-carbon issue. In the application area of process planning, approaches for manufacturing process selection [27] and assembly sequence planning [28] are presented, which apply an interaction of CBR with ontologies for knowledge representation.

It becomes clear that the application of CBR is getting explored in various industrial domains. However, a detailed examination of its usage in planning production resources and developing production layouts is currently missing. For this reason, the following section presents an approach to experience based production plant planning with a focus on the selection and arrangement of production resources by using CBR.

3. Case-based reasoning for plant planning

To explain the general application of CBR in the planning of production resources and necessary subsystems, a specific CBR cycle is derived from a generic cycle described by *Aamodt et al.* [18]. This provides the opportunity to initially explain and demonstrate the basic functionality of the approach before focusing on the individual process steps as well as associated tasks. Figure 1 illustrates the cycle specifically for production resource planning.

In general, the input of the depicted cycle consists of any description form of a problem. In this specific cycle, the problem description corresponds to a new product, represented in Figure 1 as an electrolysis stack for which suitable solutions, such as production resources for assembly, have to be determined and arranged in a layout. For this purpose, a set of permanently stored cases from the past is utilized. This set includes a combination of a problem and its solution. In the considered context, it consists of a product description and a set of production resources as well as layout information (see Figure 2). By applicating a suitable algorithm, the case that is most similar in terms of structure, characteristic properties and production requirements to the new given product is identified. Subsequently, this solution serves as an initial point for the engineering or decision support for the planning expert, who can implement necessary adjustments. Finally, the case base is supplemented with the newly developed combination of product and production system. The following subsections will demonstrate how the described subprocesses of the CBR cycle can be realized and continuously expand the case base.

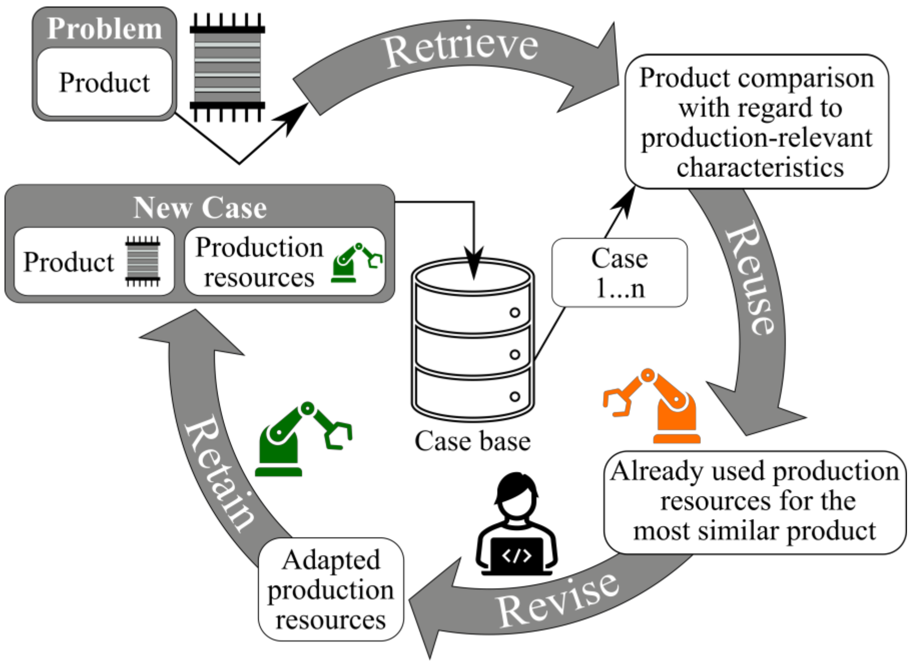


Figure 1: CBR-cycle for the planning of production resources

3.1 Case description

One crucial requirement for successfully applying the CBR approach described in the previous section is the targeted modeling and storage of information in a suitable standardized data model. This is necessary to facilitate a detailed comparison of different products. A suitable model allows to capture and provide experiences as well as expertise company-wide. Figure 2 illustrates the schematic structure of a set of information stored in the case base, consisting of product, associated production resources, and layout data.

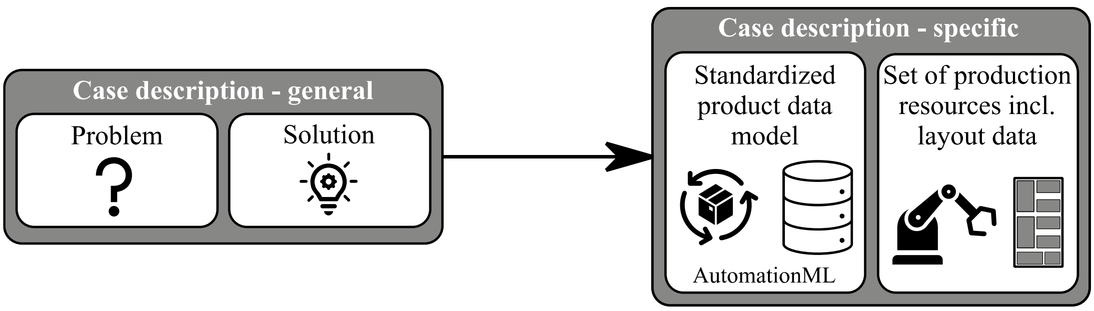


Figure 2: Case description as a combination of product and production resource information

The object-oriented modeling language AML, defined in IEC62424 [29], is used to model the product structures including related technical data. The main goal of AML is to enable a seamless data exchange across different engineering domains and tools. Thus, AML provides the opportunity to transform information into a unified machine-readable description independent of the industrial sector or data source. [30]

Figure 3 depicts how information about the product “ electrolysis stack” and how its connection to specific production resources as well as to the entire production system can be modeled. As shown, the parent product is divided into its subcomponents or individual parts. In this case into endplates, membrane electrode assemblies (MEA), bipolar plates and physical connectors or mechanical interfaces (e.g. screws or rivets). Furthermore, each product component – in a case description that already has a solution – is linked to one suitable assembly process. These resources contain assembly or manufacturing-specific sets of capabilities that meet the requirements of the processes, which also have a link to the appropriate production resources. Finally, the overarching production system, as a solution for a specific product, is composed of 1 to n production resources and a related layout description. The structures and information of the production system and resources can also be represented as AML data structures. Alternatively, based on the modeling capabilities of AML, external data in proprietary data formats can be referenced. If objects are prepared in a standardized data-technical manner according to the model described above, this offers the possibility of an efficient comparison of them. This can be done at the product level as well as the subcomponent and physical connector hierarchy levels to derive appropriate solutions for production resources based on similarities.

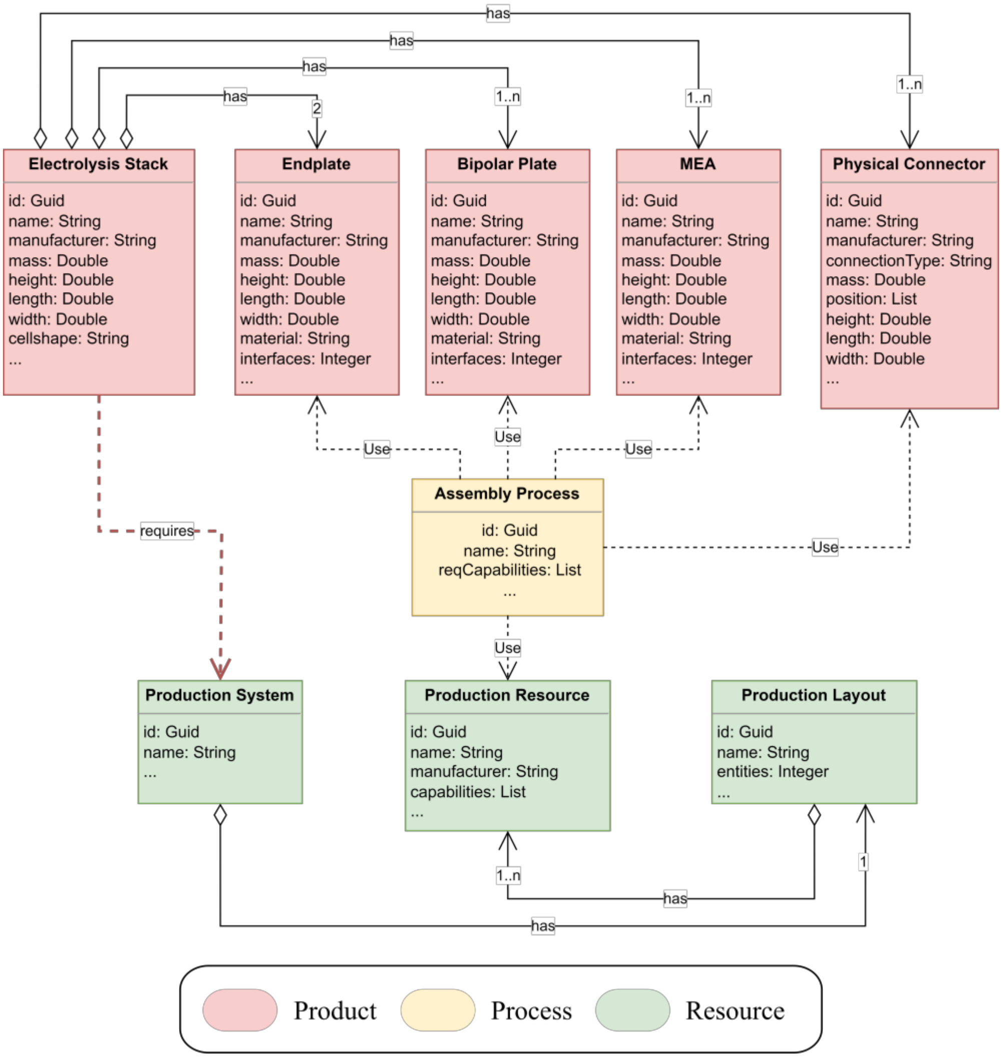


Figure 3: Data-model electrolysis stack - link between product and production resource

3.2 Determination of similarity

The aim of the similarity determination, which is necessary for the presented CBR cycle (see Figure 1), is to calculate a numerical measure that allows to assess whether multiple products are similar in terms of production-relevant factors. Two significant challenges emerge from this. These need to be addressed when implementing a suitable algorithm. First, it is necessary to define how individual technical parameters of a product, a subcomponent or a mechanical interface influence the selection of production resources and their arrangement. Second, an appropriate calculation procedure must be applied to determine a representative similarity measure.

A typical initial approach for calculating similarities in the context of CBR, intended to be applied in the following, is based on the inversion of the so-called Hamming distance (see Equation 1). Based on this, a generalized similarity measure (see Equation 2) can be established. It allows a comparison of variable values as well as the weighting of individual attributes. The weighting of the attributes and moreover the influence of single objects on the planning of the production plant can be done by the individual definition of α_i. As can be seen in the corresponding equation, the overall similarity between two objects is determined by summing the similarities of their attribute values.

$$distance_H(x, y) = \sum_{i=1}^{n} |x_i - y_i| \tag{1}$$

$$sim(x, y) = \frac{\sum_{i=1}^{n} \alpha_i \, sim_i(x_i, y_i)}{\sum_{i=1}^{n} \alpha_i} \tag{2}$$

As a result of the described relationships, the similarity of individual objects can be determined at different levels of the product hierarchy. This offers the advantage that different types of information can be presented to a planner depending on the comparison level, with varying levels of detail. For example, a comparison at the highest level of the product structure or in this case the stack level can be realized. As a result an initial overview of comparable production systems can be provided. This can supply insights into the required production resources and their quantities within the overall design. Furthermore, initial decision support regarding layout arrangement or estimation of required space can be generated. At lower levels of the product structure, which contain information about individual parts and connecting elements, solutions for different challenges can be identified. For example, by comparing the subcomponents and their attributes, a potentially suitable manipulator, such as an industrial robot with sufficient handling capacity, or an end effector for handling the respective component, can be determined. Additionally, through a similarity check of physical connectors and the corresponding interfaces of the components, a solution for selecting necessary assembly tools, for example bolting, welding, or riveting can be identified and presented. In the following, the example of an electrolysis stack is used to show the similarity determination of two products, considering the geometric dimensioning, weight and number of electrolysis cells. Table 1 lists the respective attributes and values of the products, which should be compared. In particular, it must be taken into account that the individual similarities $sim_i(x_i, y_i)$ of the single object attributes must be determined with individual calculation rules. In the presented example, the inverted distance between the attributes of two objects is normalized by the maximum distance within the complete case base concerning the specific attribute (see Table 1). This indicates that the two cases with the largest distance to the specifically considered attribute have a similarity value of 0. In the same way, two objects with identical attribute characteristics have a similarity of 1 concerning the attribute. By incorporating the similarities at the attribute level (refer to Table 1) into Equation 2, the computed similarity among the listed stacks (Stack 1, Stack 2) amounts to 0.8. The provided technical data is not specific to any particular product but serves only as an illustrative example. The similarity calculation between other objects on possibly other hierarchy levels can be realized analogously to the described procedure. However, the determination of the attribute-specific similarities must be individually adapted. This must be considered in particular in case of a comparison between not quantitative object characteristics, like the similarity determination of different connection technologies.

Table 1: Attributes for the exemplary similarity comparison of two electrolysis stacks.

Attribute	Weighting α_i	Similarities $sim_i(x_i, y_i)$ $x_i \triangleq Stack1, y_i \triangleq Stack2$	Stack 1	Stack 2	Max. distance
Mass (kg)	1	$sim_{mass}(x_i, y_i) = 1 - \frac{\lvert x_i - y_i \rvert}{\max(distance_{mass}(x, y))}$	80	125	500
Height (mm)	0,4	$sim_{height}(x_i, y_i) = 1 - \frac{\lvert x_i - y_i \rvert}{\max(distance_{heigth}(x, y))}$	500	700	1050
Width (mm)	0,5	$sim_{width}(x_i, y_i) = 1 - \frac{\lvert x_i - y_i \rvert}{\max(distance_{width}(x, y))}$	300	350	500
Length (mm)	0,5	$sim_{length}(x_i, y_i) = 1 - \frac{\lvert x_i - y_i \rvert}{\max(distance_{length}(x, y))}$	300	400	500
Cellnum. (n)	0,5	$sim_{cellnum.}(x_i, y_i) = 1 - \frac{\lvert x_i - y_i \rvert}{\max(distance_{cellnum.}(x, y))}$	25	40	30

3.3 Solution adaptation and case base extension

After determining the similarity between a new and past product description (see Section 3.2), the obtained results, including their corresponding solutions, must be adequately provided to the planner. This can be done in various ways. One option is to output only similarity values of the compared elements and indicate references to their solution. Furthermore, based on the comparison, additional assistance can be provided to the employee, such as the specific combination of production resources and individual subcomponents. For this purpose, it is no longer sufficient to compare only the characteristics of the overall products but to take component interfaces and physical connectors into account (see Section 3.2). This can be achieved by conducting an analysis of the similarity among physical connectors across various product structures, a factor that has already been taken into consideration in the provided data model. Necessary adjustments resulting from project-specific requirements of an existing similar solution can be made by the planner. This is done using a suitable tool specific to the company for resource and layout planning. Depending on the use case, this can range from a simple list of resources to complex detailed layouts in an appropriate engineering tool. Afterward, the newly generated case (see Figure 2) is included in the case base. Section 4 shows an exemplary representation of similarities and suitable solutions using a developed graphical user interface.

4. Application example

To represent the potential application of the CBR cycle as clearly as possible, an example application was implemented that visualizes the similarity determination between a new product and an existing case base. Figure 4 depicts the graphical user interface of the application. In the context of the application, information about the products and resources are entirely described and used in the form of the shown data model (see Figure 2). Ten product variants of electrolysis stacks were compared in the context of the considered example. The results are presented to the user in the most accessible form possible and are marked with corresponding colors. Furthermore, it is shown to what extent the different production systems meet the assembly requirements of the new product subcomponents and physical connection elements. In addition, the user can access referenced files in the form of listed resources and layout descriptions in their native data models. This provides a starting point for a plant planner to develop a suitable production facility, including the necessary resources and an initial layout. Moreover, the experiences regarding the overall system directly contribute to the selection and engineering of the sub-components as well as the associated knowledge is separated from individual employees. In this way, inexperienced employees can be supported in decision-making, allowing them to build on existing solutions efficiently.

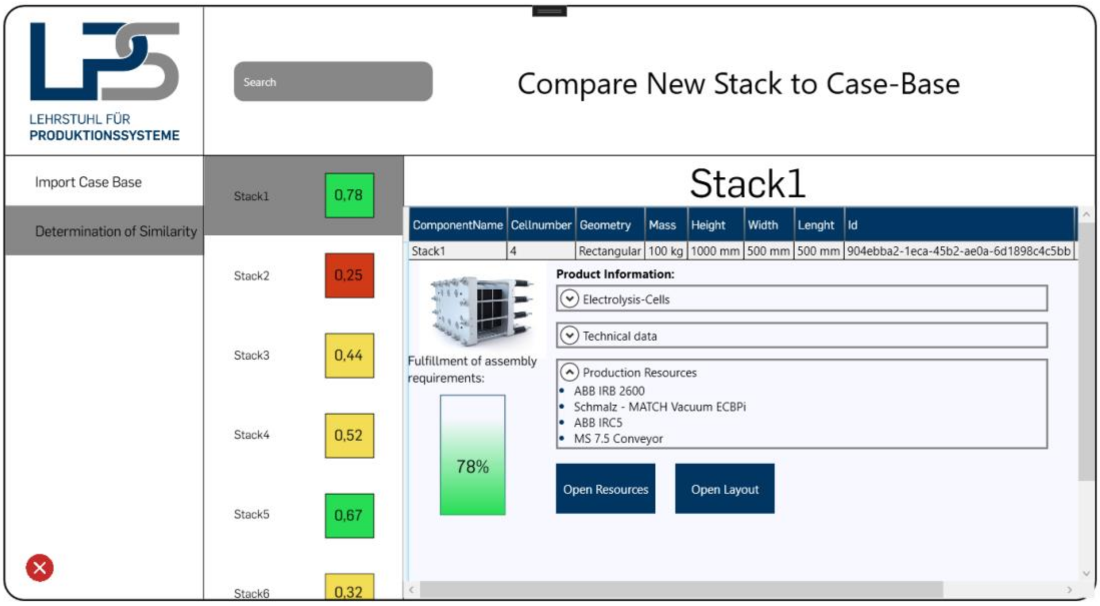


Figure 4: Expert System – Visual representation of similar cases and related production systems

5. Conclusion and outlook

The engineering of production plants is subject to industrial and social changes that have a massive influence on the associated subprocesses. Therefore, these processes have to be designed more efficiently through innovative solutions. This also applies to select suitable production resources and their arrangement in a layout. Hence, this paper demonstrates the application of CBR for the support of planning experts. Initially, the entire cyclic workflow of the overall planning approach is presented, followed by a detailed view of the necessary subprocesses. Based on the outlined systematic of a CBR cycle and the standardized case description using AML, it is possible to capture specific knowledge related to concrete engineering challenges and selectively retrieve it to assist employees in their decision-making. In subsequent research work, the individual subprocesses of the presented cycle can be examined and further developed in more detail. For example, a more profound similarity algorithm can be developed, or a lean and efficient case base regarding similarity determination can be realized. The demonstrated application scenario can be expanded to generate new production layouts based on the similarities of the subcomponents, their physical interfaces and required assembly skills, which can be presented to a planner as a more targeted planning foundation. Therefore, a potential approach involves a more intricate partitioning of the comprehensive production layout into discrete sub-components, exemplified by entities conveyor systems, sensors and robotic units. Consequently, the process can then discern a solution corresponding to each constituent, based on considerations of similarity. Nonetheless, this sequential approach introduces novel complexities, prominently including the assurance of seamless integration across all elements. This necessity the formulation of a fitting rule set or a system of constraints, effectively addressing the mentioned challenge. This could contribute to accelerate the engineering process in the described domain significantly. Future research focus especially on the combination of rule- and experience-based algorithms for the efficient planning of production plants and their evaluation.

Acknowledgments

This work was supported by the Federal Ministry of Education and Research (BMBF) through a collaboration between the projects H2Giga - HyPLANT100 (grant number: 03HY114B) and H2Giga - FertiRob (grant number: 03HY113A).

References

[1] Koren, Y., Gu, X., Guo, W., 2018. Reconfigurable manufacturing systems: Principles, design, and future trends. Front. Mech. Eng. 13 (2), 121–136.

[2] Westkämper, E., Spath, D., Constantinescu, C., Lentes, J., 2013. Digitale Produktion. Springer Berlin Heidelberg, Berlin, Heidelberg.

[3] Järvenpää, E., Siltala, N., Hylli, O., Lanz, M., 2019. Implementation of capability matchmaking software facilitating faster production system design and reconfiguration planning. Journal of Manufacturing Systems 53, 261–270.

[4] Mital, A., Siltala, N., Järvenpää, E., Lanz, M., 2019. Web-based solution to automate capability matchmaking for rapid system design and reconfiguration. Procedia CIRP 81, 288–293.

[5] Hagemann, S., Sunnetcioglu, A., Fahse, T., Stark, R., 2019. Neural Network Hyperparameter Optimization for the Assisted Selection of Assembly Equipment, in: 2019 23rd International Conference on Mechatronics Technology (ICMT). 2019 23rd International Conference on Mechatronics Technology (ICMT), Salerno, Italy. 23.10.2019 - 26.10.2019. IEEE, 1–7.

[6] Zimmermann, P., Gerber, K., Seyler, J.R., 2021. A Concept for Selecting Suitable Resources in Automated Assembly Systems, in: 2021 26th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), Vasteras, Sweden. 07.09.2021 - 10.09.2021. IEEE, 1–8.

[7] Kathrein, L., Meixner, K., Winkler, D., Luder, A., Biffl, S., 2019. Efficient Production System Resource Exploration Considering Production Requirements, in: 2019 24th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), Zaragoza, Spain. 10.09.2019 - 13.09.2019. IEEE, 665–672.

[8] Leiber, D., Hammerstingl, V., Weiß, F., Reinhart, G., 2019. Automated design of multi-station assembly lines. Procedia CIRP 79, 137–142.

[9] 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.

[10] Zuniga, E.R., Moris, M.U., Syberfeldt, A., Fathi, M., Rubio-Romero, J.C., 2020. A Simulation-Based Optimization Methodology for Facility Layout Design in Manufacturing. IEEE Access 8, 163818–163828.

[11] Tan, C.H., Yap, H.J., Musa, S.N., Chang, S.W., Sivadas, C.S., Hisaburi, A.S., Liew, K.E., Ismail, A.H., Baharudin, L.H., 2021. Augmented reality assisted facility layout digitization and planning. J Mech Sci Technol 35 (9), 4115–4123.

[12] Egel, R., Lamers, L., Brisse, M., Kuhlenkötter B. Interoperable Layout Planning based on Production Module Containers in AutomationML (accepted), in: , IFAC World Congress 2023, Yokohama, Japan.

[13] Prior, J., Karch, S., Strahilov, A., Kuhlenkötter, B., Lüder, A., 2023. Template-Based Production Modules in Plant Engineering, in: Liewald, M., Verl, A., Bauernhansl, T., Möhring, H.-C. (Eds.), Production at the Leading Edge of Technology. Springer International Publishing, Cham, 652–663.

[14] Bartelt, M., Katzwinkel, F., Kuhlenkötter, B. Method to Automatically Create an Initial Layout for a Production System, in: , 1st Conference on Production Systems and Logistics, 324–331.

[15] Schäffer, E., Penczek, L.N., Bartelt, M., Brossog, M., Kuhlenkötter, B., Franke, J., 2021. A Microservice- and AutomationML-based Reference Architecture for an Engineering Configurator Web Platform. Procedia CIRP 103, 274–279.

[16] 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.

[17] Kolodner, J.L., 1991. Improving Human Decision Making through Case-Based Decision Aiding. AI Magazine 12 (2), 52–68.

[18] Aamodt, A., Plaza, E., 1994. Case-Based Reasoning: Foundational Issues, Methodological Variations, and System Approaches. AI Communications 7 (1), 39–59.

[19] Leake, D.B. (Ed.), 1996. Case-based reasoning: Experiences, lessons & future directions. AAAI Press, Menlo Park, Calif., 420 pp.

[20] Loh, H.W., Ooi, C.P., Seoni, S., Barua, P.D., Molinari, F., Acharya, U.R., 2022. Application of explainable artificial intelligence for healthcare: A systematic review of the last decade (2011-2022). Computer methods and programs in biomedicine 226, 107161 pp.

[21] Atkinson, K., Bench-Capon, T., Bollegala D., 2020. Explanation in AI and law: Past, present and future. Artificial Intelligence (289), 103387 pp.

[22] Zinn, J., Vogel-Heuser, B., Ocker, F., 2020. A concept for fault diagnosis combining Case-Based Reasoning with topological system models. IFAC-PapersOnLine 53 (2), 8217–8224.

[23] Khosravani, M.R., Nasiri, S., Weinberg, K., 2019. Application of case-based reasoning in a fault detection system on production of drippers. Applied Soft Computing 75, 227–232.

[24] Wan, S., Li, D., Gao, J., Li, J., 2019. A knowledge based machine tool maintenance planning system using case-based reasoning techniques. Robotics and Computer-Integrated Manufacturing 58, 80–96.

[25] Li, S., Li, Y., Li, W., Chen, C., 2019. An extended case-based reasoning method and corresponding product design process. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science 233 (19-20), 6673–6688.

[26] Zheng, H., Yang, S., Lou, S., Gao, Y., Feng, Y., 2021. Knowledge-based integrated product design framework towards sustainable low-carbon manufacturing. Advanced Engineering Informatics 48, 101258 pp.

[27] Mabkhot, M.M., Al-Samhan, A.M., Hidri, L., 2019. An Ontology-Enabled Case-Based Reasoning Decision Support System for Manufacturing Process Selection. Advances in Materials Science and Engineering 2019, 1–18.

[28] Shi, X., Tian, X., Gu, J., Wang, G., Zhao, D., Ma, L., 2023. A hybrid approach of case- and rule-based reasoning to assembly sequence planning. Int J Adv Manuf Technol 127 (1-2), 221–236.

[29] International Electrotechnical Commission, 2016. Representation of process control engineering - Requests in P&I diagrams and data exchange between P&ID tools and PCE-CAE tools. VDE Verlag, Berlin. https://www.vde-verlag.de/iec-normen/223713/iec-62424-2016.html. Accessed 25 July 2023.

[30] Drath, R., Luder, A., Peschke, J., Hundt, L., 2008. AutomationML - the glue for seamless automation engineering, in: 2008 IEEE International Conference on Emerging Technologies and Factory Automation. Factory Automation (ETFA 2008), Hamburg, Germany. 15.09.2008 - 18.09.2008. IEEE, 616–623.

Biography

Daniel Syniawa (*1996), M.Sc., works as a research assistant at the Chair of Production Systems (LPS) at the Ruhr-University of Bochum. His current research topics include the digitalization of engineering processes in electrolyzer production and standardized data models in the context of Industry 4.0.

Robert Egel (*1992) works as a research assistant at the Chair of Production Systems (LPS) at the Ruhr-University of Bochum and holds the position of project leader in the H2Giga - FertiRob project. In his research, he focuses on the areas of quality assurance and automated layout planning.

Jan Schachtsiek (*1999), M.Sc., works as a research assistant at the Chair of Production Systems (LPS) at the Ruhr-University of Bochum. His current research topics include the robot-assisted electrolyzer production as well as additive and subtractive manufacturing with industrial robots.

Alfred Hypki (*1963) has been chief engineer at the Chair of Production Systems (LPS) at the Ruhr-University Bochum since 2015. His main research activities are robot simulation, robot programming and human robot collaboration. Until 2009 he was a research assistant at the Institute of Robotics Research at TU Dortmund University, where he received his doctoral degree. From 2009 to 2015, he was chief engineer at the Institute for Production Systems at TU Dortmund University.

Bernd Kuhlenkötter (*1971) has been head of the Chair of Production Systems at Ruhr University in Bochum since April 2015. He received his doctoral degree in 2001 at Dortmund University. In April 2009, after working for ABB Automation GmbH as head of product management and technology, he took over the professorship for Industrial Robotics and Production Automation at TU Dortmund, where he founded the Institute for Production Systems in 2012 and acted as manager until March 2015.

CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
CPSL 2023-2

5th Conference on Production Systems and Logistics

An Investigation Of Cost-Benefit Dimensions Of 5G Networks For Agricultural Applications

Tim B. Walter[1], Kerstin Lörsch[1], Max-Ferdinand Stroh[1], Wolfgang Boos[1]
[1]FIR an der RWTH Aachen, Aachen, Germany

Abstract

The agricultural industry is facing unprecedented challenges in meeting the growing demand for food while minimizing its impact on the environment. To address these challenges, the industry is embracing technological advancements such as 5G networks to improve efficiency and productivity. However, the benefits of 5G technology must be weighed against the costs of implementing a suitable network.

This paper presents cost-benefit dimensions that are needed to assess the economic feasibility of implementing 5G networks for several agricultural applications. The paper describes the costs of deploying and maintaining a 5G network and the benefits of several 5G-specific use cases, including precision agriculture, livestock monitoring, and swarm robotics.

Using industry reports and case studies, the model quantifies the benefits of 5G networks, such as enabling new digital agricultural processes, increased productivity, and improved sustainability. It also considers the costs associated with equipment and infrastructure, as well as the challenges of deploying a network in rural areas. The results demonstrate that 5G networks can provide significant benefits to agricultural businesses and provide an overview about the cost factors. Both benefit and cost dimensions are analyzed for the 5G-specific agricultural use cases.

Keywords

5G; Smart Farming; Communication Technology; Sustainability; Industry 4.0

1. Introduction

Since its launch, 5G technology has become increasingly important, as evidenced by the rising mobile radio standard subscription rates. By the end of last year there were almost 1 billion subscriptions reported, almost twice as many as in 2021 [1]. The consensus is that, if it hasn't already, 5G technology will have an impact on practically all industries. The consumer goods, manufacturing, logistics, and agricultural industries are predicted to see the most changes because of 5G. Higher speeds and lower latency, for instance, will enable the use of augmented reality and virtual reality in the business-to-consumer (B2C) sector, enhancing the customer experience. For instance, cities could use Augmented Reality (AR) or Virtual Reality (VR) at tourist attractions or museums to provide more information, or "points of information" (POI). In contrast, better analysis of the real-time data accessible in industry helps lower machine downtime and establish production standards [2]. 5G technology will also have an expanding impact on agriculture, with "smart farming" as the fundamental concept. The application of information and communication technologies in agriculture is referred to as "smart farming." Unmanned aerial vehicles (UAVs), unmanned ground vehicles (UGVs), and wireless sensor networks all have a significant technological impact on smart farming [3]. For instance, huge fields can be observed and monitored from the air using UAVs. With no need for a large

DOI: https://doi.org/10.15488/15240
ISSN: 2701-6277
publish-Ing.

workforce, various status information like weed growth, concealed animals, insect infestation, and water can be automatically gathered. Due to its low latency, fast connectivity, and high data throughput features, 5G technology has a lot of potential, especially when used in conjunction with (semi-)autonomous vehicles, a huge amount of simultaneously used end devices or data streams used in real time.

The adoption of 5G has the potential to influence the agricultural sector by enabling advanced applications and enhancing operational efficiency. However, the financial implications of implementing 5G networks in agricultural companies remain largely unexplored. Although the decision to invest in 5G infrastructure involves substantial financial considerations, a comprehensive financial assessment of the associated costs and benefits is noticeably lacking. Agricultural companies need to evaluate the potential financial implications, including the initial investment required for infrastructure deployment, ongoing maintenance costs, and potential revenue streams or cost savings that can be generated by implementing 5G-enabled use cases. By conducting a rigorous financial assessment, companies can make informed decisions regarding the adoption of 5G and allocate their resources efficiently. In addition to the cost factors, it is also important to consider the potential benefits of implementing a 5G network and compatible technologies. For a final evaluation, it is necessary to consider both sides.

The research presented in this paper addresses the aforementioned issue by showing the current state of an ongoing research project and providing cost and benefit dimensions. At the outset, our attention will be directed towards addressing the research gap related to this subject. Subsequently, the use cased and detailed dimension of both benefits and costs associated with the implementation and utilization of a 5G network will be described. Lastly, an overview of forthcoming developments will be provided.

2. Methodology

The development of the proposed 5G cost and benefit dimensions was grounded in the method described subsequently. Initially, extensive desk research was conducted to collect information pertaining to 5G-specific use cases within the agricultural sector. Furthermore, insights from the research project 5G.NATURAL and other related research endeavours were utilized to refine these dimensions. Drawing upon the desk research findings and insights gleaned from the research projects, a deductive approach was adopted to deduce relevant beneficial factors associated with 5G technologies in agriculture. These factors were clustered into three dimensions in terms of content to enhance clarity and structure. Subsequently, these dimensions were applied to the use cases to elucidate the specific benefits for each scenario.

The identification of cost factors influencing the decision to implement 5G use cases was accomplished through a combination of desk research, practical research experience, and expert interviews. In the case of expert interviews, several professionals from the information and communication technology (ICT) industry, possessing practical expertise in implementing 5G networks, were interviewed. Leveraging these insights, we conducted an exemplary analysis of benefits and costs for the evaluation of 5G networks in the context of specific agricultural applications.

3. Research Results

In the following, the results of our research will be presented.

3.1 Research Gap

Despite the increasing interest in the integration of 5G technology within the agricultural sector, a significant research void exists concerning the comprehensive financial assessment of associated costs and benefits. While the potential advantages of 5G networks for advanced agricultural applications and operational efficiency are widely acknowledged, limited research has been conducted to run a rigorous financial evaluation. Specifically, there is a dearth of studies examining the initial investment required for infrastructure deployment, ongoing maintenance costs, and the potential revenue streams or cost savings that can be generated by implementing 5G-enabled use case in agricultural enterprise [4].

To date, only a small number of studies have addressed the issue of costs, and when they have, it has not been in the context of both 5G and agriculture. Existing research of 5G feasibility has focused on specify topics, such as an economic model for 5G drones in production, or another cost analysis for 5G drones in emergency situations [5,6]. Other research focused on an open source techno-economic assessment framework for 5G deployment but again there is no connection with agriculture [7]. Overall, there are a few sources that delve deeper into the costs, and even they do, the analysis is limited. Most studies merely acknowledge that 5G will incur higher costs compared to previous generations and emphasize the need to consider factors such as income levels, population density, and other socioeconomic influences [8–10]. Most surveys that focus specifically on 5G technologies in agriculture are mainly concerned with benefits and lack of cost aspects [11-16]. Table 1 shows the summary of surveys regarded in this research paper.

This research paper aims to fill this research gap by presenting the cost-benefit dimensions that evaluate the economic feasibility of implementing 5G networks for various agricultural applications. By describing both the costs and benefits of 5G networks, this study provides valuable insights for stakeholders in the agricultural industry. Furthermore, the dimensions serve as the basis for cost-benefit analysis models.

Table 1: Surveys to benefits and costs aspects of 5G applications in agriculture.

Survey	Kumar et al. [4]	Kiesel & Schmitt[6]	Hunukumbure & Tsoukaneri [5]	Oughton et al. [7]	Das & Damle [8]	Frank et al. [9]	Oughton et al. [10]	Aruubla-Hoyos et al. [11]	Bacco et al. [12]	Li & li[13]	Said Mohammed et al. [14]	Abbas et al. [15]	Irudaya Raj et al. [16]
Year	2022	2020	2019	2019	2023	2022	2019	2022	2018	2020	2021	2022	2021
5G Technology	●	●	●	●	●	◑	◑	●	◑	●	●	●	●
Benefits of 5G	●	◑	○	◑	◑	◑	○	●	●	◑	◑	○	●
Costs of 5G	○	◑	●	●	◑	●	●	○	○	○	○	○	○
Agriculture	●	○	○	○	○	○	○	●	●	●	●	●	●

●: Supported; ◑: Partially supported; ○: Unsupported.

3.2 Results

3.2.1 Benefit dimensions

In the following, general benefit factors from the application of a 5G network are discussed first. Three factors in particular stand out compared to existing 4G LTE technologies.

With speeds of up to 20 Gbit per second in the data rate, a significantly higher transmission rate is possible [13]. A lower latency of less than 1 millisecond makes real-time applications possible. The third factor is given by the higher density of the 5G network, with which significantly more devices can be networked in a physical area. It must be mentioned, that current 5G networks are not able to perform optimal in all three features at the same time. Optimizing a network for one feature weakens its ability for the others. The 5G network is to be understood to an end because it is only through the combined use with corresponding technologies that these advantages come to fruition. Examples include the use of autonomous machines, artificial intelligence or swarm logic [17].

The above factors, in combination with the deployment of 5G compatible technologies, enable a range of benefits that can be categorised into three dimensions. These are elaborated below in relation to the benefits for agriculture. The first dimension includes benefits in terms of **flexibility**. 5G technologies allow automated and autonomous machines due to the latency and transmission rate. As a result, farmers, for example during harvest, are less dependent on additional personnel, as fewer staff are needed, which counteracts the shortage of skilled workers and overall less physical effort is required [12,18]. In addition, machines can work autonomously due to real-time transmission and can thus be used in a target- and demand-oriented manner. In this way, optimal times for work can be chosen and the flexibility of farmers can be strengthened.

The second dimension concerns aspects of **security**. Since several devices can be connected over a 5G network and real-time transmission is possible, communication between the individual devices is increased, which can have a positive effect on various security aspects. The continuous ingestion and exchange of data provides greater resilience and increases the resilience of digital technologies in agricultural use [19]. Another security issue that can be improved with the use of 5G and related technologies are environment-related aspects by collecting weather or field data to detect arid lands or fire that can cause harm to fields or animals [11].

The third dimension covers the topic of **quality**. Due to the option to collect real-time data through sensors, these can be analysed and used as a basis for decisions or for predictions. Predictive analyses, for example, enable recommendations to be made regarding harvesting times, so that planning and the deployment of personnel and machinery can be optimised [16]. In addition, a 5G network can be used to implement technologies that ensure greater transparency through data analyses and thus make processes more sustainable and resource-efficient [20]. By the overall efficient use of 5G related technologies the operating costs, personnel costs and resource costs as well can be significantly reduced [14].

In chapter 3.2.4. the specific benefits related to the use cases are highlighted.

3.2.2 Cost dimensions of 5G network implementation and operation

The cost factors were collected as described in the methodology by specifying and implementing a rural 5G network and then validated through expert interviews. They and their dependencies are presented below.

Basically, 5G-specific costs can be divided into capital expenditures and operational expenditures. The former is subdivided into hardware, software, infrastructure, and service costs; the latter into service costs and licensing costs for the spectrum of bandwidth to be used. Most of the cost factors depend on the specific design of the network in terms of the area covered, the internal or external location of the network, the users involved, and the required performance and quality of the network.

In the experience of our research partners and other experts, it has been shown that use cases can be divided into small, medium, and large ones to estimate the costs. The classification is shown in Table 2. The actual costs incurred sometimes differ considerably by up to a factor of 4. An overview with the relative cost differences is shown in Table 3. They are derived from the practical experience of a research partner within 5G.NATURAL, who is from the ICT industry and has vast experience in implementing 5G networks. The network quality factor refers to whether the 5G network can use high-end features such as super low latency or high giga bit bandwidths. Correspondingly powerful hardware and software is currently expensive and not necessary for every application. However, it can be assumed that due to the technical further development of the products, a price relaxation can be expected in the next few years. It should be borne in mind that all prices are also a matter of negotiation and depend on the order quantity, the company, etc.

It should be noted that investment costs depend on whether a public or private 5G network is used. Since it cannot be guaranteed, especially in agricultural use cases, that the public networks will achieve sufficient coverage and quality everywhere in the field, in many cases it will have to be assumed that own private, possibly transportable 5G networks will be used. However, this entails higher investment costs.

Table 2: Criteria for determining the size of a 5G network.

Size of 5G network	Indoor area	Outdoor area	User
Small	1 acre / 4048 m^2	0.25 acre / 1012 m^2	20
Medium	5 acre / 20240 m^2	1.25 acre / 5060 m^2	50
Large	10 acre / 40480 m^2	2.50 acre / 10120 m^2	100

Table 3: Relative cost comparison of differently designed 5G networks

	Small		Medium		Large	
	Low/normal Features	High End Features	Low/normal Features	High End Features	Low/normal Features	High End Features
Indoor	1	2.0	1.3	2.9	1.9	3.9
Outdoor	1.1	2.4	1.4	3.2	1.9	4.1

Table 4 shows the individual cost factors identified for implementing a 5G network. Costs marked with an * are independent of the size of the network, the indoor and outdoor location, and the number of integrated end devices. Factors in brackets () are optional depending on the use case and are not mandatory. For a better overview, the factors were clustered into capital expenditures (CAPEX) and operational expenditures (OPEX). Note that service and license factors are divided between the two categories.

Table 4: Cost factors for implementing 5G networks.

	Cost Components	Line Items
CAPEX	Network Element	Core Hardware* (e.g., server, switch)
		Core Software & supporting Software*
		RAN Hardware (e.g., RAN, antenna, server, switch)
		RAN software & supporting software
		(Savings potential with split indoor and outdoor network)
		Fiber / Connectivity (passive component)
		5G end device (incl. SIM card)
	Network Element Redundancy	Core Hardware (e.g., server, switch)
		Core software & supporting software
	Infrastructure	Power Supply, cable layout, rack, tower installation, etc.
		(Cell on wheel / mobile antennas)
		(Internet / external network connectivity)

		(Remote connectivity infrastructure)
	Services and licenses	Requirement Capturing and solution design
		Procurement and delivery
		RF planning and optimization
		Deployment, Integration & testing
		Device onboarding and use case integration
OPEX		RAN software license renewal
		Core software license renewal
		Spectrum license
		Spectrum license renewal
		(Maintenance)
		(Additional infrastructure, rentals, energy costs etc.)

3.2.3 5G-specific use cases in agriculture

In the following, three 5G-specific use cases in agriculture are presented. A use case is considered 5G specific if it exploits the unique features and capabilities of 5G networks not provided by other mobile technologies equally. In particular, the three characteristics of low latency, high transmittable data rates, and high network capacity will be considered below for this purpose. [21]

Swarm robotics for harvesters: The first use case was elaborated within the 5G.NATURAL research project. Multiple harvesting and logistic machines manoeuvre over the field as a swarm, while harvesting or transporting crops from the harvesters to a collection station. All machines move autonomously, but can be controlled, if necessary, via a central unit installed at the edge of the field. The machines are connected to a platform and retrieve relevant data, such as a navigation map of the field including starting point, end point, rows of fields to be harvested, the position of the harvesting machines and a route. The use case is 5G-specific, as the real-time transmission of the waypoints and sensor data requires a high transmittable data rate and short latency times to be able to securely control the harvesting machines via 5G.

Condition monitoring using drones: In the second use case condition monitoring is conducted using drones, for example to monitor crop health or locate weeds [22]. Precision farming enables agricultural management decisions to be tailored locally and to treat a field as a heterogeneous instead of a homogeneous unit [23]. Waypoints are communicated to the drone to fly over the field by an edge server via 5G. A camera is attached to the drone that transmits large amounts of image data during flight to the edge server, which uses machine learning to analyse the crop health and detect weeds [24]. Outsourcing weed detection will save energy for computing power and weight for the same resulting in cheaper drones that have longer flight times. The use case is 5G-specific, as real-time transmission of image data requires a high transmittable data rate and short latency to control the drone over 5G [25].

Precision Livestock Farming (PLF): PLF involves the use of various sensors and actuators to improve management capacity for large groups of animals and relies on the collection and analysis of real-time. [26] In the third use case information on physiological conditions of animals is collected in real time. Cameras and on-animal sensors are used to collect information, e.g., on movement, heart rate and temperature, and transmit it via 5G to an edge computing device. Furthermore, information on grazing and resting behaviors as well as feed intake can be collected. On the edge device, the information is analyzed and abnormalities are transmitted to the farmers. [27] The use case is 5G-specific due to the large number of sensors using the 5G network, the high network capacity, and the high data rates to be transmitted.

3.2.4 Benefits and costs of use cases

In the following, the three use cases are each considered from the perspective of the benefit dimensions and cost specific aspects.

Swarm robotics for harvesters: In terms of safety, the use of 5G and related technologies has the benefit of collision avoidance. Through the networking of the machines via a 5G network and the real-time transmission of data, the location can be determined continuously. This prevents the machines from colliding with each other. Camera recordings and their transmission can detect people or animals in front of the machine. Due to the low latency, the direct transmission of a stop signal is possible, so that collisions can also be avoided here. In terms of quality, the swarm logic allows the use of many small harvesters instead of fewer harvesters that put less pressure on the soil. Due to the much higher accuracy with which autonomous robots operate, they can also harvest more precisely. Generally, the use of smaller and resource saving, autonomous harvesting robots enables new agricultural use cases with new potentials, e.g., sustainable, and economic mixed cropping farming. The consideration of the flexibility dimension shows a clear benefit from the possibility to use harvesting machines autonomously via a 5G network. Here, farmers are less dependent on the use of harvest workers.

For this use case, the outdoor area size is particularly relevant to dimension the 5G network and derive the costs. As it is a safety-critical application, since the harvesters are controlled via the 5G network, high data transmission rates, low latency and high reliability are essential. For this reason, the choice results in a more powerful and thus costly 5G network with high-end features. Beyond the essential components of a 5G network, the seasonality of harvests requires a mobile network and that may require infrastructure building costs, if necessary.

Condition monitoring using drones: The greatest benefit lay in the quality dimension. The use of drones, high-resolution camera images and the analysis of these enables the precise detection of weeds. Pesticides and herbicides can be sprayed precisely in this case, which saves resources on the one hand and protects the environment on the other. The precise detection is also a benefit for the safety dimension, as any diseases, which in the worst case mean crop failure, can be detected, and treated at an early stage. The amount of work and the associated deployment of personnel can also be reduced, as in the first use case. As the data is not processed on the drone itself, additional weight on it is saved, prolonging its range for each charge cycle.

High data transmission rates and low latency times are relevant to be able to transmit the image recordings and operate the drone via the 5G network. For this reason, the choice of a more powerful 5G network results in a more costly 5G network with high-end features. Beyond the essential components of a 5G network, it must be considered that the network could be mobile and may require infrastructure costs.

Precision Livestock Farming (PLF): This use case largely touches on the benefit dimensions of security and flexibility. The condition data transmitted gives farmers an overview of any diseased animals so that they can react quickly and take appropriate action. In this way, an extension to the entire herd can ideally be prevented and costs can be saved. Likewise, female animals that are about to give birth can be digitally monitored so that appropriate measures can be taken here as well. Determining the appropriate data eliminates the need for on-site visual monitoring, reducing labour costs.

This use case involves many animals, which means the amount of end user devices is large, albeit numerous sensors transmit a rather small amount of data over the 5G network, except for certain devices as cameras. Thus, the network capacity is crucial for a 5G networks design. In contrast, the indoor area of a barn is relatively small when compared to the first two outdoor use cases. Due to the required network capacity and the high data rates to be transmitted, a more powerful 5G network will be needed. If adjacent outdoor areas also need to be covered for the third use case, the area to be covered increases, but on the other hand, synergies and overlaps arising can be considered, which make the network expansion more cost-effective.

4. Conclusion and Outlook

This paper described the costs and benefits of implementing and using 5G networks in agricultural applications. These provide initial indications for both research and practice. As already pointed out in the research gap, many research papers deal with the costs and benefits of 5G in the agricultural context, but in isolation from each other. However, in order to understand both aspects and, above all, their interplay, it is necessary to bring the two factors into a common context. This paper offers a first approach that can serve as a basis for further research. This could, for example, be the quantification of the benefit dimensions to enable a more in-depth cost-benefit analysis. On this basis, precise cost-benefit models can be created that allow for a more in-depth analysis. By the end of 2023 a software based business case calculator is planned to be developed and published within the project 5G.NATURAL. The identified factors and use cases will be used as the basis for the software. For practical purposes, the dimensions provide reference points for farmers to create an initial awareness of a cost framework. In addition, concrete benefits in agricultural terms are shown that can drive the use of 5G technologies in agriculture.

Acknowledgements

We thank the ministry of economic affairs, industry, climate action and energy of the state of North Rhine-Westphalia for founding the project 5G.NATURAL - 5G networks for autonomous and resilient rural applications (founding code: 005-2108-0037).

References

[1] Möller, R., 2023. Ericsson Mobility Report. Ericsson.

[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), 1–10.

[3] Moysiadis, V., Sarigiannidis, P., Vitsas, V., Khelifi, A., 2021. Smart Farming in Europe. Computer Science Review (39), 1–22.

[4] Kumar, R., Sinwar, D., Pandey, A., Tadele, T., Singh, V., Raghuwanshi, G., 2022. IoT Enabled Technologies in Smart Farming and Challenges for Adoption, in: , Internet of Things and Analytics for Agriculture, Volume 3. Springer, Singapore, pp. 141–164.

[5] Hunukumbure, M., Tsoukaneri, G., 2019. Cost Analysis for Drone Based 5G eMBB Provision to Emergency Services, in: 2019 IEEE Globecom workshops (GC wkshps). Proceedings : Waikoloa, HI, USA, 9-13 December 2019. 2019 IEEE Globecom Workshops (GC Wkshps), Waikoloa, HI, USA. 12/9/2019 - 12/13/2019. IEEE, Piscataway, NJ, pp. 1–5.

[6] Kiesel, R., Schmitt, R.H., 2020. Requirements for Economic Analysis of 5G Technology Implementation in Smart Factories from End-User Perspective. Personal, Indoor and Mobile Radio Communications, 1–7.

[7] Oughton, E.J., Katsaros, K., Entezami, F., Kaleshi, D., Crowcroft, J., 2019. An Open-Source Techno-Economic Assessment Framework for 5G Deployment. IEEE Access 7, 155930–155940.

[8] Das, S., Damle, M., 2023. Implementation Challenges & Applications of 5G and Ecosystems, in: "2023 International Conference on Sustainable Computing and Data Communication Systems (ICSCDS)". 2023 International Conference on Sustainable Computing and Data Communication Systems (ICSCDS), Erode, India. 3/23/2023 - 3/25/2023. IEEE, pp. 1492–1499.

[9] Frank, H., Colman-Meixner, C., Assis, K.D.R., Yan, S., Simeonidou, D., 2022. Techno-Economic Analysis of 5G Non-Public Network Architectures. IEEE Access 10, 70204–70218.

[10] Oughton, E.J., Frias, Z., van der Gaast, S., van der Berg, R., 2019. Assessing the capacity, coverage and cost of 5G infrastructure strategies: Analysis of the Netherlands. Telematics and Informatics 37, 50–69.

[11] Arrubla-Hoyos, W., Ojeda-Beltrán, A., Solano-Barliza, A., Rambauth-Ibarra, G., Barrios-Ulloa, A., Cama-Pinto, D., Arrabal-Campos, F.M., Martínez-Lao, J.A., Cama-Pinto, A., Manzano-Agugliaro, F., 2022. Precision

Agriculture and Sensor Systems Applications in Colombia through 5G Networks. Sensors (Basel, Switzerland) 22 (19).

[12] Bacco, M., Berton, A., Ferro, E., Gennaro, C., Gotta, A., Matteoli, S., Paonessa, F., Ruggeri, M., Virone, G., Zanella, A., 2018. Smart farming: Opportunities, challenges and technology enablers, in: 2018 IoT Vertical and Topical Summit on Agriculture - Tuscany (IOT Tuscany). 2018 IoT Vertical and Topical Summit on Agriculture - Tuscany (IOT Tuscany), Tuscany. 08.05.2018 - 09.05.2018. IEEE, pp. 1–6.

[13] Li, T., Li, D., 2020. Prospects for the Application of 5G Technology in Agriculture and Rural Areas, in: 2020 5th International Conference on Mechanical, Control and Computer Engineering (ICMCCE). 2020 5th International Conference on Mechanical, Control and Computer Engineering (ICMCCE), Harbin, China. 25.12.2020 - 27.12.2020. IEEE, pp. 2176–2179.

[14] Said Mohamed, E., Belal, A., Kotb Abd-Elmabod, S., El-Shirbeny, M.A., Gad, A., Zahran, M.B., 2021. Smart farming for improving agricultural management. The Egyptian Journal of Remote Sensing and Space Science 24 (3), 971–981.

[15] Syed Muhammad Zaigham Abbas Naqvi, Shoaib Rashid Saleem, Muhammad Naveed Tahir, Shixin Li, Saddam Hussain, Syed Ijaz Ul Haq and Muhammad Awais, 2022. Role of 5G and 6G Technology in Precision Agriculture. environmental science proceedings 23 (3), 1–5.

[16] Fantin Irudaya Raj, E., Appadurai, M., Athiappan, K., 2021. Precision Farmin in Modern Agriculture, in: Choudhury, A., Biswas, A., Singh, T.P., Ghosh, S.K. (Eds.), Smart Agriculture Automation Using Advanced Technologies. Data Analytics and Machine Learning, Cloud Architecture, Automation and IoT, 1st ed. 2021 ed. Springer Singapore; Imprint Springer, Singapore, pp. 61–88.

[17] Seelmann, V., Abbas, M., Stratmann, L., 2020. 5G - eine Mobilfunkrevolution verändert die Industrie. UdZ Praxis.

[18] Horstmann, J., 2020. Digitalisierung und Vernetzung - Landwirtschaft im Wandel, in: Frerichs, L. (Ed.), Jahrbuch Agrartechnik 2019. Institut für mobile Maschinen und Nutzfahrzeuge, Braunschweig, pp. 1–8.

[19] Eberz-Eder, D., Kuntke, F., Schneider Wolfgang, Reuter, C., 2021. Technologische Umsetzung des Resilient Smart Farming (RSF) durch Einsatz von Edge Computing, in: Informatik in der Land-, Forst- und Ernährungswirtschaft. Informations-und Kommunikationstechnologie in kritischens Zeiten. 41. GIL-Jahrestagung, Potsdam. Gesellschaft für Informatik e.V., pp. 79–84.

[20] Bosse, S., Berns, K., Bosch, J., Dörr, J., Eichhorn, F.C., Eisert, P., Fischer, C., Gassen, E., Gerstenberger, M., Geringhausen, H., Heil, J., Hilsmann, A., Hirth, J., Huber, C., Hussaini, M., Kasparick, M., Kloke, P., Krause-Edler, H., Mackle, L., Magnusson, J., Möhrle, F., Möller, M., Pickel, P., Rautenberg, C., Schotten, H.D., Stanczak, S., Thiele, L., Ücdemir, H., Wania, A., Stein, A., 2021. Nachhaltige Landwirtschaft mittels Künstlicher Intelligenz - ein plattformbasierter Ansatz für Forschung und Industrie, in: Informatik in der Land-, Forst- und Ernährungswirtschaft. Informations-und Kommunikationstechnologie in kritischens Zeiten. 41. GIL-Jahrestagung, Potsdam. Gesellschaft für Informatik e.V., pp. 41–52.

[21] Ramraj Dangi, Praveen Lalwani, Gaurav Choudhary, Ilsun You and Giovanni Pau, 2022. Study and Investigation on 5G Technology: A Systematic Review. Sensors 22 (26), 1–32.

[22] Hafeez, A., Husain, M.A., Singh, S.P., Chauhan, A., Khan, M.T., Kumar, N., Chauhan, A., Soni, S.K., 2023. Implementation of drone technology for farm monitoring & pesticide spraying: A review. Information Processing in Agriculture 10 (2), 192–203.

[23] Finger, R., Swinton, S.M., El Benni, N., Walter, A., 2019. Precision Farming at the Nexus of Agricultural Production and the Environment. Annu. Rev. Resour. Econ. 11 (1), 313–335.

[24] Mario Vento, Gennaro Percannella, Sara Colantonio, Daniela Giorgi, Bogdan J. Matuszewski, Hamideh Kerdegari, Manzoor Razaak, Simone Diniz Junqueira Barbosa, Joaquim Filipe, Ashish Ghosh, Igor Kotenko, Junsong Yuan, Lizhu Zhou (Eds.), 2019. Computer Analysis of Images and Patterns, 140 pp.

[25] GSMA, KPN. Smart Farming: Weed Elimination with 5G Autonomous Robots, 12 pp.

[26] Cadero, A., Aubry, A., Dourmad, J.Y., Salaün, Y., Garcia-Launay, F., 2018. Towards a decision support tool with an individual-based model of a pig fattening unit. Computers and Electronics in Agriculture 147, 44–50.

[27] Odintsov Vaintrub, M., Levit, H., Chincarini, M., Fusaro, I., Giammarco, M., Vignola, G., 2021. Review: Precision livestock farming, automats and new technologies: possible applications in extensive dairy sheep farming. Animal: an international journal of animal bioscience 15 (3), 1–10.

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. Wolfgang Boos (*1975) is the head of the Institute for Industrial Management (FIR) at the RWTH Aachen University since 2023. Prof. Dr. Boos led the operations of the Laboratory for Machine Tools and Production Engineering (WZL) of RWTH Aachen University for 10 years. In addition to his current role as CEO he is involved in managing other entities of the RWTH Aachen Campus. His research focuses on sustainable production and circular economy.

5th Conference on Production Systems and Logistics

Organizational, Sociological and Procedural Uncertainties in Statistical and Machine Learning: A Systematic Literature Review

Nick Große[1], Maximiliane Wilkesmann[2], Andrea Bommert[3]

[1]*Chair of Enterprise Logistics, TU Dortmund University, Germany*
[2]*Sociology of Work and Organization, TU Dortmund University, Germany*
[3]*Department of Statistics, TU Dortmund University, Germany*

Abstract

Driven by the potential of digitalization, statistical learning and machine learning methods are commonly used for scheduling complex processes or forecasting in supply chain domains. However, trust in such methods is hampered by uncertainties in data quality, data exchange platforms, and data processing, affecting its traceability and reliability. Decision-relevant output provided by such methods is prone to trust issues in the data used for training, in the resulting model, and in the infrastructure in which the model is embedded. Considering the vulnerability of supply chains, wrong decisions have far-reaching consequences, raising the question of to what extent systems alone should be trusted for strategic, operational, and tactical decision-making. In this paper, we take a multidisciplinary perspective with the intention to analyze trust in statistical learning and machine learning methods from an organizational, sociological, and procedural perspective. The information base for this article is gathered through a systematic literature review. The central results of our research are a concept matrix comparing papers based on relevant criteria derived from literature and subsequent findings derived from this matrix. We encourage researchers in the fields of supply chain management, sociology, and statistics or machine learning to open up for interdisciplinary research and to build upon our findings.

Keywords

Trust; Uncertainty; Statistical Learning; Machine Learning; Supply Chain Management; Literature Review

1. Introduction

Supply chain actors are subject to vulnerability and interdependence of partners within a value network, in which trust becomes increasingly relevant [1]. In the era of digitalization and Industry 4.0, the omnipresent efforts of data collection and utilization provide companies with a decision basis for estimating the recent status and upcoming changes of asset conditions and processes [2]. As part of so-called decision support systems, companies use statistical learning and machine learning methods exemplarily for forecasting or classification [2]. Statistical learning and machine learning methods belong to the ubiquitous field 'artificial intelligence' (AI) [3]. Because most decision-makers in supply chain management are less experienced in statistics and computer science, ambiguity in their use is considerable [4]. Knowing when and why to trust such methods is mandatory to enable decision-makers to make resilient decisions under remaining uncertainty in the data and its further processing [4].

Our research deals with trust and uncertainty issues evoked by statistical learning and machine learning methods resulting from a lack of transparency about the interplay of the data, model, and the infrastructure in which it is embedded. However, considering only an organizational lens neglects a profound

DOI: https://doi.org/10.15488/15255
ISSN: 2701-6277

understanding of how and why uncertainties arise in statistical learning and machine learning methods at different levels (micro, meso, macro). Therefore, a complementary view from an organizational, sociological, and statistical or machine learning perspective (which we call a procedural perspective) is necessary. The research question of our article is: "To what extent do recent research activities investigate uncertainties from organizational, sociological, and procedural perspectives, considering the use of statistical learning and machine learning methods in the field of supply chains?". Our paper consists of the following structure: In chapter 2 we introduce relevant criteria for each perspective as related background. In the third chapter, we present the methodology and specifics of our literature review. In chapter 4 we visualize the results of our literature review with a concept matrix. We condense our findings intra- and inter-perspectively. Chapter 5 concludes our key findings and gives an outlook for future research.

2. Criteria on Trust and Uncertainty in Statistical Learning and Machine Learning

The triad of organizational, sociological, and procedural perspectives allows us to take a sociotechnical view on trust in statistical learning and machine learning methods. For each perspective, we present the related background and derive appropriate criteria, which provide the deductive framework for the systematic literature review.

2.1 Organizational Perspective on Trust and Uncertainty in Statistical and Machine Learning

From an organizational perspective, contributions differ to the underlying coordination structure, which is either an inter-organizational (market, network) or an intra-organizational (hierarchy) perspective [5,6]. With the era of Industry 4.0 and associated digitalization efforts, trust becomes relevant to information systems in buyer-consumer relationships [7]. For supply chain management (SCM), inter-organizational trust plays an important role, especially if dependencies with partners or third-party intermediates are involved [1]. The literature on trust is manifold. Trust can take different forms [8] and is affected over time [9]. Trustworthiness as an antecedent of trust can be affected by the triad interplay of ability, benevolence, and integrity [10]. According to Zaheer et al. [11], trust relates to a single person (interpersonal trust) or to an organization (inter-organizational trust). Once established, trust within a network contributes to reduced coordination effort [5] relevant for deciding about make-or-buy [12]. Artificial intelligence is considered as an instrument enhancing the competencies of decision-makers, but the effort to calibrate such tools varies with the complexity of the planning scenario (e.g. supplier selection, layout planning, etc.) [4]. To prevent the use of statistical and machine learning leads to an increase in ex-post coordination effort, such as subsequent follow-up discussions between supply chain partners, an understanding of the upcoming uncertainties and the extent of trust in such methods is required, before applying those for (inter-)organizational purposes.

2.2 Sociological Perspectives on Trust and Uncertainty in Statistical and Machine Learning

In sociology, trust and uncertainty are complex and multidimensional concepts. Trust in AI refers to the confidence, belief, and trust that individuals (micro level), organizations (meso level), or societies (macro level) place in AI systems, algorithms, and technologies. It includes the expectation that AI systems will behave in a trustworthy and reliable manner, taking into account their impact on individuals, communities, and society as a whole. In other words, when AI systems are implemented in social environments, they assume social roles, engage in social practices, and form social ties [13]. Social action is, in general, complex and involves a high degree of uncertainty and lack of control [14]. Thus, from a sociological perspective, it is important to consider how AI systems penetrate and transform social institutions, redefining social life in the process [15]. In the 1980s and 1990s, AI was discussed in sociology as a system of science and knowledge that attempted to make machines capable of doing what humans can [13]. AI's various applications are the subject of most recent studies [16–18]. One of the most debated issues in this context is whether AI threatens human (knowledge) workers or not. The goal of a sociological perspective is to understand how trust in AI is formed, maintained, or eroded, and how it affects social relationships, institutions, and power dynamics.

2.3 Procedural Perspectives on Trust and Uncertainty in Statistical and Machine Learning

Trust in AI models is necessary for their deployment in any application. In this paper, we consider statistical learning and machine learning methods which are an important subset of AI methods. Statistical learning and machine learning methods comprise classification and regression techniques that create models serving two purposes: prediction and interpretation. The focus of machine learning methods traditionally is predicting the target of interest for new data as accurately as possible. For statistical learning methods, the interpretability of the resulting models is of utmost importance as the aim is to understand the influence of the features on the target variable [19]. From a statistical learning and machine learning point of view, trust in a predictive model depends on its accuracy, its communication of statistical uncertainty, and its interpretability. Accuracy refers to the average quality of the model's predictions for new data. Knowing the accuracy of a model is essential for judging the credibility of predictions as well as any conclusions derived from the model [20]. Statistical uncertainty refers to the model's confidence in individual predictions and consists of epistemic uncertainty (model uncertainty) and aleatoric uncertainty (data uncertainty) [21]. Quantifying statistical uncertainty allows for assessing the believability of individual predictions as well as specifying ranges of plausible prediction values. The model's interpretability refers to the understandability of why a certain prediction is obtained for a certain input. While interpretability comes naturally for statistical learning methods, various tools for explaining complex black-box machine learning models have been proposed in the last decades [22].

3. Methodology: Systematic Literature Review

We follow the systematic literature review (SLR) proposed by vom Brocke et al. [23] to ensure a rigorous approach. Similar to [24], we transfer our findings into a concept matrix. Following [23], we define and review our scope, followed by the conceptualization of logic and the resulting literature research. The literature analysis and synthesis lean against the dimension proposed in the prior section (e.g. the criteria of each perspective). Based on the resulting concept matrix, we derive a research agenda for multidisciplinary research. Relating to [25], the focus of our SLR set on research outcomes with the goal of depicting central issues, organized conceptually, taking a neutral representation, and using general scholars with a representative, but not exhaustive coverage of literature.

Table 1 illustrates the process of our SLR. To ensure a high degree of coverage of literature, we use Scopus, Web of Science, and AISeL as preferred databases. Since Scopus allows the most complex constellation of keywords, we use it as the primary database and adapt the query to the possible functionalities of each database (such as limited wildcard operators, non-availability of near- or within-operators, etc.). We export the results of each database as a BibTex and merge them in the literature management program Citavi to remove duplicates. Then, we exclude non-available since we need access to data beyond the regular meta information (author, title, abstract, keywords) to ensure that the content is relevant to our research.

The literature review relates to queries conducted in June 2023. In the first iteration, we filter the paper by screening the title and abstract based on their contextual relevance, resulting in 48 papers. Subsequently, we select the papers based on a deep-dive analysis, in which we excluded papers that are out of our intended scope, leading to a remaining amount of 35 papers. We analyze and discuss our findings in the next chapter.

Table 1: Overview of the SLR

Database	**Scopus**	**Web of Science**	**AISeL**
Search String Composition	TITLE-ABS-KEY (("trust*" OR "quality uncertaint*" OR "uncertaint*") AND ("Machine Learning" OR "Data Mining" OR "Pattern Recognition" OR "Computational Intelligence" OR "Statistical Learning" OR "Statistical Modeling" OR "Predictive Modeling" OR "Supervised Learning" OR "Regression Analysis") AND ("Socio*" OR "Socia*" OR "ethics" OR (Human AND Interaction)) AND ("interorganization*" OR "interorganisation" OR "network") AND ("logistic*" OR "Supply Chain*" OR "product*" OR "maint*" OR "purchas*" OR "sales and distribution"))		
Notes to Search String	The search string above is the final query used for Scopus. The query deviates between WoS and AISeL due to functionality restrictions.		
Initial Results	345	46	36
Results: 1st Iteration	48		
Results: 2nd Iteration	35		

4. Findings and Discussion

Considering the publication year, 77% of the papers have been published within the last five years. An almost constant distribution over the years can be stated. This suggests that the research topic addressed in our paper retains a constant level of attention. In the next step, we analyze each perspective and underlying criteria (see section 2). Coming from different disciplines, we have chosen nine criteria for our review to provide a comprehensive assessment of our research topic. In addition, the nine criteria allow for a more in-depth assessment of different aspects, which can be particularly useful for a complex or multifaceted topic such as uncertainties in statistical learning and machine learning. Table 2 visualizes the findings through a concept matrix. For each perspective, we discuss the central findings, based on quantitative and qualitative material. Each of the selected paper addresses at least one criterion of each perspective.

4.1 Findings from an Organizational Perspective

From an organizational perspective, 71% of the papers deal with trust and trustworthiness. Relating to the coordination structure, 9% of the papers cannot be assigned to any [26–28]. Of the 32 papers, 25% address hierarchical, 6% market-based, and 65% network-based issues (including multiple assignments). While both market-based papers consider trust or trustworthiness, e.g. [29,30], it is only considered in 75% of the contributions assigned to hierarchy and in 65% of the ones relating to networks. 25% address topics related to the supply chain. All of them can be assigned to network-based content, e.g. [31–39]. However, only 33% of them mention trust or trustworthiness, e.g. [31,34,37], which are the only contributions covering content on all three criteria. This shows that there is scarce literature addressing trust-related issues in supply chain management using statistical learning and machine learning methods.

4.2 Findings from a Sociological Perspective

Facing the sociological perspective, about 85% of the papers are based on empirical research. Considering the engagement of AI in social practices, 34% of the papers address a macro-layer, 42% a meso-layer, whereas 22% consider a micro-layer (including multiple assignments). 8% of the paper cannot be assigned to any of them. Out of all 35 papers, there is no contribution elaborating on a sociological understanding of uncertainty. Analyzing the set of publications from a sociological perspective, it must be noted that the role of trust and uncertainty in social dynamics does not play a role in the literature review at this point in time. This is particularly evident in the lack of definitions of trust and uncertainty, although these concepts play a central role in the present papers. Thus, addressing societal concerns, ensuring responsible AI development and deployment, and promoting individual (micro-level), organizational (meso-level), and public (macro-level) participation in shaping AI policy and practice remains a gap in AI research.

4.3 Findings from a Procedural Perspective

Of the 35 publications presented in Table 2, 80% address predictive accuracy by discussing it on a conceptual level, e.g. [26,40,41], or by assessing the predictive performance of one or more models in their empirical study, e.g. [42–45]. 60% of the publications in Table 2 deal with the topic of statistical uncertainty. [27] propose a new approach for non-overly-optimistic uncertainty quantification. [46,47] account for uncertainty by providing confidence intervals instead of just point estimates. 69% of the publications in Table 2 broach the issue of interpretability. [32,48,49,33,46,34,47,30,50,39] create statistical models with the purpose of interpreting them in order to gain insight into the influence of features on the target of interest. [26,40,51,41,52] address the topic 'explainable AI' on a conceptual level. [28] provide an overview of methods for interpretable machine learning. [53] base the choice of learning method on the understandability of the resulting model for practitioners. 21% of the publications thematizing accuracy neither address uncertainty nor interpretability. Most of these are method comparison studies, e.g. [42,44,45,54]. 86% of the papers thematizing uncertainty and 75% of the papers thematizing interpretability also talk about accuracy, often because accuracy is an aspect commonly reported when elaborating on models in detail.

Table 2: Concept matrix
(H: Hierarchy, N: Network, M: Market; EM: Empirical; NE: Non-Empirical; MI: Mikro; ME; Meso; MA: Makro)

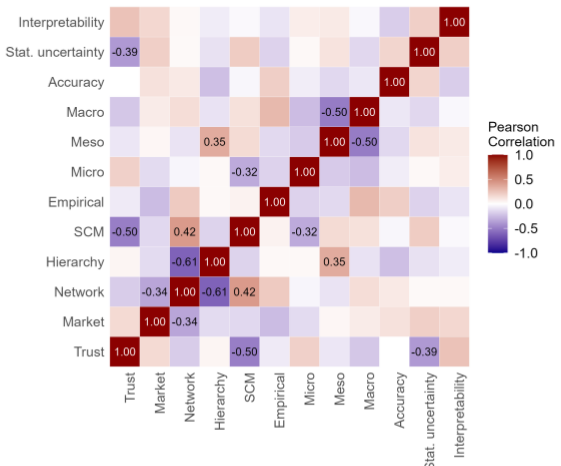
Sources	Publication Year	Perspective								
		Organizational			Sociological			Procedural		
		Trust or Trust-worthiness	Coordination Structure	SCM	Type of paper	Engagement of AI in social practices	Sociological understanding of uncertainty	Accuracy	Statistical uncertainty	Interpretability
[26]	2019	X			NE	MI		X	X	X
[27]	2022	X			EM			X	X	
[28]	2019	X			EM			X		X
[29]	2020	X	M		NE	ME		X	X	X
[30]	2022	X	M		EM	MA		X	X	X
[31]	2021	X	N	X	EM	MA		X		X
[32]	2018		N	X	EM	MA		X	X	X
[33]	2014		N	X	EM	MA			X	X
[34]	2011	X	H, N	X	EM	ME		X	X	X
[35]	2017		N	X	EM	ME		X	X	
[36]	2018		N	X	EM	MA		X		
[37]	2019	X	N	X	EM	ME		X	X	X
[38]	2021		N	X	NE	ME			X	
[39]	2018		N	X	EM	ME		X	X	X
[40]	2020	X	N		EM	ME		X		X
[41]	2023	X	N		NE	MI		X	X	X
[42]	2023	X	H		EM			X		
[43]	2015		H		EM	MA		X	X	
[44]	2021	X	N		EM	MA		X		
[45]	2019	X	N		EM	ME		X		
[46]	2017	X	N		EM	MI		X	X	X
[47]	2017	X	H		EM	ME		X	X	X
[48]	2017		N		EM	ME		X	X	X
[49]	2020	X	N		EM	MA			X	X
[50]	2017		N		EM	MA		X	X	X
[51]	2022	X	H		NE	ME				X
[52]	2023	X	H		EM	ME				X
[53]	2018	X	N		EM	ME		X	X	X
[54]	2020	X	N		EM	MI		X		
[55]	2020	X	H		EM	MI, ME, MA				X
[56]	2023	X	N		EM	MI				X
[57]	2020		H		EM	MI, ME		X	X	
[58]	2021	X	N		EM	MI		X	X	X
[59]	2019	X	N		EM	MA		X		
[60]	2021	X	N		EM	MA		X		X

4.4 **Overfall findings**

None of the publications in our analysis addresses all 9 criteria displayed in Table 2. Three publications address 8 criteria, nine publications address 7 criteria, eight publications address 6 criteria, twelve publications address 5 criteria, and three publications address 4 criteria. On average, the publications address 65% of the criteria stated in Table 2.

To analyze the intra- and interdisciplinary connections between the criteria stated in Table 2, we compute the Pearson correlation coefficients between all pairs of criteria using R [61]. We dummy-encoded the criteria with more than two categories and removed the constant criterion “sociological understanding of uncertainty” (for which the Pearson correlation is undefined). The Pearson correlation takes values from - 1 to 1. A negative correlation value indicates that only one (but not the other) encoded criterion is addressed in comparably many publications, whereas a positive correlation value indicates both or neither of the criteria being addressed in the same publication for comparably many papers. Table 3 illustrates the correlation matrix. To reduce the visualization to the most relevant results, we applied a threshold of ±0.30. Based on this, the associations of eight pairs of criteria are analyzed more closely in Table 3.

Table 3: Findings based on Pearson correlations and ±0.30 as threshold

Results	Analysis
	**<u>Organization only:</u>** 1. Network-like approaches correlate negatively with hierarchical approaches due to almost exclusive assignment (-0.61) 2. Market-like approaches correlate negatively with networks due to mutually exclusive assignment (-0.34) 3. Trust and SCM correlate negatively due to the high amount of trust-related literature outside the case of SCM (-0.50) 4. SCM and networks correlate positively due to the fact that inter-organizational networks are inherent in supply chains (+0.42) **<u>Sociology only:</u>** 5. Macro- and meso-layer correlate negatively due to the absence of intersecting or all-encompassing paper (-0.50) **<u>Organization and Statistic:</u>** 6. Statistical uncertainty and trust correlate negatively since statistical analyses incorporate statistical uncertainty but do not mention trust explicitly (-0.39) **<u>Organization and Sociology:</u>** 7. Hierarchical approaches correlate positively to meso-layer, since both terms address institutional facets (+0.35) 8. SCM correlates negatively to micro-level (-0.32) since the 8 papers about SCM are only focussing on network issues

5. Conclusion

The aim of this paper was to assess the extent to which the recent literature covers the triad interplay of organizational, sociological, and procedural perspectives in the context of trust in statistical and machine learning. To answer the question, we conducted a systematic literature review in which we assessed whether nine criteria introduced by us were addressed in the publications. Subsequently, we analyzed the results based on the Pearson correlations.

Our analysis has revealed several key insights and implications for both researchers and practitioners in the field. First, our findings suggest that the existing literature in supply chain management does indeed recognize the importance of the interplay between organizational, sociological, and procedural factors when it comes to trust in statistical learning and machine learning technologies. This recognition is crucial as it reflects a holistic understanding of trust dynamics in the context of modern supply chains, which increasingly rely on data-driven decision-making processes. Second, we have identified certain gaps in the current body of knowledge. We observed that none of the papers analyzed in our literature review addressed all criteria and that on average, the papers addressed 65% of the criteria. While there is a growing body of research that touches on these three perspectives individually, there is room for more comprehensive studies that explicitly explore how they interact and influence each other. Analyzing the associations between the criteria led us to insights such as that many statistical analyses incorporate uncertainty without mentioning explicitly the trust-building effects of these incorporations. Future research should aim to delve deeper into these interactions to provide a more nuanced understanding of trust dynamics in supply chain management. In addition, our analysis highlights the importance of considering the practical implications of these findings. Supply chain managers and decision-makers should be aware of the complex relationship between organizational culture, social factors, and procedural aspects when implementing statistical learning and machine learning technologies. Creating an environment that fosters trust requires not only investing in cutting-edge technology, but also fostering a culture of data literacy, transparency, and accountability.

Note that the criteria displayed in the concept matrix have been assessed independently. Thus, at the current stage, the overall findings make no claim of generalizability. A complementary analysis including inter-coder-reliability with more than one person assessing each perspective could give indications about the existence and extent of a subjectivity bias [62]. Building upon this, we encourage researchers to conduct more research from multidisciplinary perspectives with the intention to consider the interdependencies between all perspectives.

Acknowledgments

This research project is funded by the Chair of Enterprise Logistics at TU Dortmund University. A special thanks is directed to our student assistants Katharina Hast and Tobias Schrage supporting the authors during the literature review.

References

[1] Schmidt, C.G., Wagner, S.M., 2019. Blockchain and supply chain relations: A transaction cost theory perspective. Journal of Purchasing and Supply Management 25 (4), 100552.

[2] Schuh, G., Anderl, R. Dumitrscu, R., Krüger, A., Hompel, M. ten. Industry 4.0 Maturity Index: Managing the Digital Transformation of Companies - UPDATE 2020 - (acatech STUDY), Munich 2020.

[3] Ongsulee, P., 2017 - 2017. Artificial intelligence, machine learning and deep learning, in: 2017 15th International Conference on ICT and Knowledge Engineering (ICT&KE). 2017 15th International Conference on ICT and Knowledge Engineering (ICT&KE), Bangkok. 22.11.2017 - 24.11.2017. IEEE, pp. 1–6.

[4] Hoberg, K., Thornton, L., Wieland, A., 2020. Editorial: How to deal with the human factor in supply chain management? IJPDLM 50 (2), pp. 151–158.

[5] Powell, W.W., 1990. Neither Market Nor Hierarchy: Network Forms of Organization. Research in organizational behavior 12, pp. 295–336.

[6] Williamson, O.E., 1975. Markets and hierarchies: analysis and antitrust implications: A study in the economics of internal organization, 1. Free Press paperback ed., [4. Dr.] ed. The Free Press, New York, NY, 286 pp.

[7] Hawlitschek, F., Teubner, T., Weinhardt, C., 2016. Trust in the Sharing Economy. Die Unternehmung 70 (1), pp. 26–44.

[8] Nielsen, B.B., 2011. Trust in strategic alliances: Toward a co-evolutionary research model. Journal of Trust Research 1 (2), pp. 159–176.

[9] Lewicki, R.J., Bunker, B.B., 1995. Trust in relationships: A model of development and decline, in: Bunker, B.B., Rubin, J.Z., Oskamp Stuart (Eds.), Conflict, cooperation, and justice. Essays inspired by the work of Morton Deutsch, 1. ed. ed. Jossey-Bass, San Francisco, Calif., pp. 133–173.

[10] Mayer, R.C., Davis, J.H., Schoorman, F.D., 1995. An integrative model of organizational trust. Academy of management review 20 (3), pp. 709–734.

[11] Zaheer, A., McEvily, B., Perrone, V., 1998. Does trust matter? Exploring the effects of interorganizational and interpersonal trust on performance. Organization science 9 (2), pp. 141–159.

[12] Suematsu, C., 2014. Transaction Cost Management. Springer International Publishing, Cham, 298 pp.

[13] Liu, Z., 2021. Sociological perspectives on artificial intelligence: A typological reading. Sociology Compass 15 (3).

[14] Sztompka, P., 1999. Trust: A Sociological Theory. Cambridge University Press, Cambridge.

[15] Schwartz, R.D., 1989. Artificial Intelligence as a Sociological Phenomenon. Canadian Journal of Sociology / Cahiers canadiens de sociologie 14 (2), 179 pp.

[16] Brynjolfsson, E., McAfee, A., 2014. The second machine age: Work, progress, and prosperity in a time of brilliant technologies, First published as a Norton paperback ed. W. W. Norton & Company, New York, London, 306 pp.

[17] McClure, P.K., 2018. "You're Fired," Says the Robot. Social Science Computer Review 36 (2), pp. 139–156.

[18] Pettersen, L., 2019. Why Artificial Intelligence Will Not Outsmart Complex Knowledge Work. Work, Employment and Society 33 (6), pp. 1058–1067.

[19] Boulesteix, A.-L., Schmid, M., 2014. Machine learning versus statistical modeling. Biometrical journal. Biometrische Zeitschrift 56 (4), pp. 588–593.

[20] Yin, M., Wortman Vaughan, J., Wallach, H., 2019. Understanding the Effect of Accuracy on Trust in Machine Learning Models, in: Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems. CHI '19: CHI Conference on Human Factors in Computing Systems, Glasgow Scotland Uk. 04 05 2019 09 05 2019. ACM, New York, NY, USA, pp. 1–12.

[21] Hüllermeier, E., Waegeman, W., 2021. Aleatoric and epistemic uncertainty in machine learning: an introduction to concepts and methods. Mach Learn 110 (3), pp. 457–506.

[22] Molnar, C., 2022. Interpretable machine learning: A guide for making black box models explainable, Second edition ed. Christoph Molnar, Munich, Germany.

[23] vom Brocke, J., Simons, A., Niehaves, B., Niehaves, B., Reimer, K., Cleven, A., 2009. Reconstructing the giant: On the importance of rigour in documenting the literature search process. ECIS 2009 Proceedings. 161., pp. 2206–2217.

[24] Webster, J., Watson, R.T., 2002. Analyzing the past to prepare for the future: Writing a literature review.

[25] Cooper, H.M., 1988. Organizing knowledge syntheses: A taxonomy of literature reviews. Knowledge in Society 1 (1), pp. 104–126.

[26] Beil, M., Proft, I., van Heerden, D., Sviri, S., van Heerden, P.V., 2019. Ethical considerations about artificial intelligence for prognostication in intensive care. Intensive Care Medicine Experimental 7 (1).

[27] Martínez-Ferrer, L., Moreno-Martínez, Á., Campos-Taberner, M., García-Haro, F.J., Muñoz-Marí, J., Running, S.W., Kimball, J., Clinton, N., Camps-Valls, G., 2022. Quantifying uncertainty in high resolution biophysical variable retrieval with machine learning. Remote Sensing of Environment.

[28] Xiaocong Cui, Jung Min Lee, and J. Po-An Hsieh, 2019. An Integrative 3C evaluation framework for Explainable Artificial Intelligence. AMCIS 2019 Proceedings. 10.

[29] Forestal, R.L., Zhang, C.P., Pi, S.-M., 2020. Prediction markets: a systematic review and meta-analysis, i n: Proceedings of the 20th International Conference on Electronic Business, pp. 250–264.

[30] Reyes, J.A.L., 2022. Willingness to share information for energy efficiency: exploring differences and drivers across the Nordic countries. Energy, Sustainability and Society 12 (1).

[31] Anggraeni, M.C., Silaban, C.A., Anggreainy, M.S., Cahyadi, E., 2021. Role of Artificial Intelligence in the Management of Food Waste. 2021 2nd International Conference on Artificial Intelligence and Data Sciences, AiDAS 2021.

[32] Bernards, R., Morren, J., Slootweg, H., 2018. Development and Implementation of Statistical Models for Estimating Diversified Adoption of Energy Transition Technologies. IEEE Transactions on Sustainable Energy 9 (4), pp. 1540–1554.

[33] Cagliano, A.C., Marco, A. de, Mustafa, M.S., Zenezini, G., 2014. Analysing the determinants of logistics service provider efficiency in urban distribution. Proceedings of the Summer School Francesco Turco 09-12-September-2014.

[34] Lu, Y., K. Ramamurthy, 2011. Understanding the link between information technology capability and organizational agility: An empirical examination. MIS quarterly, pp. 931–954.

[35] Samet, A., Bouzembrak, Y., Lefèvre, E., 2017. Supply chain network design under uncertainty with evidence theory. Logistics Research 10 (1).

[36] Su, C.-J., Chen, Y.-A., 2018. Risk assessment for global supplier selection using text mining. Computers and Electrical Engineering 68, pp. 140–155.

[37] Swain, A.K., Cao, R.Q., 2019. Using sentiment analysis to improve supply chain intelligence. Information Systems Frontiers 21 (2), pp. 469–484.

[38] Tordecilla, R.D., Juan, A.A., Montoya-Torres, J.R., Quintero-Araujo, C.L., Panadero, J., 2021. Simulation-optimization methods for designing and assessing resilient supply chain networks under uncertainty scenarios: A review. Simulation Modelling Practice and Theory 106.

[39] Wiengarten, F., Longoni, A., 2018. How does uncertainty affect workplace accidents? Exploring the role of information sharing in manufacturing networks. International Journal of Operations and Production Management 38 (1), pp. 295–310.

[40] Burkhardt, D., Lasi, H., 2020. A conceptual model of data-driven solutions. AMCIS 2020.

[41] Knickrehm, C., Voss, M., Barton, M.-C., 2023. Can you trust me? Using AI to review more than three decades of AI trust literature. ECIS 2023.

[42] Alrashidi, M., Rahman, S., 2023. Short-term photovoltaic power production forecasting based on novel hybrid data-driven models. Journal of Big Data 10 (1).

[43] Chinde, V., Heylmun, J.C., Kohl, A., Jiang, Z., Sarkar, S., Kelkar, A., 2015. Comparative evaluation of control-oriented zone temperature prediction modeling strategies in buildings. ASME 2015 Dynamic Systems and Control Conference, DSCC 2015 2.

[44] Hansrajh, A., Adeliyi, T.T., Wing, J., 2021. Detection of Online Fake News Using Blending Ensemble Learning. Scientific Programming 2021.

[45] Kyriazidou, I., Drakopoulos, G., Kanavos, A., Makris, C., Mylonas, P., Bozzon A., Mayo F.J.D., Filipe J., 2019. Towards predicting mentions to verified twitter accounts: Building prediction models over MongoDB with keras. WEBIST 2019 - Proceedings of the 15th International Conference on Web Information Systems and Technologies.

[46] Kim, K.K., Sankar, P., Wilson, M.D., Haynes, S.C., 2017. Factors affecting willingness to share electronic health data among California consumers. BMC Medical Ethics 18 (1).

[47] Mundia, L., Mahalle, S., Matzin, R., Nasir Zakaria, G.A., Abdullah, N.Z.M., Abdul Latif, S.N., 2017. Prediction of employer–employee relationships from sociodemographic variables and social values in Brunei public and private sector workers. Psychology Research and Behavior Management 10, pp. 257–269.

[48] Burghardt, K., Alsina, E.F., Girvan, M., Rand, W., Lerman, K., 2017. The myopia of crowds: Cognitive load and collective evaluation of answers on Stack Exchange. PLoS ONE 12 (3).

[49] Čábelková, I., Strielkowski, W., Firsova, I., Korovushkina, M., 2020. Public acceptance of renewable energy sources: A case study from the Czech Republic. Energies 13 (7).

[50] Toulouki, M.A., Vlahogianni, E.I., Gkritza, K., 2017. Perceived socio-economic impacts of cooperative Intelligent Transportation Systems: A case study of Greek urban road networks. 5th IEEE International Conference on Models and Technologies for Intelligent Transportation Systems, MT-ITS 2017 - Proceedings.

[51] Gerling, C., Meier, P., Koehler, C., 2022. AI meets Digital: A Critical Review on Artificial Intelligence in Digital Entrepreneurship. ECIS 2022.

[52] Raftopoulos, M., Hamari, J. Human-AI Collaboration in Organisations: a Literature Review on Enabling Value Creation. ECIS 2023.

[53] Badami, M., Tafazzoli, F., Nasraoui, O., 2018. A case study for intelligent event recommendation. International Journal of Data Science and Analytics 5 (4), pp. 249–268.

[54] Wang, Q., Zhao, W., Yang, J., Wu, J., Zhou, C., Xing, Q., Plant C., Wang H., Cuzzocrea A., Zaniolo C., Wu X., 2020. AtNE-trust: Attributed trust network embedding for trust prediction in online social networks. Proceedings - IEEE International Conference on Data Mining, ICDM 2020-November.

[55] Anton, E., Behne, A., Teuteberg, F., 2020. The humans behind Artificial Intelligence-An operationalisation of AI competencies. ECIS 2020.

[56] D'Uggento, A.M., Biafora, A., Manca, F., Marin, C., Bilancia, M., 2023. A text data mining approach to the study of emotions triggered by new advertising formats during the COVID-19 pandemic. Quality and Quantity 57 (3), pp. 2303–2325.

[57] Roveda, L., Maskani, J., Franceschi, P., Abdi, A., Braghin, F., Molinari Tosatti, L., Pedrocchi, N., 2020. Model-Based Reinforcement Learning Variable Impedance Control for Human-Robot Collaboration. Journal of Intelligent and Robotic Systems: Theory and Applications 100 (2), pp. 417–433.

[58] Sander, T., Teh, P.L., Rocha A., Adeli H., Dzemyda G., Moreira F., Correia A.M.R., 2021. Reasons of Individuals to Trust What They Read on Social Network Sites. Advances in Intelligent Systems and Computing 1366 AISC, pp. 23–33.

[59] Varma, S., Sameer, N., Chowdary, C.R., 2019. ReLiC: entity profiling using random forest and trustworthiness of a source. Sadhana - Academy Proceedings in Engineering Sciences 44 (9).

[60] Vyas, P., Liu, J., El-Gayar, O., 2021. Fake news detection on the web: An LSTM-based approach. AMCIS 2021 Proceedings.

[61] R Core Team, 2023. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

[62] Landis, J.R., Koch, G.G., 1977. The Measurement of Observer Agreement for Categorical Data. Biometrics 33 (1), pp. 159-174.

Biography

Nick Große (*1992) is a postdoctoral researcher and research coordinator at the Chair of Enterprise Logistics at the TU Dortmund University. Accompanying his supervising and lecturing activities in the Department of Maintenance and Service Management, his research focuses on the empirical justification of trust in inter-organizational networks through innovative technologies and services.

ORCID: 0000-0001-8066-8796

Maximiliane Wilkesmann (*1975) is Heisenberg Professor of Sociology of Work and Organization and speaker of the College for Social Sciences and Humanities of the University Alliance Ruhr. Her research focuses on digitalization, work, organizations, knowledge, and the interactions among these research areas.

ORCID: 0000-0001-7111-7554

Andrea Bommert (*1991) is a postdoctoral researcher at the Department of Statistics of the TU Dortmund University. Her research interests include statistical learning and machine learning methods with a focus on feature selection and its stability as well as optimization, simulation, and data similarity.

ORCID: 0000-0002-1005-9351

CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
CPSL 2023-2

5th Conference on Production Systems and Logistics

Self-Optimization In Gear Manufacturing And Assembly For Automotive Electric Drive Production

Bastian Friedrich[1,3], Daniel Buschmann[2], 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]*BMW Group, Dingolfing, Germany*

Abstract

Due to the trend of electrification in the automotive industry, the economic production of electric drives with high acoustic quality requirements is a crucial factor to stay competitive in the global market. Low noise levels in the interior are an important criterion for the perceived quality of electric vehicles. Consequently, the noise generated by mounted gear components within integrated electric drive topologies must be minimized. Gears with unavoidable manufacturing deviations are usually randomly assembled, leading to random non-defined gear-related acoustic properties of the assembled electric drive. Furthermore, parameters of the gear manufacturing machines do not dynamically adapt to unknown changes in the production system leading to non-ideal quality output. To address these challenges, this paper presents a self-optimization concept in gear manufacturing and assembly in the production of electric drives by cognition enhanced control. A digital twin is developed which estimates the transmission error based on in-line measurements. Through optimization, an optimal selection of gear pairs is achieved. Based on quality predictions, adaptive control of the gear manufacturing process can be implemented, leading towards a closed-loop self-optimization of the production system. The concept is developed and validated using an exemplary use case from the commercial vehicle industry.

Keywords

Self-Optimization; Cognitive Control; Digital Twin; Gears; Electric Drive Production

1. Introduction

With the ongoing global focus on electromobility and the increasing demand and requirements, efficient and effective processes for manufacturing and assembling of components take on a decisive role in international competition. Due to the absence of the combustion engine's sound in electric vehicles, the overall noise level decreases significantly, bringing previously unnoticed noise sources such as ancillaries or the electric drive train into focus [1]. Consequently, new product requirements arise in the production of drive train components, including gears. Today quality-related backward loops are used in electric drive production, enabling a detection of noise related cause-effect relationships and consequently an implementation of counter measures in gear manufacturing [2]. However, since this process is carried out reactively, it could lead to a considerable delay in the use of information and hence in a waste of energy and resources due to production of scrap parts or loss in quality. Additionally, the random assembly of gear components is leading to undefined acoustic properties of the individual gearbox, caused by typical manufacturing deviations. With the ongoing digitalization in the context of Industry 4.0, self-optimizing systems in manufacturing and assembly show high potential to overcome these issues by integrating control systems with real time quality predictions in the production system. This publication therefore presents a self-optimization concept for

DOI: https://doi.org/10.15488/15277
ISSN: 2701-6277

model-based control by parameter optimization in gear manufacturing and selecting optimal gear pairs in the series production of electric drives, complementing the conventional quality backward loop. The paper is structured as follows: In section two, the state-of-the-art of self-optimizing production systems is described. Section three outlines the proposed concept to optimize the overall efficiency of the production system through self-optimization. Exemplary results are shown in chapter four followed by chapter five with a summary and outlook.

2. State of the art

Self-optimizing systems are control systems, which autonomously adapt their objectives based on internal decisions to achieve a certain result and therefore extend the capabilities of classical adaptive control [3]. Due to the potential to learn autonomously, self-optimization is closely related to the term cognition [4]. By processing and utilizing information from the production process, cognitive systems can adapt to their environment, allowing them to serve as a central component in a self-optimizing production system [5]. The enhancement of production systems with cognitive and adaptive capabilities is considered as paradigm shift [6], [7]. On a conceptional basis cognition enhanced control systems can be integrated in multiple levels within the production process [8]. Nonetheless, use-cases mainly focus on the optimization of process steps in either manufacturing [9], [10], [11] or assembly [12], [13], [14], [15], primarily aiming to optimize a parameter of that process step or a functional key characteristic (FKC) of the product to improve overall efficiency. Although a combined integration of adaptive control loops in manufacturing and assembly show potential to reduce overall production costs [16], [17], a simultaneous integration of selective assembly and adaptive manufacturing in cognition enhanced control systems has not yet been considered. With new acoustic quality requirements in gear production for automotive electric drives, manufacturing processes reach a technological limit. In complex serial production unknown environmental influences can cause a high number of possible failure states of the finished drives. Cognition enhanced control systems are able to adjust the parameters of the production system autonomously to changing environmental influences and thus have the potential for a self-adaptive optimization of tolerance chains in the production process [18]. In the following chapter the proposed self-optimization concept for cognitive control in manufacturing and assembly is introduced.

3. Self-optimization through cognitive control in manufacturing and assembly

Within this chapter a concept for a self-optimizing system based on a cognition enhanced quality control in manufacturing and assembly is introduced. The controller can adapt the objectives autonomously based on the current state of the production system and retrieve optimal gear manufacturing parameters as well as optimal gear pairings. The developed concept for a cognition enhanced quality control is shown in figure 2 with focus on adaptive manufacturing and assembly pairing strategies. Manufacturing deviations are unavoidable and can cause quality deviation of the final product. Therefore, inspections assure that individual components are within defined specifications. After storage the individual components are assembled to the final product. Further quality tests at the end of line ensure the specified quality fulfilment of the final product.

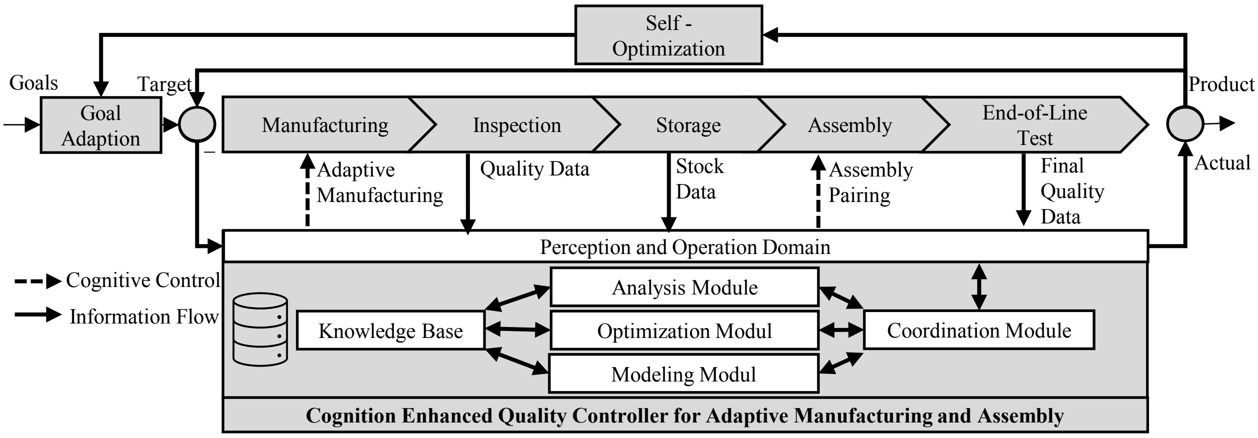


Figure 2: Self-Optimization through cognitive control in manufacturing and assembly.

In the bottom of Figure 2, the concept for a cognition enhanced quality controller is shown. The individual elements of the controller are related to the self-optimizing cognitive control according to [18]. The controller perceives the environment based on production data in near real time and monitors the current state of the production system. The controller retrieves measurement data from inspection in manufacturing as well as final quality data from end-of-line tests and traces the location of components and subassemblies in stock and upstream manufacturing processes. Considering external economic, environmental, as well as quality related boundary conditions, the cognition enhanced controller can take multi-criteria target values into account, which are used to autonomously find an optimum operating point for its production processes [10]. Based on the defined external objectives such as quality requirements, costs or throughput, internal objectives of the system can be derived [19]. Within the proposed concept internal objectives aim to optimize manufacturing by adaptive parameter adjustments and tool control, as well as selection strategies for the optimum component pairing for assembly. Based on function-oriented quality predictions and optimization ideal adaptive control parameters for manufacturing and assembly can be derived and fed back into the production system. Further information about function-oriented product models for quality predictions as well as the proposed control strategies for manufacturing and assembly are outlined in the following chapters.

3.1 Function oriented modelling approaches for predictive quality

To implement cognition enhanced control strategies, functional models need to be developed to enable the quality controller to predict the FKC of the final product based on the measured properties of the individual components. The objective is to model the relationship for each component of the assembly, described as a set of component related parameters $x_1,\dots,x_n$, to the FKC $f(x_1,\dots,x_n)$ measured at the end-of-line testbench at a quality critical operating point. The development of a function-oriented product model can be achieved by using different approaches including simulation or data driven advanced statistical approaches depending on the availability of accurate simulation models or sufficient level of information in the available measurement data. Since quality predictions based on simulation can be time consuming and thus not suitable for real time quality predictions, functional surrogate models can be developed and integrated in the knowledge base of the cognition enhanced controller. For the development of those models a calculus of variations can be used, incorporating the parameter space of possible production related tolerance distributions $\varphi(x_{i,j})$ for each parameter of a component as well as the simulation results of the FKC $f(x_1,\dots,x_n)$. In order to validate the simulation results, an evaluation with experiments is necessary [10]. Based on the simulation results regression-based surrogate-models can be trained and used for quality predictions in the controller. Next to simulation-based approaches, data driven approaches can also enable a functional model building for near real time quality predictions using measurements from the process. The model building in this regard is based on in-process measurement data and FKC quality data. Machine-Learning based approaches such as

Neural Networks, *Random-Forests*, *Support-Vector-Machines,* or other regression techniques can be used. The selection of an appropriate simulation- or data-driven approach finally depends on the ability to accurately predict the quality critical FKC of the assembled product with given boundary conditions of the production process. The integration of predictive models into the cognitive controller enables cognitive control strategies in manufacturing and assembly which are described in the following chapter.

3.2 Cognition enhanced quality control in manufacturing and assembly

Based on developed functional models near real time predictions enable the control system to select optimum parameter settings in manufacturing as well as ideal gear pairing strategy in gear assembly. The controller is therefore able to select an optimal option based on a set of possible solutions in terms of selective assembly or optimize its parameters and tools in manufacturing, see Figure 3.

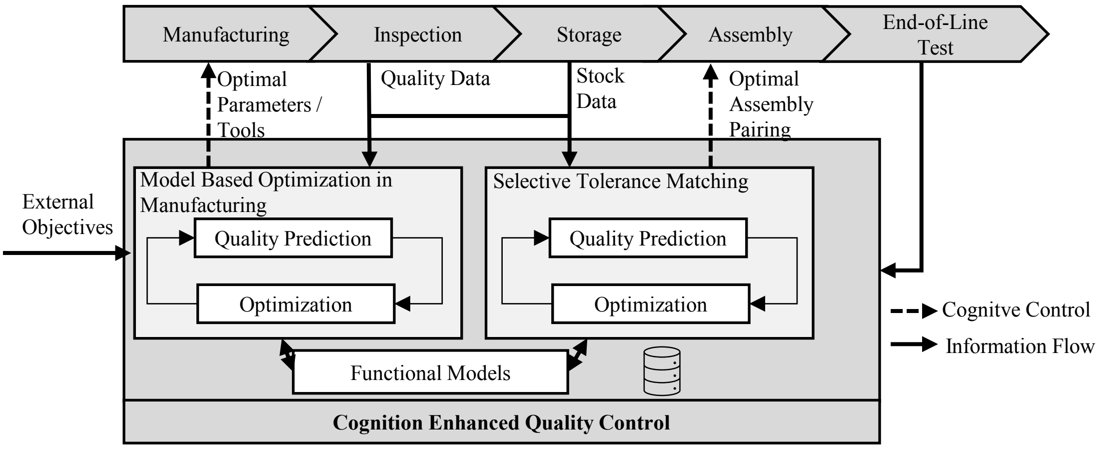


Figure 3: Cognition enhanced control in manufacturing and assembly based on function-oriented product models.

The focus of selective assembly is often on partitioning components in classes of certain width [20].The pairing of components without partitioning based on measurement values is called individual assembly [16], [21] or tolerance matching [12], [22]. The selective matching of parts with individual tolerance values based on the external objectives of the cognitive controller is referred to as selective tolerance matching in the following. One major element of selective tolerance matching is the ability of the controller to precisely predict FKC of the product based on the model $f(x_1,\dots,x_n)$, developed in chapter 3.2. The developed model gets incorporated into the knowledge base of the cognition enhanced quality controller. Given a set of component related in-line measurements for each part of an assembly $x_1,\dots,x_n$, and the developed meta-model, the controller is able to virtually assemble possible part combinations and assess the corresponding FKC $f(x_1,\dots,x_n)$ through quality predictions. By using the optimization module of the controller, the best match for a set of components is then selected regarding the defined strategies and external objectives.

With reference to [9] a model-based optimization of the manufacturing process can be achieved. Based on functional models the system compares the predicted and the targeted process result which eventually leads to a set of internal objectives such as parameter adaptions. A further example for the proposed cognition enhanced control in manufacturing is a dynamic process for tool selection. Since the characteristics of a certain tool are known, the system can predict the expected quality output of each tool and evaluate its accuracy regarding the actual quality output of the currently used tools. The decision to change a tool finally depends on the ability to optimize the overall efficiency production system defined by multiple external objectives, e.g., in a quality, yield and costs. In the following chapter the concept of cognition enhanced control is applied to an automotive gear manufacturing and assembly process for electric drive production.

4. Industry case study

The presented concept is validated on an automotive gear manufacturing and assembly process for electric drive production focusing on the improvements of noise and vibration characteristics of the electric drive through cognition enhanced control strategies.

4.1 Production process of highly integrated electric drives

The considered electric drive is highly integrated containing the stator, rotor, inverter, gearbox, and bearings in a central housing unit, see Figure 4. The electric machine is classified as an electrically excited synchronous machine. The gearbox consists of a two-stage gear reducing the rotational speed of the electric drive to the desired speed of the tires.

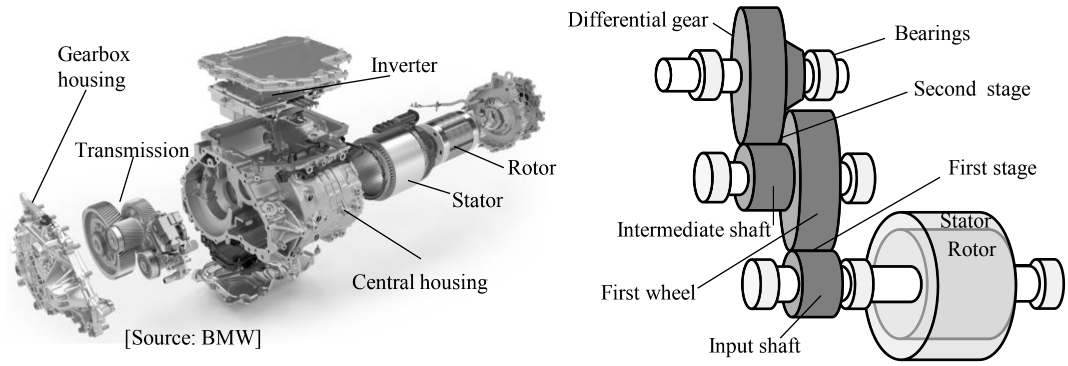


Figure 4: The considered automotive electric drive (left) and its schematic gearbox (right).

Within this case study the first stage of the gearbox has been evaluated. The manufacturing process of these gear components consists of multiple steps including turning, hardening and a final hard finishing step, optimizing the profile quality of the teeth before assembly. Based on a tactile coordinate measurement machine the profile of the gears is measured. Gear components are randomly assembled. Afterwards, the gearbox is assembled along with other components to a finished drive. At the end of the assembly process, the drive is tested for functional characteristics including acoustics. In this measurement step, structure-born noise is measured at certain speed ramps and loads using accelerometers at the housing. The permissible noise-levels are restricted by tolerance limits derived from customer requirements and vehicle tests. Applying the concept presented in chapter 3, the process is controlled by a conceptional cognition enhanced quality controller, see Figure 5.

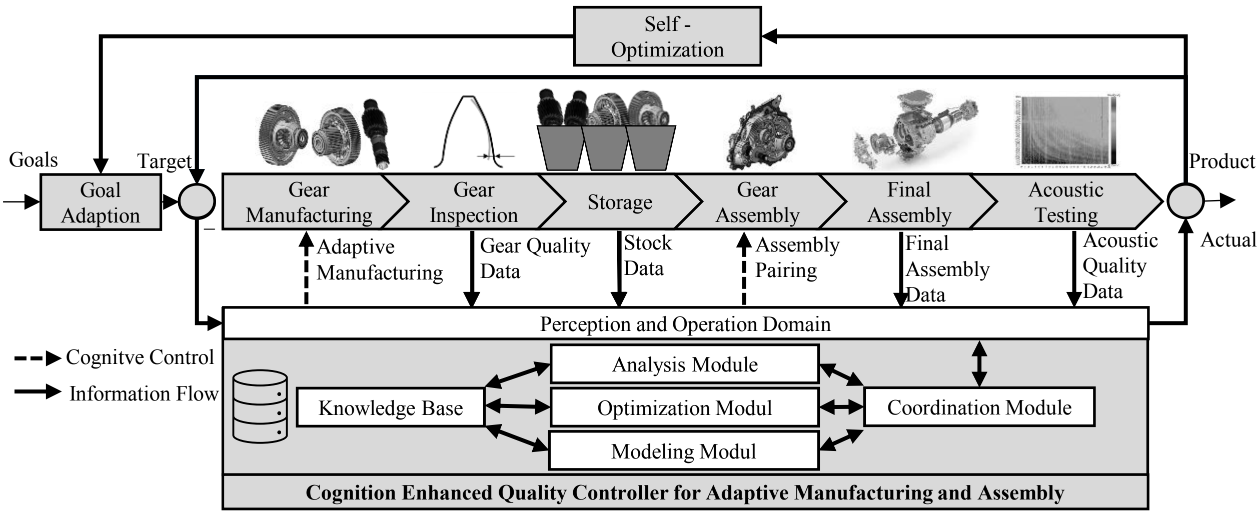


Figure 5: Self-Optimization through cognitive control in gear manufacturing and assembly for automotive electric drive production.

Due to manufacturing deviations caused e.g., by tool wear in gear finishing, systematic shifts in the final acoustic properties of a produced lot might occur. This can lead to critical noise at specific operation points of the engine and therefore to higher production costs due to rework, scrap parts, as well as waste of energy and material. Through a continuous analysis of the acoustic quality data, critical frequencies, speeds, and loads can be retrieved and optimization objectives can be adjusted. By means of cognitive control in gear manufacturing, parameters of the gear manufacturing process can be adjusted, or relevant tools can be changed. Based on the defined objectives and available measurement data, specific gear pairing strategies through quality predictions based on the individual topological properties become possible. Therefore, functional models need to be developed. The development of functional surrogate models is described in the following chapter.

4.2 Function oriented modelling

The objective of functional modelling in this case study is to model the relationship for each gear of an assembly, described as a set of gearbox related parameters $x_1,\ldots,x_n$, to parameters $f(x_1,\ldots,x_n)$ which correlate to gearbox related frequencies measured at the end-of-line testbench at a quality critical operating point. Therefore, a functional surrogate model is developed. A Monte-Carlo-Simulation (MCS) has been run, varying the gear micro geometry of the gear pairs in a defined range with a uniform distribution. Based on the variation of the gear pairs micro geometry, the peak-to-peak transmission error (TE) has been simulated at the quality critical speed and load, using the commercial CAE software *SMT MASTA*, see Figure 6.

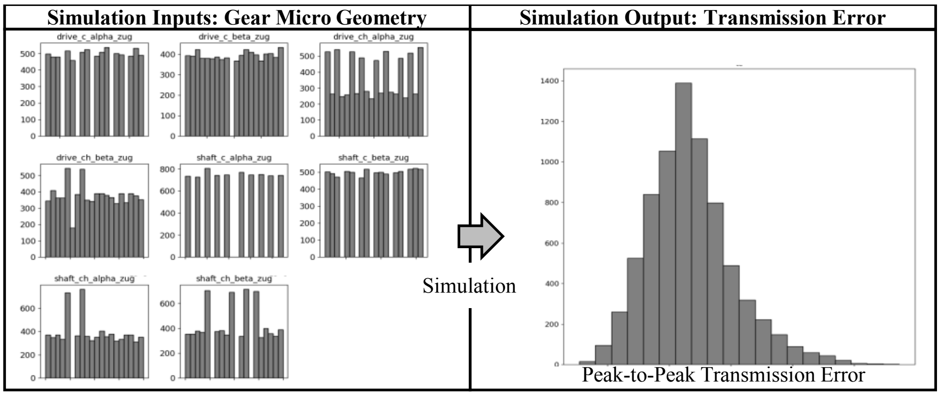


Figure 6: Gear micro geometry (left) and simulated peak-to-peak TE (right) using MCS.

Overall, 7500 variations have been calculated. The parameter range was chosen to cover typical manufacturing deviation in serial production. Since simulations are time consuming and thus are not suitable for in-process optimizations and quality predictions, the simulation results shown in Figure 6 have been used to develop a surrogate model. To find a surrogate with good precision for the simulation, different machine-learning algorithms were tested. After pretesting the scikit-learn implementations of *Histogram-based Gradient Boosting Regression Tree* [23], *Bagging Regressors* [24] and a *Random-Forrest* [25] were chosen for further optimization. Hyperparameters of these algorithms were tuned using grid search cross validation with ten folds. Therefore, the simulation results were split into a random training set containing 80 % of the samples and a test set containing 20 % of the samples. The best algorithm in training was defined by having the highest coefficient of determination, R^2, see Formular 1, The metric represents the proportion of variation in the dependent variable, which is predictable by the independent variables. To check the algorithms' ability for generalization, these surrogate models were used to predict the peak-to-peak TE based on samples of the test set. The mean squared error (MSE) was also calculated for the test sets. The results of these predictions can be found in Table 1.

Table 1: Accuracy results of the surrogate model with highest R^2 in randomized cross validation on train and test data

Algorithm	Hist. Gradient Boosting		Bagging Regressor		Random-Forrest	
Data set	Train	Test	Train	Test	Train	Test
R^2	0.86	0.88	0.79	0.80	0.79	0.80
MSE	---	0.0006	---	0.001	---	0.001

A mathematical definition of the metrics R^2 and mean squared error (MSE) can be found in Formula 1-2:

$$R^2(y,\hat{y}) = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y}_i)^2} \tag{1}$$

$$MSE(y,\hat{y}) = \frac{1}{n}\sum_{i=1}^{n-1}(y_i - \hat{y}_i)^2 \tag{2}$$

With n being the number of samples, y the actual value of a sample, $\bar{y}$ the mean of actual values in the dataset, $\hat{y}$ the predicted value. Since the *Gradient Boosting* algorithm performs best on the training set and generalizes well on the test-set, the model with the identified hyperparameters was chosen and stored in the knowledge base of the controller for further quality predictions, see chapter 4.3.

4.3 Cognition enhanced control through selective tolerance matching

To obtain a realistic scenario, a discrete event simulation was modelled in python simulating the fine finishing manufacturing process of the input shaft and the wheel, a measurement step at gear inspection, the storage of the components, as well as the gear assembly process in a virtual environment. The cognitive controller has also been implemented in this virtual production environment. It extends the ideas of adaptive control loops in cyber-physical production systems [16] by means of cognition enhanced control, see Figure 7.

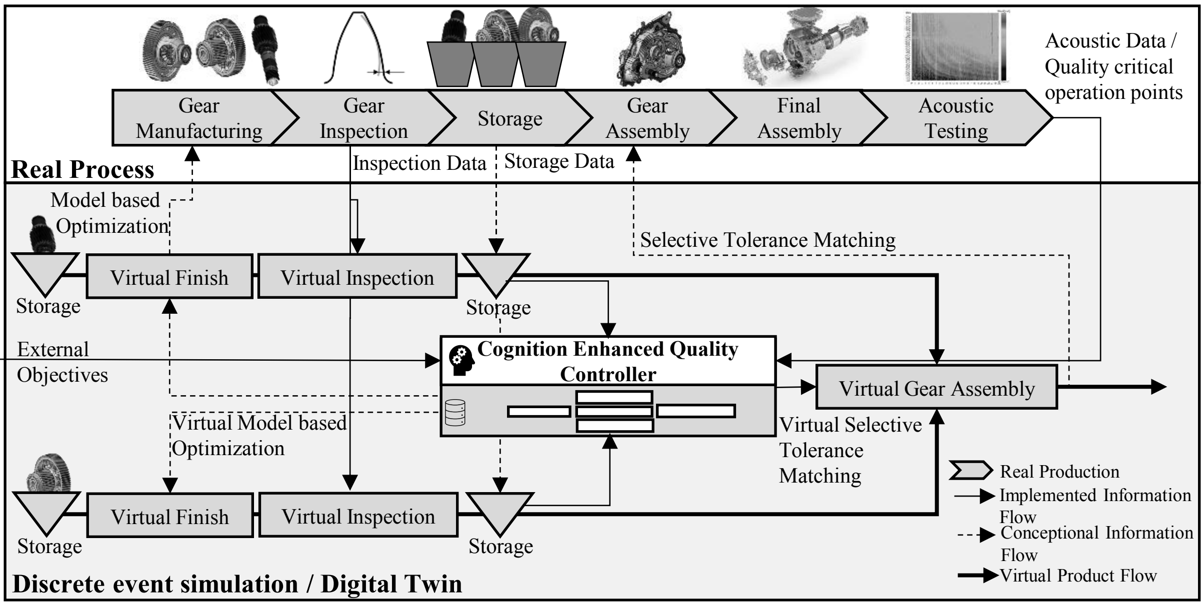


Figure 7: Schematic representation of the virtual implementation of cognitive control in a discrete event simulation.

The measurement values of the virtual inspection were retrieved from a real-world inspection of the gear components. Afterwards the virtual components are stored in a virtual storage. At each time step the virtual controller monitors locations of the components within stock and corresponding measurement values. Therefore, the virtual controller can simulate optimization strategies for the real production in a virtual environment. By using selective tolerance matching based on the model developed in chapter 4.2, gear pairings in current stock can be selected which minimizes the TE. The virtual assembly process has been run twice to compare the predicted results of random assembly with selective tolerance matching, see Figure 8.

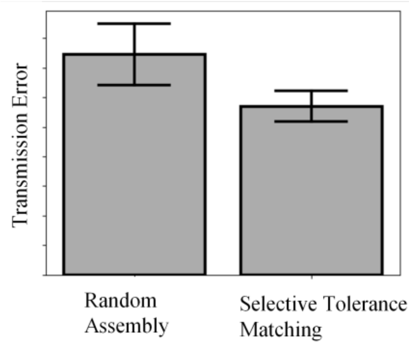


Figure 8: Comparison of the predicted TE with selective tolerance matching and random assembly.

The results of the predicted peak-to-peak TE with selective tolerance matching show a reduced standard deviation and mean compared to the random assembly. Since the TE is considered as a primary source of gear noise and vibration [26], the concept has the potential to optimize acoustic properties of the produced drives, and therefore reduce costs and waste. Current limitations of the concept are discussed in the following chapter.

4.4 Limitations

The presented concept for cognitive enhance quality control has limitations, which have not been considered due to simplification and scope within the use-case. To obtain a more realistic scenario, the use-case can be extended by adding the full topology of the gears to the simulation, adding the second gear stage including both flanks and simulating multiple speeds and loads. Optical in-line measurements can be used to obtain higher information density in the measurements [27]. Also, functional models can further be optimized to obtain higher prediction accuracies. Currently only the gears micro geometry has been considered. In real-world serial production however multiple other sources, e.g., misalignment of the shafts through tolerance deviations of the housing can also influence the acoustic properties of the drive, which have not been considered yet. Even if some studies show a correlation between the TE and noise [28] the direct relationship between TE and level of gear whine is considered as unrevealed [26]. Functional models should be integrated predicting the actual structure-born noise. This will enable the cognitive quality controller to realistically predict scrap parts and thus also estimate costs and sustainability indicators using actual tolerance limits in the virtual assembly. Finally, a combined validation of the concept in serial production incorporating both methods of model-based optimization strategies in manufacturing and selective tolerance matching is necessary.

5. Summary and outlook

In this publication a self-optimization concept based on cognitive quality control in manufacturing and assembly processes has been presented and validated in the gear production of automotive electric drives. The proposed concept incorporates model based control in manufacturing as well as selective tolerance matching for an optimal selection of components in assembly using function-oriented quality predictions. Within an industrial use-case a discrete event simulation was developed incorporating the cognition enhanced controller. On a simulation basis it was shown that the proposed method lowered the predicted peak-to-peak TE for the first gear stage and thus has the potential to improve acoustic characteristics of the electric drive. However, to increase the potential of cognition enhanced control in gear manufacturing and assembly for electric drive production, further research is required to overcome the discussed limitations of the current concept leading towards the goal of self-optimized cognition enhanced production systems.

Acknowledgements

„Funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany´s Excellence Strategy – EXC-2023 Internet of Production – 390621612”.

References

[1] Albers, A., Fischer, J., Behrendt, M., Lieske, D., 2014. Messung und Interpretation der Wirkkette eines akustischen Phänomens im Antriebsstrang eines Elektrofahrzeugs. ATZ Automobiltech Z, 116(3), 68–75.

[2] Bonart, J., Hülsmann, A., Maurice, J.-B., Schürmann, G., 2023. The power of silence composing BMW's electric powertrains.

[3] Schmitt R., Beaujean, P., 2007. Selbstoptimierende Produktionssysteme: Eine neue Dimension von Flexibilität, Transparenz und Qualität. Zeitschrift für wirtschaftlichen Fabrikbetrieb, 102(9), 520–524.

[4] Frank U. et al., 2004. Selbstoptimierende Systeme des Maschinenbaus. Definitionen und Konzepte. Sonderforschungsbereich 614.

[5] Schmitt R. et al., 2011. Selbstoptimierende Produktionssysteme. Integrative Produktionstechnik für Hochlohnländer, C. Brecher, in VDI-Buch, Berlin, Heidelberg: Springer, 747–1057.

[6] ElMaraghy, H., Monostori, L., Schuh, G., ElMaraghy, W., 2021. Evolution and future of manufacturing systems. CIRP Annals, 70(2), 635–658.

[7] ElMaraghy H., ElMaraghy, W., 2022. Adaptive Cognitive Manufacturing System (ACMS) – a new paradigm. International Journal of Production Research, 60(24), 7436–7449.

[8] Permin E. et al., 2016. Self-optimizing Production Systems. Procedia CIRP, 41, 417–422.

[9] Thombansen U. et al., 2011. Model-based self-optimization for manufacturing systems. in 2011 17th International Conference on Concurrent Enterprising ICE.

[10] Klocke F. et al., 2017. Self-optimizing Production Technologies. in Integrative Production Technology, Brecher, C., Özdemir, D., Cham: Springer International Publishing, 745–875.

[11] Gloy, Y.-S., 2020. Selbstoptimierende Textilmaschinen. in Industrie 4.0 in der Textilproduktion, Berlin, Heidelberg: Springer Berlin Heidelberg, 125–187.

[12] Loosen P. et al., 2011. Self-optimizing assembly of laser systems. Prod. Eng. Res. Devel., 5(4), 443–451.

[13] Laass, M. C., Niggemann, C., Schmitt, R., 2013. Cognitive Failure Cluster as an Approach to Enhance the Precision of a Self-optimizing Process Model. Procedia CIRP, 12, 486–491.

[14] Schmitt, R., Isermann, M., Niggemann, C., Laass, M., Matuschek, N., 2010. Cognition-based self-optimisation of an automotive rear-axle-drive production process. Journal of Machine Engineering, 10(3), 68–77.

[15] Schmitt R. et al., 2017. Cognition-Enhanced, Self-optimizing Assembly Systems. Integrative Production Technology, Brecher, C. Özdemir, D., Cham: Springer International Publishing, 877–990.

[16] Lanza, G., Haefner, B., Kraemer, A., 2015. Optimization of selective assembly and adaptive manufacturing by means of cyber-physical system based matching. CIRP Annals, 64(1), 399–402.

[17] Wagner, R., Haefner, B., Lanza, G., 2018. Function-Oriented Quality Control Strategies for High Precision Products. Procedia CIRP, 75, 57–62.

[18] Schmitt, R., Permin, E., Fuhrmann, M., 2014. Cognitive Self-Optimization for Quality Control Loops – Potentials and Future Challenges in Research. AMR, 1018, 477–484.

[19] Schmitt R. et al., 2012. Self-optimising Production Systems, in Integrative Production Technology for High-Wage Countries. Brecher, C., Berlin, Heidelberg: Springer Berlin Heidelberg, 697–986.

[20] Mease, D., Nair, V. N., Sudjianto, A., 2004. Selective assembly in manufacturing: statistical issues and optimal binning strategies. Technometrics, 46(2), 165–175.

[21] Khezri, A., Schiller, V., Homri, L., Etienne, A., Dantan, J.-Y., Lanza, G., 2023. Development and analysis of a holistic function-driven adaptive assembly strategy applied to micro gears, Journal of Manufacturing Systems. 69, 48–63.

[22] Funck, M. C., Loosen, P., 2009. Statistical simulation of selectively assembled optical systems. Optical Engineering + Applications, M. A. Kahan, San Diego, CA, S. 74270B.

[23] Ke, G. et al., 2017. Lightgbm: A highly efficient gradient boosting decision tree. Advances in neural information processing systems, 30.

[24] Breiman, L., 1996. Bagging predictors. Mach Learn, 24(2), 123–140.

[25] Breiman, L., 2001. Random Forests. Machine Learning, 45(1), 5–32.

[26] Sun, M., Lu, C., Liu, Z., Sun, Y., Chen, H., Shen, C., 2020. Classifying, Predicting, and Reducing Strategies of the Mesh Excitations of Gear Whine Noise: A Survey. Shock and Vibration, 2020, 1–20.

[27] Gauder, D., Wagner, R., Gölz, J., Häfner, B., Lanza, G., 2019. Funktionsorientierte Qualitätssicherung von Mikrozahnrädern hinsichtlich des Geräuschverhaltens: In-Line-Topographiebewertung von Mikroverzahnungen zur Prognose und Optimierung der akustischen Emissionen beim Abwälzverhalten. tm - Technisches Messen, 86(9), 469–477.

[28] Åkerblom, M., 2008. Gearbox noise: Correlation with transmission error and influence of bearing preload.

Biography

Bastian Friedrich (*1991) studied mechanical engineering at FAU Erlangen-Nürnberg University. Since 2021, he has been working as PhD student at BMW and guest research associate at the Laboratory for Machine Tools and Production Engineering of RWTH Aachen University, focusing on data driven approaches for production optimization.

Daniel Buschmann (*1992) studied automation engineering at RWTH Aachen University. Since 2018, he has been working on his doctorate as a research associate and group leader at the Laboratory for Machine Tools and Production Engineering of RWTH Aachen University, focusing on quality intelligence and failure management.

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).

5th Conference on Production Systems and Logistics

Concept of a Data-Driven Business Model for Circular Production Equipment

Michael Riesener[1], Maximilian Kuhn[1], Aileen Blondrath[1], Balaj Tariq[1], Günther Schuh[1]
[1]Laboratory for Machine Tools and Production Engineering (WZL) of RWTH Aachen University, Aachen, Germany

Abstract

New legislation and the social movement around circular economy issues are currently forcing manufacturing companies to reassess the sustainability of their production and value chain. The circular economy is becoming an important economic concept, challenging manufacturing companies to develop approaches for realising resource-efficient production and usage of products. One potential area for sustainable production lies in the production equipment used for example in automotive production, such as robots, grippers and fixtures. However, new business models are needed to realise sustainable and recyclable production equipment, as existing ones do not take this into account. This paper presents an approach that deals with business model innovation and a digital platform ecosystem for circular production equipment. First, established business models are analysed for their transferability to automotive production. In particular, the use of subscriptions for production equipment is focused on and evaluated. The assessment is based on interviews with experts from equipment manufacturers and is quantified by them. The result is a presentation of the potential of the developed business model and a corresponding "as-a-service" concept for implementation using a digital platform.

Keywords

Business model innovation; Digital platform ecosystem; Automotive production; Production equipment; Circular economy; Pay per use

1. Introduction

The sustainability debate has established itself as a central issue in society and politics worldwide. The increasing demands on sustainability and the unstoppable development of digital technologies have led to a paradigm shift. It is no longer sufficient to focus only on the production of sustainable products. Rather, the entire value chain must be considered and the focus also has to be placed on sustainable production. The German government, for example, has revised its sustainability strategy and defined six prioritised transformation fields. One transformation field is the circular economy with the goal of sustainable production [1]. The automotive industry is responsible for a significant part of global CO2 emissions and is therefore under immense pressure to make its contribution. Accordingly, the transformation approach is forcing the automotive industry, Germany's leading industrial sector, to re-evaluate and rethink its previous linear economic orientation [2]. The urgency to implement sustainable production practices thus results from the growing environmental and climate problems. At the same time, customers and stakeholders are increasingly aware of the impact of automotive production on the environment and are demanding more sustainable solutions. By establishing a circular economy, sustainable design of production, manufacturing

DOI: https://doi.org/10.15488/15315
ISSN: 2701-6277

equipment, and processes could be realised in equal measure. This should reduce energy consumption, optimise the associated data cycles and reuse production equipment wherever possible rather than disposing of it at the end of its lifecycle [3].

In parallel, digital technologies are revolutionising the way products are made. The Internet of Things (IoT) and artificial intelligence offer enormous opportunities to optimise production processes, achieve efficiency gains and open up new business opportunities [4]. Automation, connected vehicles and smart factories are just a few examples of how digitalisation is transforming the automotive industry [5]. As a result, automotive manufacturers and suppliers must find new ways to implement sustainable production methods, strengthen their competitiveness and meet the demands of an increasingly digitalised world. In this context, this paper presents the concept of sustainable automotive production with a data-driven business model innovation approach for a digital platform ecosystem. The aim is to reorient conventional linear automotive production towards circular production. The focus will be on the production equipment used in automotive production, such as grippers, robots and fixtures. These production equipment are generally used in every automotive production line, and their consideration makes a significant contribution to the main focus of circular production.

In a first step, suitable business models for establishing the circular economy at production equipment level will be identified and selected. The selected business models are then evaluated in a utility value analysis based on defined criteria in collaboration with experts from the field of equipment and fixture construction in vehicle production. The business model innovation developed is described for the integration of a digital platform ecosystem. This platform should enable the exchange of data and, above all, the service behind the business model.

2. Fundamentals and methods

2.1 Business Model

A business model is a representative definition of entrepreneurial action to generate profits or revenue for a company while adding value for the customer [6]. The business model innovation methodology can be used to increase profitability or reduce costs in a company [7]. However, the methodology can also be applied to achieve innovation and sustainability [8]. The St. Gallen Business Model Navigator (BMN) describes 55 different model concepts for business model innovations. The authors assume that nine out of ten business model innovations are a recombination of known ideas, concepts and elements of business models from other industries. According to the BMN, the process of business model innovation is divided into four phases: Initiation, Ideation, Integration and Implementation [9]. In addition, the authors identify three basic strategies for developing new business models based on the 55 existing business model concepts:

- Transferring an existing business model to another industry
- Combining two or more existing business models to take advantage of both
- Replicating a successful business model in other product areas

2.2 Digital platform ecosystems

Digital platforms are becoming increasingly important in the industry as they can enable new business models, increase efficiency and enable collaboration easier. A digital platform in industry is a virtual environment that acts as an interface between different actors, processes and technologies to enable information sharing, collaboration and increased efficiency in production [10]. The digital platform is the focus of a digital ecosystem and maps its service, see Figure 1. It enables the interaction of the ecosystem's various stakeholder groups of partners, developers, customers and other stakeholders. The ecosystem itself is a socio-technical system, it includes not only digital and technical systems but also the organisations and people and their relationships with each other [11]. Usually the ecosystem is organised as a two-sided market. On the one hand, the supply and on the other hand, the demand is coordinated on the platform [12]. The platform ecosystem is characterised by the interactions and interdependencies between the participants [13]. Each participant contributes to increasing the value of the entire ecosystem. For example, if more providers are present on a platform, the offer for customers increases, which in turn attracts more customers. This creates a network effect where the value of the platform increases exponentially with the number of further users [14].

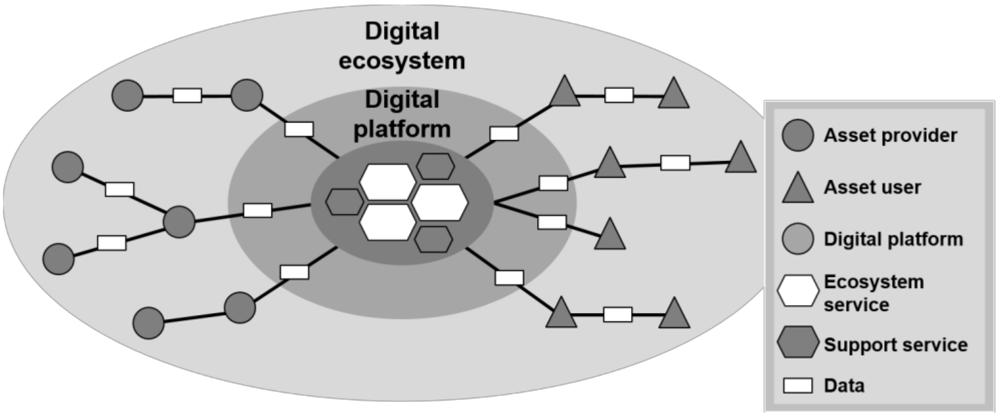


Figure 1: Digital ecosystem framework [15]

2.3 Circular Economy

The circular economy is an approach to reducing resource consumption, minimizing waste and creating a more sustainable economy. This approach is based on the concept that products and materials are kept in closed loops so that they are reused as much as possible [16]. Circular production aims to replace the current largely linear production chain, in which raw materials are extracted, processed into products, used and then disposed of. Instead, products are to be designed in such a way that they can be broken down into their constituent parts at the end of their life cycle and these can be fed back into the production process in a way that adds as much value as possible [17]. To implement such circularity, the 9-R-framework from KIRCHHERR presents an approach [18]. This comprises 9-R-strategies for returning products and components to the process in the most value-adding way possible. These are, for example, Reuse, Repair, Remanufacture and Recycle [19]. According to KIRCHHERR, a classification can be made between R-strategies for smarter product use and manufacturing, extension of the life of the product and its parts, and the useful application of materials [18]. Depending on the R-strategy, materials can be extracted from products and reused in new products. The nine R-strategies are sorted in descending order of circularity.

3. Application

In this paper, the implementation of business model innovation is based on three steps and is illustrated in Figure 2.

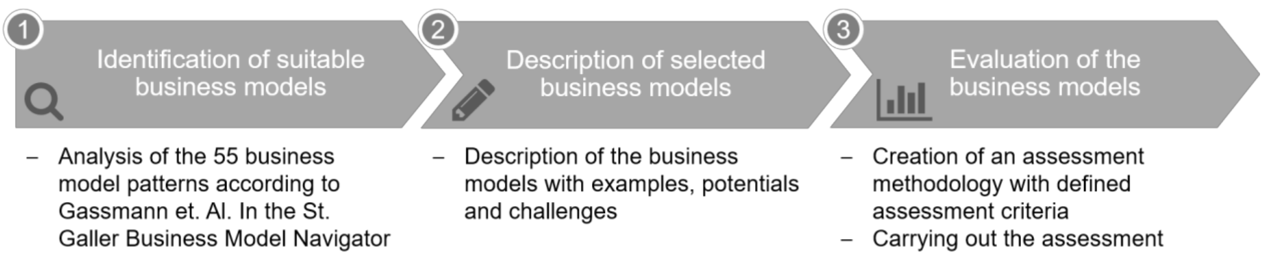


Figure 2: Methodological approach of this paper

The first step is to identify suitable business models. The focus of the business models to be selected should be on the possibility of establishing a circular economy in automobile production. In the context of this work, the 55 business models of the St. Gallen Business Model Navigator are used for the implementation of a business model innovation. The methodology shows a high suitability for the identification of suitable business model concepts for the implementation of a new business model innovation. In a second step, the concepts behind the selected business models are described and examples of companies that are already successfully using the business models are presented. Furthermore, the potentials and challenges arising from the use of the different business models are highlighted. The last step is an evaluation of the identified business models using two evaluation methods: pairwise comparison and utility analysis. For the evaluation by means of pairwise comparison, corresponding criteria are first defined and then weighted accordingly. After defining and weighting the evaluation criteria, the business models identified as suitable in step 1 are evaluated using the utility value analysis method. The results of the assessment by pairwise comparison and utility analysis are based on interviews with experts from the field of equipment and fixture manufacturing. In the second part, the focus is placed on the digital platform ecosystem for the feasibility of the business model innovation. For this purpose, a concept for the implementation of the business model through a corresponding digital platform will be developed.

3.1 Identification of suitable business models for circular automotive production

The business model concepts to be developed must enable sustainable automotive production. The focus should be on using one of the 9-R-strategies to extend the life of the production equipment and its components. For this, the principle of leasing, renting and sharing of durable products shall be supported and the possibility of managing is to be ensured through a corresponding digital platform. In his research on business model innovations, SCHALLMO defines three classes for categorising business model ideas. These classes are Pursue, Consider and Discard [20]. In the context of this paper, the 55 business model concepts of the St. Gallen Business Model Navigator are examined and assigned to the three categories mentioned:

Pursue: The circular economy principle is fulfilled. Fact sheets are prepared for the business model concepts, which present the relevant information on the respective concepts. The identified business model concepts are then evaluated by the assessment methodology in cooperation with experts from the automotive industry.

Consider: The principle of circular economy is not directly fulfilled. The business model concepts are therefore considered for use as a supplement in the conceptual design. No profiles are created for this category.

Discard: The circular economy principle is not present. Therefore, these business model concepts are not considered further in the assessment and subsequent conceptualization

3.2 Description of selected business models

After examining the 55 business models with regard to their possibility of establishing circular automotive production at the production equipment level and classifying the models into the three categories mentioned above, six suitable business models were identified. The identified models are described below.

Crowdfunding is the outsourcing of a product or project to several customers or investors. The investors, also called crowd funder, are private individuals or companies, who are free to decide how much they want to contribute to the project [21]. For money contributed, a right to use the product is acquired. Crowdfunder are usually not interested in maximizing returns, but in the implementation of the project [22].

The *Fractionalised Ownership* model represents a business model in which a community of buyers exists, in which each buyer receives a pro-rata right to use the object of purchase [23]. The company that offers the fractional ownership of its services is usually responsible for the management of the object of purchase. Car-sharing concepts have already successfully implemented the business model pattern in which several customers share a car. This makes the use of the car more economically viable [24].

In the *Pay-per-Use* business model, the customer does not buy any products, but pays a monthly or annual fee for the use of the products. A costumer pays within the framework of this business model exclusively for the effective use of resources [24]. A successful business model that uses the pay-per-use method is the Car-Sharing concept Car2Go by Daimler, which was established in 2008. Unlike conventional Car-Sharing services or car rentals, where a automotive is typically only rented on an hourly or daily basis, Car2Go charges the rental exactly by the used minutes [25].

In the *Rent Instead of Buy* business model, the customer acquires a temporary, paid right to use a product. The concept is like the pay-per-use business model. The difference is that the customer commits to paying a fee for the temporary use of the product, irrespective of the actual effective period of use [26]. SolarCity, which was purchased by Tesla in 2016, represented a company, that successfully applied the Rent Instead of Buy model in their business [27]. The solar equipment manufacturer designed and installed solar panels on residential rooftops. The customer could choose between two options, the immediate purchase of the system or the Rent Instead of Buy option.

In a *Subscription* model, the customer acquires a temporary right of use or takes out a subscription to a product. The frequency and duration of use are contractually agreed with the company and paid by the customer in advance or at regular intervals [28]. The software provider Salesforce transferred the model to the software industry over more than 15 years ago. The customer pays an amount in return for which he receives the company's software, including all updates, via the internet [29].

The *Trash-to-Cash* pattern represents a concept of sustainable economy. Used goods that are waste products at the end of their life in the value chain are recycled and then reused [30]. One company that has established the principle of the business model pattern in the company, is Caterpillar. The company has introduced a remanufacturing program, in which used parts are refurbished and resold. By reintroducing them into the product cycle, waste is reduced and, on average, about 85 per cent of the individual components can be recycled [6].

3.3 Evaluation method of identified business models

Table 1: Overview of the business models to be evaluated

	Product Financing	**Potentials**	**Challenges**
Crowdfunding	Leveraged	Product financing by costumers	Product manufacture only if financial targets are met
Fractionalized ownership	Self-financed	Denomination of the purchase amount	Limited adaptability
Pay-per-use	Self-financed	Payment only for actual use	Precise forecast of future revenues
Rent instead of buy	Self-financed	Short-term rent for capital-intensive goods	Forecast of rental income
Subscription	Self-financed	Long-term rent for capital-intensive goods	Client must conclude long-term rental agreement
Trash-to-cash	Self-financed	Sustainable economic model	New product manufacturing requires new warehousing

For the six business models identified and described, a classification was made within the levels of product financing, potentials and challenges, seen in Table 1.

The methodology of utility value analysis was used to evaluate the business models. For this purpose, corresponding evaluation criteria were first developed for the identified business models. The evaluation criteria are based on the objective of identifying the most suitable business models for establishing the circular economy approach within automotive production at the operating resources level. The criteria are based on SCHALLMO [20] and are listed in table 2.

These evaluation criteria were first weighted through expert interviews from the automotive industry with a focus on equipment manufacturing using a pairwise comparison. To carry out the utility analysis, a corresponding evaluation of the criteria was carried out for each business model using dimensionless evaluation numbers. The calculation of the individual utility value per criterion is carried out according to the following formula:

$$Utility\ value = Rating * Weighting\ in\ \% \tag{1}$$

By adding up the individual utility values accordingly, an overall utility value could then be summarised for each business model. On the basis of the total utility value, a raking could then be created that determines which business model optimally fulfils the previously defined guiding question. For the utility value analysis carried out in this work, the following evaluation numbers from 0-3 were chosen:

- Rating 0: the alternative does not fulfil the criterion
- Rating 1: the alternative hardly fulfils the criterion.
- Rating 2: the alternative partly fulfils the criterion.
- Rating 3: the alternative fulfils the criterion completely.

4. Results and discussion

4.1 Business Model Innovation

This chapter presents the results of the pairwise comparison and the utility analysis. Both methods were carried out in cooperation with experts from the equipment manufacturing industry. When conducting the comparative methods, the experts' assessment was made from the perspective of introducing the respective business models in their own companies.

A total of the four expert interviews were conducted. The results of the pairwise comparison were used to weight the evaluation criteria in the utility value analysis. The average results of the four utility analyses carried out are shown below in Table 2.

Table 2: Average results of the four utility analyses

		Crowdfunding	Fractionalized Ownership	Pay-per-Use	Rent Instead of Buy	Subscription	Trash-to-Cash
	Weighting	Utility Value					
Customer benefits (focus: sustainability)	11,1 %	0,2	0,1	0,3	0,3	0,2	0,2
Acquisition of new customers	15,7 %	0,2	0,2	0,5	0,3	0,3	0,3
Corporate image	11,8 %	0,1	0,1	0,4	0,4	0,4	0,4
Market acceptance	12,5 %	0,1	0,1	0,4	0,3	0,4	0,3
Technical feasibility (internal)	5,6 %	0,1	0,1	0,2	0,2	0,2	0,1
Financial feasibility (internal)	12,9 %	0,3	0,3	0,4	0,3	0,3	0,3
Need for know-how for employees	8,0 %	0,2	0,1	0,2	0,2	0,2	0,2
Customers' willingness to pay	16,3 %	0,3	0,3	0,5	0,5	0,5	0,3
Differentiation in competition	6,3 %	0,1	0,1	0,2	0,1	0,1	0,1
Total utility value		**1,6**	**1,4**	**2,9**	**2,4**	**2,5**	**2,1**

The aim of the evaluation is to make the currently largely linear car production sustainable by introducing the principle of circular economy, i.e. renting, leasing and sharing production resources at equipment level. The examination of the results shows that the pay-per-use business model achieves the highest utility value, followed by the subscription and renting instead of buying business models. For the experts, therefore, the classic rental models are the most attractive solutions for business model innovations to implement the principle of the circular economy in the currently largely linear automotive production. According to the experts, the pay-per-use business model is a good way to support car manufacturers in making their automotive production sustainable. In addition, the business model is expected to attract a large number of new customers. The reason for this is the fact that the customer only pays for the actual use of the respective production equipment. Although the trash-to-cash business model is a business model for sustainable business in the literature, it does not achieve the highest utility value. According to the experts, the technical and financial feasibility of the business model leads to an increased effort. The two business models crowdfunding and fractionalised ownership achieve the lowest utility values and are thus at the end of the ranking. The acceptance on the market and the customers' willingness to pay for the business model are not considered to be given.

With the establishment of the pay-per-use business model in car production, the scenario arises that automotive manufacturers do not buy capital-intensive production equipment such as grippers or fixtures, but acquire the right to use the product for a certain amount of money. However, it is agreed that the customer only pays for the actual use of the product. In the chosen concept, the supplier in the field of operating equipment retains ownership of its own product. This means that the supplier can refurbish and reuse the product at the end of its useful life if possible. Reusing the production equipment prevents it from being disposed of at the end of its life. The identified business model establishes the principle of the circular economy and makes the currently largely linear automotive production sustainable at equipment level.

4.2 Concept digital platform business model “as a service”

As digitalisation progresses, "as a service" approaches are becoming increasingly important in the field of business model innovation. The "as a service" approach enables companies to offer their products or services in the form of a subscription-based model in which customers pay for access to the use and added value of the solutions offered. For the realisation of a circular automotive production, this approach lends itself to the "pay per use" business model. At the equipment level, this concept is called "Equipment as a Service", whereby production equipment is rented instead of purchased. This not only ensures that resources are used as needed, but also makes it possible to recycle production equipment. After the utilisation phase, the production equipment is to be returned to the manufacturer and reprocessed according to an R-strategy (Reuse, Recycling, Remanufacturing,...) and re-rented as often as possible. The business model "equipment as a service", which is based on the pay-per-use approach, is to represent the core of a digital platform ecosystem. For this purpose, stakeholder groups from different equipment manufacturers will make their production equipment available to the corresponding user group. Besides the easily calculable costs, another main advantage of this approach is its flexibility. It allows manufacturers to offer their customers customised solutions that are tailored to their specific requirements. Customers thus have the option of using production equipment as needed and are no longer tied to long-term contracts, allowing them to adapt their production to rapidly growing requirements and changes. Similarly, in-house storage of production equipment will be eliminated in the long term, saving storage costs. In 2020, Porsche and Munich RE founded the joint venture Flexfactory, which was to implement the Production as a Service approach on a large scale. In August 2023, however, the dissolution of Flexfactory was announced. The exact reasons for this are not known, but the following challenge could be considered [32].

One of the main challenges behind this approach is internal company standards, which makes it difficult to use the same production equipment more than once in different companies. However, 85% of entrepreneurial respondents to a BCG survey said they would share their newly built factory, while 62% said they would share existing facilities [32] . Similarly, data must be collected during the use phase in order to be able to derive an appropriate R-strategy after use. The security and data protection of customer data plays an essential role here, as it is transmitted via the internet and stored in the cloud. Thus, a distinction must be made between data relevant to the production and utilisation phases, but with successful implementation, the user of the production equipment can also benefit from appropriate monitoring.

5. Conclusions and Outlook

The focus of this paper is on designing sustainable automotive production by conceptualising through business model innovation. The aim was to establish the circular economy approach for renting, leasing and sharing durable production equipment. Looking at sustainability aspects in automotive production at equipment level, it was found that the concept of sustainability is already firmly anchored in the corporate strategy of leading car manufacturers. Measures are being taken to increase energy efficiency in automotive production. However, the potential of the circular economy in automotive production is not yet exploited. Currently, there are no existing circular business models in automotive production. This shows how important it is to develop innovative business models to establish the circular economy in automotive production for production equipment. The evaluation showed that the four experts agree that the pay-per-use business model is the best solution for establishing a circular economy for production equipment in automotive production. The pay-per-use business model approach reduces the share of investment costs in capital-intensive production equipment. The user only pays for the actual use phase, and the equipment manufacturers can then recondition the production equipment and rent it out again. The conceptualisation of sustainable automotive production through recyclable production equipment was described in this paper through the "Equipment as a Service" approach. However, the business model alone is not sufficient. For the realisation, in addition to the modularity of the production equipment, a suitable sensor concept must also be identified in order to be able to classify it into an R-strategy after the utilisation phase. The core of further consideration will be the realisation in the digital platform. Suitable data interfaces must be created between all business partners, such as the customer and the service provider of the equipment-as-a-service model, in order to guarantee effective and efficient implementation.

Acknowledgements

This project received funding from the Federal Ministry of Education and Research under funding code 02J21E000. The responsibility for the content of this publication lies with the author.

References

[1] Kishita, Y., Matsumoto, M., Inoue, M., Fukushige, S. (Eds.), 2021. EcoDesign and Sustainability I: Products, Services, and Business Models. Springer Singapore, Imprint: Springer, Singapore, 1 online resource.

[2] Calabrese, G., 2012. The greening of the automotive industry. Palgrave Macmillan, Basingstoke

[3] Hesselbach, J., Herrmann, C. (Eds.), 2011. Glocalized Solutions for Sustainability in Manufacturing: Proceedings of the 18th CIRP International Conference on Life Cycle Engineering, Technische Universität Braunschweig, Braunschweig, Germany, May 2nd - 4th, 2011, 1st ed. 2011 ed. Springer Berlin Heidelberg, Berlin, Heidelberg, 1 online resource.

[4] Sisinni, E., Saifullah, A., Han, S., Jennehag, U., Gidlund, M., 2018. Industrial Internet of Things: Challenges, Opportunities, and Directions. IEEE Trans. Ind. Inf. 14 (11)

[5] Kusiak, A., 2018. Smart manufacturing. International Journal of Production Research 56 (1-2)

[6] Gassmann, O., Frankenberger, K., Choudury, M., 2021. Geschäftsmodelle entwickeln: 55 innovative Konzepte mit dem St. Galler Business Model Navigator, 3., überarbeitete und erweiterte Auflage ed. Carl Hanser Verlag GmbH & Co. KG, München, 1 online resource.

[7] Remane, G., Hanelt, A., Tesch, J., Kolbe, L., 2017. The Business Model Pattern Database — A Tool For Systematic Business Model Innovation. Int. J. Innov. Mgt. 21, 1750004.

[8] Ferlito, R., Faraci, R., 2022. Business model innovation for sustainability: a new framework. INMR 19 (3)

[9] Taran, Y., Boer, H., Nielsen, C., 2021. The business model innovation process: Preparation, organization and management / Yariv Taran, Harry Boer, and Christian Nielsen, 1st ed. Routledge, London.

[10] Gawer, A., 2009. Platforms, markets and innovation: An introduction. Platforms, Markets and Innovation

[11] Kohtamäki, M., 2021. The Palgrave Handbook of Servitization. Springer International Publishing AG, Cham

[12] Dahm, M.H., 2019. Strategie und Transformation Im Digitalen Zeitalter: Inspirationen Für Management und Leadership. Gabler, Wiesbaden

[13] Hodapp, D., 2021. How Incumbent Firms Navigate Nascent Digital Platform Ecosystems in the Internet of Things: A Contextualized Perspective on Value Co-Creation in Platform Ecosystems, 1st ed. ed. Cuvillier Verlag, Göttingen

[14] Engelhardt, S. von, Petzolt, S. (Eds.), 2019. Das Geschäftsmodell-Toolbook für digitale Ökosysteme. Campus Verlag, Frankfurt, New York,

[15] Jung, C., Naab, M., 2020. Digitales Ökosystem: Plattform und Ökosystem und Daten.

[16] Wysokińska, Z., 2016. The "New" Environmental Policy Of The European Union: A Path To Development Of A Circular Economy And Mitigation Of The Negative Effects Of Climate Change. CER 19 (2)

[17] Aguiar, M.F., Jugend, D., 2022. Circular product design maturity matrix: A guideline to evaluate new product development in light of the circular economy transition. Journal of Cleaner Production 365, 132732.

[18] Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the Circular Economy: An Analysis of 114 Definitions. SSRN Journal.

[19] Diaz, A., Schöggl, J.-P., Reyes, T., Baumgartner, R.J., 2021. Sustainable product development in a circular economy: Implications for products, actors, decision-making support and lifecycle information management. Sustainable Production and Consumption 26

[20] Schallmo, D., 2015. Bestehende Ansätze zu Business Model Innovationen: Analyse und Vergleich der Geschäftsmodelle / Daniel Schallmo. Springer Gabler, Wiesbaden.

[21] Schmitz, L., 2016. A Critical Analysis of Crowdfunding as an Alternative Form of Financing for Startups in Europe. GRIN Verlag GmbH, München,

[22] Briggman, S., 2016. Nonprofit crowdfunding explained. Salvador Briggman, [New York]

[23] Aigerim Bogyrbayeva, 2020. An iterative combinatorial auction design for fractional ownership of autonomous vehicles.

[24] Sobti, R.C., Malhotra, S.K., Jaiswal, K., Puri, S., 2022. Environmental studies and climate change, 1st ed. CRC Press, Boca Raton.

[25] Nancy M.P. Bocken. Pay-per-use business models as a driver for sustainable consumption: Evidence from the case of HOMIE.

[26] Rainer, R.K., Prince, B., 2022. Introduction to Information Systems: Supporting and Transforming Business, Ninth Edition, International Adaptation ed. John Wiley & Sons, Inc, Hoboken, N.J.

[27] Remané, G., 2017. Digital business models in the mobility sector: Using components and types to understand existing and design new business models, 1. Auflage ed. Cuvillier Verlag, Gottingen [Germany]

[28] Parrino, R., Bates, T.W., Gillan, S.L., Kidwell, D.S., 2018. Fundamentals of corporate finance. Wiley, Hoboken, NJ, 1 volume (various pagings).

[29] Tzuo, T., Weisert, G., 2018. Subscribed: Why the subscription model will be your company's future - and what to do about it / Tien Tzuo. Portfolio Penguin, London.

[30] Murru, E., 2020. Hands-on low-code application development with salesforce: Build customized CRM applications that solve business challenges in just a few clicks / Enrico Murru. Packt Publishing, Birmingham.

[31] Berman, F., 2020. Trash to cash: How businesses can save money and increase profits / Fran Berman, 1st ed. CRC Press, Boca Raton.

[32] Jannik Deters, 2023. Flexibel nutzbare Fabriken: Munich Re löst Joint Venture mit Porsche auf. WirtschaftsWoche, 2023.

Biography

Dr.-Ing. Michael Riesener (*1986) has been Managing Chief Engineer at the Chair of Production Engineering at the Laboratory for Machine Tools and Production Engineering (WZL) of RWTH Aachen University since 2017. Furthermore, he holds several positions in various entities at RWTH Aachen Campus connecting science and industry.

Dr.-Ing. Maximilian Kuhn (*1991) has been Chief Engineer and Head of the Innovation Management Department at the Chair of Production Engineering at the Laboratory for Machine Tools and Production Engineering (WZL) of RWTH Aachen University since 2021. He is also the CEO of the Complexity Management Academy and the Innovation Factory Aachen.

Aileen Blondrath (*1996) has been a research associate at the Laboratory for Machine Tools and Production Engineering (WZL) of RWTH Aachen University since 2021. She earned a M.Sc. degree in Mechanical Engineering and is now a PhD candidate at the chair of Production Engineering.

Balaj Tariq (*1996) joined Siemens AG in 2022 as a management consultant with focus on strategy and transformation. Previously, he earned a M.Sc. degree in Production Engineering and conducted his master's thesis at Laboratory for Machine Tools and Production Engineering (WZL) of RWTH Aachen University.

Prof. Dr.-Ing. Günther Schuh (*1958) has been head of the Chair of Production Engineering at the Laboratory for Machine Tools and Production Engineering (WZL) of RWTH Aachen University since 2002. He is director of FIR e.V. as well as a member of the board of WZL and Fraunhofer IPT. He is also a member of numerous technical-scientific committees and founder and CEO of several start-ups in the field of electromobility.

CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
CPSL 2023-2

5th Conference on Production Systems and Logistics

Reducing Wastage In Manufacturing Through Digitalization: An Adaptive Solution Approach For Process Efficiency

Valesko Dausch[1], Sebastian Beckschulte[2], Louis Huebser[2], Tobias Schulze[2], Robert H. Schmitt[2,3], Matthias Kreimeyer[1]

[1]*Institute for Engineering Design and Industrial Design IKTD of University of Stuttgart, Stuttgart, Germany*
[2]*Laboratory for Machine Tools and Production Engineering WZL of RWTH Aachen University, Aachen, Germany*
[3]*Fraunhofer Institute for Production Technology IPT, Aachen, Germany*

Abstract

The transformation to digital manufacturing has become increasingly critical for companies to remain competitive and achieve efficient manufacturing processes. However, manufacturing operations are often plagued by suboptimal allocation of resources, which can lead to higher costs and lower productivity. Digitalization has the potential to address these challenges by enabling real-time data monitoring, reducing quality costs, and improving process quality.

Previous studies have shown that digital manufacturing can improve the efficiency of manufacturing processes and lead to productivity increases in organizations. However, despite these advantages, many digital innovation projects in manufacturing fall short of their initial ambitions, often resulting in incremental improvements to an existing manufacturing system. This is partly due to the challenges faced by manufacturing companies in quantifying the added value versus the costs of digitization technologies.

Therefore, the objective of this paper is to propose an adaptive solution approach that addresses the need of aiding the decision process in selecting and assessing digital technologies to reduce wastage in manufacturing processes. The approach combines the 'Makigami' methodology, an 'Activity Diagram' (AD) modelling methodology, and a simplified 'Flow Chart', representing an aggregated view of the more detailed AD via a custom modelling schema, into one coherent framework. We further introduce the 'Methods-Misallocation-Measure' (3M-Graph) framework, which maps methods onto elements of wastage and misallocation, and subsequently assigns potential countermeasures. This tripartite mapping facilitates the identification of wastage during process analysis, the allocation of digital optimization measures and eases the assessment of cost effectiveness. The proposed approach aims to improve process efficiency and reduce wastage in manufacturing through digitalization. We conduct a case study of the approach and its application to an industrial assembly station, comparing the initial and then optimized processes. Future work includes the identification of further improvements and extending the framework by methodologies for estimating cost effectiveness more concisely.

Keywords

Digitalization; Efficiency; Cost-benefit analysis; Adaptive approach; Wastage reduction; Process Mapping

1. Introduction

The shift towards digital manufacturing has become increasingly crucial for companies seeking to maintain their competitiveness and optimize manufacturing processes effectively. Nonetheless, manufacturing operations often suffer from suboptimal resource allocation, leading to escalated costs and decreased

DOI: https://doi.org/10.15488/15317
ISSN: 2701-6277

productivity [1], [2]. The adoption of digitalization offers promising solutions to tackle these challenges by facilitating real-time data monitoring, reducing quality costs, and enhancing process quality [3], [4]. Various studies have demonstrated that digital manufacturing can significantly enhance manufacturing process efficiency and foster productivity gains within organizations [4], [5], [6].

Despite these advantages, many digital innovation projects in manufacturing have fallen short on their initial ambitions, often resulting in only incremental improvements to existing manufacturing systems [1]. This outcome can be attributed, in part, to the challenges faced by manufacturing companies when it comes to quantifying the added value versus the costs of implementing digitization technologies [1], [7].

Therefore, the main objective of this paper is to propose an adaptive solution approach that addresses the necessity of supporting the decision-making process in selecting and evaluating digital technologies for manufacturing processes.

2. State of the art

With reference to the state of the art, a collection of approaches exist that aim to introduce digital technologies into production to avoid wastage in a targeted manner. LANZA ET AL. developed strategies for the introduction of Industry 4.0 technologies. This includes the provision of a toolbox with standardized methods such as paperless production in manufacturing [8]. In addition to a description of certain methods, information is provided e.g., about potentials and risks, and prerequisites regarding the implementation level [9]. For the roll-out of digital methods, a quick check is first carried out to determine the degree of maturity in regard to the prevailing digitalization level. Next, maturity levels required by the methods of the toolbox are compared against the surveyed maturity level. Finally, measures for achieving the maturity level required by the methods of the toolbox are identified and conducted [8].

Whilst this approach is high level, other approaches address different process steps separately along the value stream. SALVINETTI adapts value stream mapping for the use within the context of Industry 4.0. The conventional value stream analysis is conducted first, followed by an analysis of the existing and required data ingestion. The same approach is employed for data processing, data preparation and data transfer successively. Finally, the by then digitized process is fully modeled [10].

METTERNICH ET AL. and MEUDT ET AL. extend value stream mapping to include information flow. For this purpose, the information flow is recorded at the level of individual process steps and linked to their media of storage such as paper or ERP systems by applying a Makigami analysis. The intended use of such information is recorded as well. This includes quality management and shop floor management, amongst others [11], [12]. Based on this representation, weak points in the information flow that contradict Lean principles can be identified. For this purpose, METTERNICH ET AL. defined Digital Lean principles of information flows in accordance with the Lean principles of material flows i.e., ‘only digitize lean processes’ or ‘do not allow information flows unless information is used’. The former principle states that material flow must first be optimized before digitization of any processes are considered. The latter principle states that only useful information should be collected, as otherwise it would be considered digital waste. Digital wastage is divided into eight categories, inspired by the eight Muda: data selection, data quality, data collection process, data transfer & transport, inventory & processing times, moving & searching, data analysis, and decision support [11].

Whilst most approaches with respect to the mitigation of wastage tend to focus on using digital technologies to reduce physical wastage in terms of the eight Muda (e.g., [13], [14], [15]), further sources besides METTERNICH ET AL. exist that recognize the importance of capturing and minimizing wastage induced by digital technologies. ALIEVA AND VON HAARTMAN identified three fundamental types of digital wastage: failure to consider expert knowledge of product and processes when collecting data, failure to use collected data to generate information for process improvement, and failure to improve processes despite collected and analyzed data [16]. ALIEVA AND POWELL examine digital wastage within real-world cases and recommend considering it in value stream mapping [17].

Despite these first approaches, there are still several research gaps evident related to the implementation of digitalization technologies in manufacturing processes. Firstly, there is still a lack of clarity on how to implement digitalization in an interoperable way, as pointed out by HODAPP AND HANELT [18]. Secondly, there is a dearth of theoretical studies on how to implement digitalization technologies to achieve data-driven process efficiency in manufacturing processes, as noted by TROPSCHUH ET AL. [19]. Therefore, it is necessary to map digital and physical wastages onto process activities as well as to recommend potential digitalization measures that minimize these wastages.

3. Methodological solution approach

The main goal of our methodological solution approach centers around the idea to ease systematic process analysis and to relax the dependency on expert knowledge. Conventional process analysis heavily relies on experts to create an adequate process description and to identify process inefficiencies, followed by an often-non-formalized process to identify potential mitigation strategies, e.g., brainstorming. Instead, we propose an approach to capture an observed process on multiple levels of granularity with predefined elements in a well-defined manner, which fosters successive analysis steps, and to secondly guide the ideation of mitigation strategies by tripartite graph consisting of "observed methods" – "potential wastage" – "possible measures". Instead of deducing potential measures from observed misallocations (failure mode, cause and effect chain), we propose a solution-neutral approach by starting from unbiasedly observed process methods, then narrow down a collection of potential misallocations linked to the observed process method and finally determine predefined countermeasures linked to the previously narrowed down collection of potential misallocations. Therefore, the main effort during process analysis shifts from a-priori/in-situ perception of process inefficiencies by means of expert knowledge to a-posterior evaluation of devised improvements, which can be conducted by less experienced personnel. To derive our methodological solution approach, this chapter describes our model for describing manufacturing processes, their associated information flow and their subsequently linkage to classic and digital wastage. Section 3.1 explains the inherent problem of choosing a sufficiently but not too finely detailed process model. Section 3.2 presents an adapter layer to combine analysis conducted on different levels of granularity, which is especially useful to connect information flow to physical assembly actions in Section 3.3. This section then discusses the mapping of the associated information flow to the process model. The approach concludes with the formulation of the 3M-Gaph, which assigns possible improvement measures to previously identified wastage in Section 3.4.

3.1 Problem Statement: Choosing an adequate abstraction level

Optimizing manufacturing processes via digital measures poses two main challenges. Firstly, identifying sources of wastage and misallocation, and secondly, determining appropriate countermeasures. In contrast to optimizing physical aspects of a process, operating in the digital domain is especially sensitive to choosing a suitable level of abstraction. For instance, information flows represent abstract concepts only, whereas track-and-trace technologies are heavily hardware-related, and databases incorporate hardware aspects while abstracting information flows and models. Connecting abstract information flow, material flow, manufacturing steps performed by human workers, and process peripheries such as the supply chain in a meaningful and analyzable manner, is still a key challenge for identifying potential sources of wastage as well as for allocating digital optimization measures. Therefore, the abstraction level is subsequently oriented towards shop floor operations (according to withdrawn VDI 2860 [20]), see Figure 1.

Figure 1: Shop floor operations

3.2 Adapter Layer: Aligning operational and informational analysis

To overcome the aforementioned challenges, we propose combining the detail leveled 'Makigami' approach, an abstract 'Activity Diagram' (AD) modeling approach, and a simplified 'Flow Chart', which only depicts aggregated manufacturing actions and methods, into one coherent framework, see Figure 2. Each component serves a specific purpose. The Makigami diagram excels at identifying wastage regarding digital information flow, database architecture, and data modeling, which we broadly subsume under the term 'digital Muda'. In contrast, physical wastage, which can be mitigated via digital measures (e.g., deploying computer vision-based quality control, etc.), can be analyzed more easily in a simple flow chart that only depicts high-level relations. To combine the deep-dive insights of the Makigami diagram with the high-level analysis of a simple flow chart, we interlace both analysis levels via an AD. The AD serves as an adapter layer between the mostly digital and very detailed analysis and the more holistic and mainly physical analysis. Ideally, the detailed process flow of the AD can be clustered, thus directly forming the simplified flow chart.

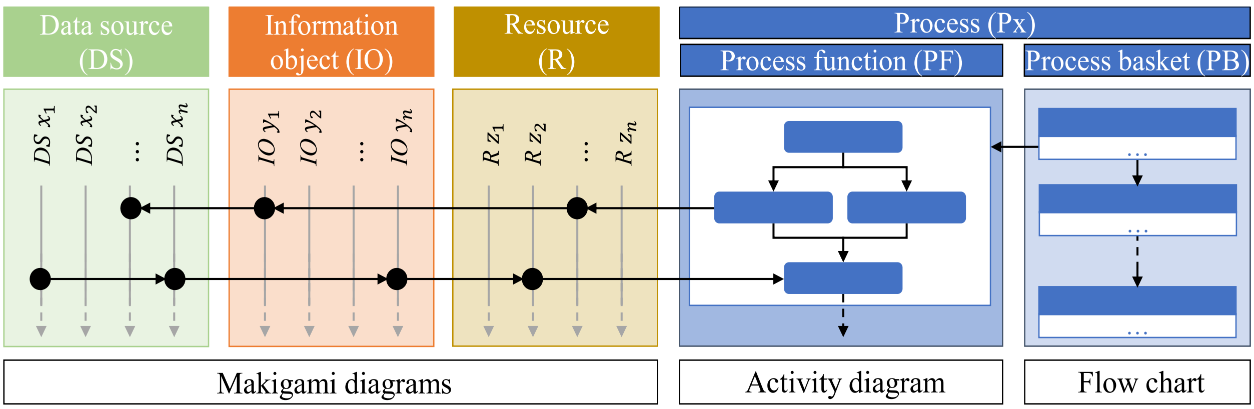


Figure 2: Framework for MAM-Chart approach

3.3 MAM-Chart: Fusing 'Makigami-Activity-Method' into a holistic approach

Whilst Makigami and AD are well defined approaches, we experienced that it is difficult to choose an appropriate level of abstraction regarding the flow chart. The family of industry standards such as i.e., VDI 2860, DIN 8580 and DIN 8593 [20], [21], [22], deliver a solid basis in terms of well-defined standards and terminology to build upon. Whilst the already mentioned industry standards define broader families of process actions and then quickly deepen into very specific terminology, we employ an intermediate terminology more appropriate for clustering and aggregating the AD process description. The implementation of this intermediate terminology is indeed use case specific but geared towards MTM-UAS (Methods-Time Measurement - Universal Analysis System) in terms of abstraction. Thereby, this intermediate terminology represents a collection of 'methods' (in terms of clustered manufacturing steps), which we call “process basket”, see Figure 2 right column. Whereas the AD and flow chart are interlaced via their clustering relation, AD and Makigami are interconnected via depicting flows, sources, and media of data. We therefore extend the standard Makigami approach by building upon the scheme ‘data source (where the information originates?) – information object (what the information is about?) – resource (how the information is actually conveyed?)’. Firstly, one Makigami is utilized to list data sources accessed within the scope of the process to be optimized. This Makigami in turn maps onto a second Makigami only depicting different types of information objects (e.g., order ID, part number, sequence number, etc.), which then maps onto a third Makigami containing only resources such as worker, parts, tools, etc. The third Makigami then finally connects to the actual AD process flow, see Figure 2. By doing so, handovers into multiple information objects or duplicate data sources can easily be identified. Finally, the AD serves as an adapter between the Makigami relations and the clustering into a simplified flow chart. We refer to this three-parted approach as ‘MAM’-Chart.

3.4 3M-Graph: Linking ‘Methods-Misallocation-Measure’

Whilst above mentioned MAM-Chart comes in handy for identifying wastage, it is not particularly useful for assigning (digital) measures to already identified wastage. Therefore, we propose a second framework building upon the MAM-Chart by mapping methods (from the ‘process basket’ used for the simplified flow chart in the MAM-Chart, Figure 2 most-right column) onto elements of misallocation and wastage, which in turn are mapped onto potential countermeasures. Thereby, we form a tripartite graph consisting of assigned triplets of [method, misallocation, measure], wherein we refer to ‘method’ in terms of clustered manufacturing steps (see above). Even though the 3M-Graph depicted in Figure 4 is tailored to a specific use case, the 3M-Graph can be generalized to support a wide range of process optimization. Furthermore, the 3M-Graph can be extended by additional methodologies to estimate costs and potential benefits of measures listed in the most-right column of Figure 4. Within an industrial process optimization workflow, firstly, a MAM-Chart would be created with the specific use case in point. Secondly, based on this process mapping and the acquired methods (see ‘process basket’ in Figure 2 most-right column), potential misallocations and wastage can be gathered (see middle column of Figure 4) and compared to the MAM-Chart. Thirdly, appropriate countermeasures can be identified by the right-most column of the 3M-Graph (see Figure 4). Not yet implemented, but conceivable for the future, suggested estimation methodologies for costs and benefits can be linked to each measure to guide the decision-making process when it comes to choosing appropriate optimization strategies.

4. Evaluation

The approach described above is examined as part of a case study using a real-life example, which is discussed in this section. The example depicts the pre-assembly process of a front bumper within one of the leading European commercial vehicle manufacturers. In section 4.1 the real-life example is described in detail. In section 4.2 we evaluate the MAM-approach by an excerpt of the results from section 4.1 with regards to the process modelling as well as the corresponding information flow. Afterwards wastage was identified and added to the MAM-model. Finally, potential countermeasures were derived from an exemplary 3M-Graph in section 4.3. The final remarks and conclusion are presented in Section 4.4.

4.1 Description of the use case and the manufacturing process

In this process, workers first need to identify the order of assembly and the assigned assembly duration per order from an overview list by themselves. Then, workers stamp on a paper printout to confirm the assignment of the order to their unique ID. Next, workers search for an order-specific bill of material, which serves as an overview to determine which parts need to be assembled at which location on the assembly (e.g., right vs. left hand drive) as well as the parts’ location in the logistics supermarkets. From a nearby supermarket, all necessary components are successively picked into an assembly trolley and brought to the assembly station. This procedure must be done at least twice. Workers then pick up an assembly rack to load it with the basic structure using a manipulator. The assembly rack is then moved to an assembly workstation as well. Next, the actual assembly is carried out at the assembly workstation. After the assembly is done, workers move the assembly trolley with the pre-assembled bumper to a Q-Gate. There, plug connections, scratches or further damage are manually checked. In addition, the installation of the radar sensor must be confirmed by scanning a data matrix code. Finally, workers place the pre-assembled bumper in the correct spot and sequence within a buffer zone, which is then emptied again by other workers from the main assembly line using the pull principle. The whole pre-assembly of the front bumper takes between 20 and 35 minutes, depending on the variant. To apply the approach consisting of the MAM-Chart and 3M-Graph, an on-site inspection was carried out. During modeling, the higher-level process steps were first recorded in the correct order (see 'process basket' at the MAM-Chart, Figure 2 most-right column). Then the objects of the respective Makigami diagrams (data sources, information objects and resources) were determined based on the process observation. In the next step, the process building blocks were refined by modelling them in an AD (adapter) and linking them to the Makigami diagram. For reasons of clarity, only an excerpt of the entire process is shown in this paper, which is visualized in Figure 3. The excerpt ranges from the beginning of the process (finding the right order to assemble) up to the end of the part picking in the supermarket. The loading of the basic structure, the assembly process in and of itself, the Q-Gate, the scan of the radar sensor as well as the sequencing into a buffer zone are not analyzed in this paper.

4.2 Evaluation of the MAM-Chart connecting process and information flow

For the examined excerpt of the pre-assembly, delay times due to the order acceptance sub-process, searching for information on the printout, and searching for the appropriate bill of material, were identified as conventional wastage. Furthermore, the movement of the assembly trolley per se represents an unnecessary transportation loss (misallocated worker time). Due to the undersized assembly trolly, multiple walking cycles are required, resulting in overprocessing during part picking. Because of the insufficient worker guidance, the dependency on implicit knowledge of the workers is identified as a weak point from the Makigami diagrams. Furthermore, it can be observed that digital information is transformed into an analogous media format (printouts). In addition, extra analog information is then generated by a stamping procedure. An a-posteriori data analysis would require additional digitization of this data. Additionally, data is required repeatedly. For example, the order ID is referenced several times in the process but is transferred via different documents. Finally, data is presented and interpreted without any reference context during the picking process.

4.3 Evaluation of the 3M-Graph for deducing potential countermeasures

By identifying possible wastages within the observed process and by employing the 3M-Graph approach to our use case (see Figure 4), countermeasures were compiled to mitigate process inefficiencies. The dotted red line in Figure 4 constitutes one exemplary instance. To confirm orders without stamping printouts (analog data), the 3M-Graph proposes to use Worker ID cards as authentication method. Thereby, digitally captured data can easily be analyzed without resulting in higher process times and by also adding timestamps. Figure 4 also contains further combinations to reduce wastage like substituting the paper printouts with a smart watch. A smart watch would display a worker guidance system to assign orders to workers by using live data and the actual shift performance. The depicted 3M-Graph does not claim to be exhaustive. Depending on the use case, the graph must be adjusted and extended accordingly by the analysis of the case in point.

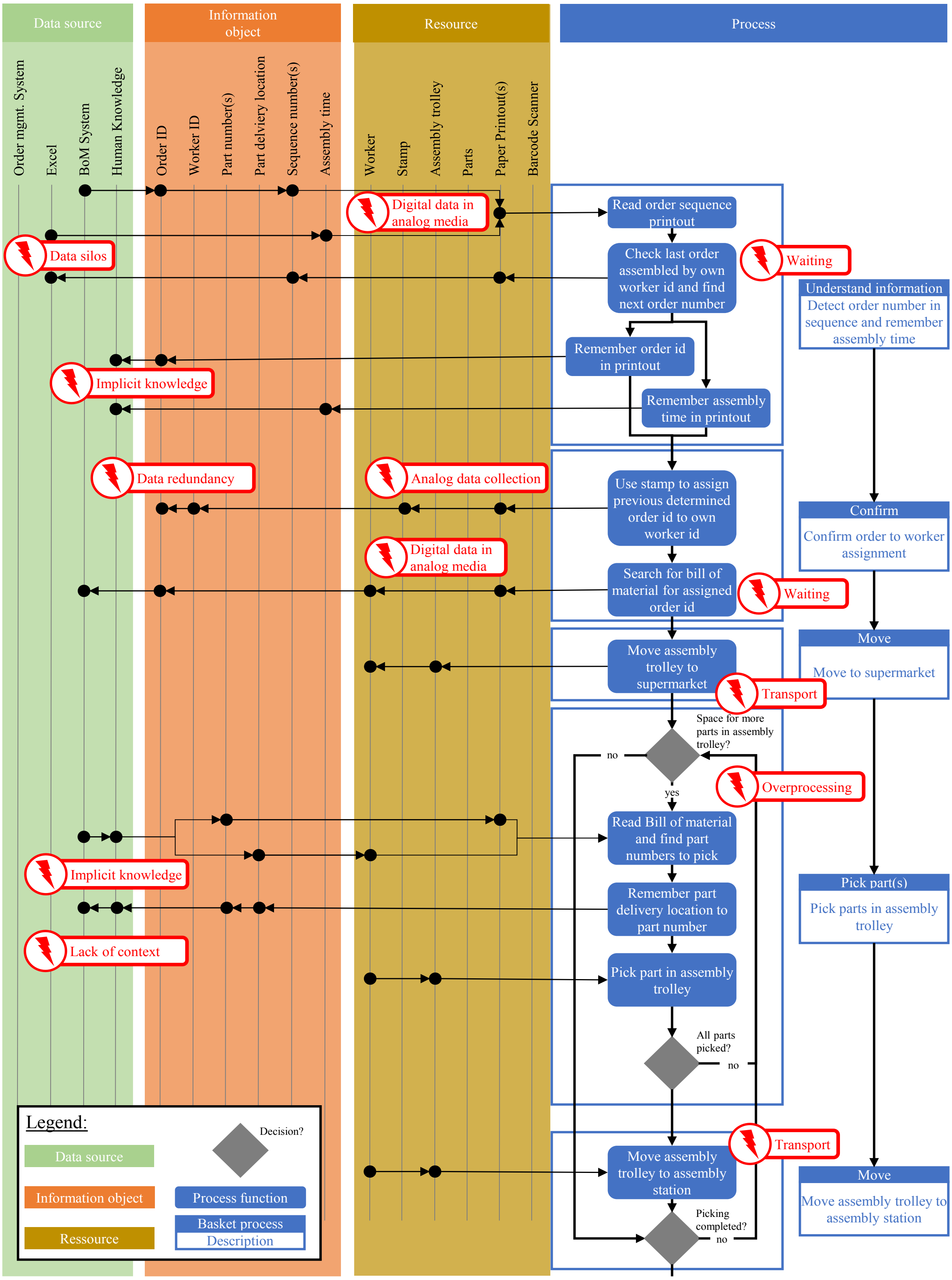


Figure 3: Extract of a MAM-Chart from a pre-assembly station

4.4 Final remarks and conclusion

In comparison, processes at the use case company have typically been analysed using conventional Gemba walks. In contrast to the current method, our approach considerably accelerates the identification of wastage by integrating information flows and physical actions at different aggregation layers through the MAM-

Chart. This proves especially advantageous given the complex and intertwined information and process flows involved in the simultaneous manufacturing of numerous product variants within the same facility.

Conventional process mappings have struggled to systematically capture wastage between handovers of various entities, particularly at the interface between physical and digital domains. Furthermore, the 3M-Chart fosters a systematic approach in regards of identifying adequate countermeasures.

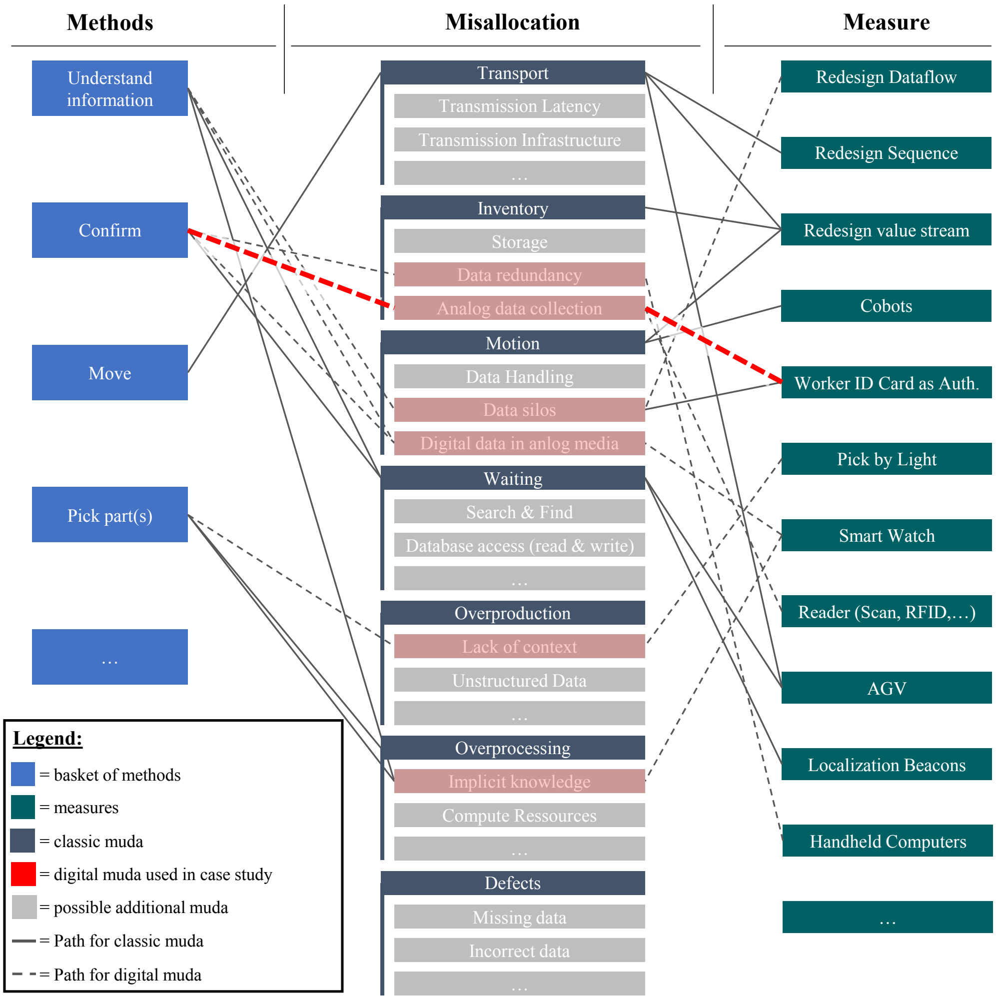


Figure 4: Excerpt of a 3M-Graph

5. Limitations and outlook

This article focuses on the presentation of a generic, applicable approach for reducing both, classic and digital wastage in assembly processes through measures aimed towards digitization. For this purpose, basic modules from a process basket (see Figure 2) are used for the process descriptions, which are then transferred into a more concrete process description using an AD. Subsequently, the wastages found are assigned to measures from the 3M-Graph (see Figure 4). Both, the process basket, and the 3M-Graph were only compiled initially. A completion is therefore not yet given. This requires the analysis of further processes, which will successively contribute to an extension of the basket and the 3M graph. Currently, the presented approach is oriented towards assembly processes. The representation considers the process itself as well as associated resources on the shop floor. However, the product to be manufactured is not taken into account. By additionally considering the product, the procedure could be further refined, e.g., to link a digital representation of the product itself or related information into a fully digital model. This would allow further (classical and digital) wastages in the processes to be modelled accordingly. To further optimize the procedure, it seems sensible to extend the approach to include digitization KPIs. The KPIs mentioned in

METTERNICH ET AL. [11] provide orientation for this. The KPIs presented therein can be used to record the proportion of digitized data in a process, the availability of information and the use of information. However, these metrics should be expanded to include metrics that take wastage into account to ensure that digitization in processes is also done purposefully and does not just prioritize the use of modern technologies. Finally, the measures from the 3M-Graph should be correlated with the efforts necessary. This should consider that the efforts for digitization do not exceed the expected benefit of digitization. Such an assessment cannot be provided in a generic way in the form of catalogues. However, it does seem possible and feasible to derive a procedure for determining the costs, both technically and economically.

Acknowledgements

Funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany´s Excellence Strategy – EXC-2023 Internet of Production – 390621612.

References

[1] Moschko, L., Blazevic, V., Piller, T.F., 2023. Paradoxes of implementing digital manufacturing systems: A longitudinal study of digital innovation projects for disruptive change, in: Journal of Product Innovation Management 40 (4), 1–24.

[2] Clancy, R., O'Sullivan, D., Bruton, K., 2023. Data-driven quality improvement approach to reducing waste in manufacturing. In: Total Quality Management Journal 35 (1), 51–72.

[3] Beckschulte, S., Huebser, L., Günther, R., Schmitt, R.H., 2023. Datengetriebenes Fehler-management in der Produktion, in: Zeitschrift für wirtschaftlichen Fabrikbetrieb 118 (4), 192–197.

[4] Clancy, R., et al. 2020. Systematic mapping study of digitization and analysis of manufacturing data, in: International Journal of Industrial and Systems Engineering 14 (9), 717–731.

[5] Weill, P., Woerner, S.L., 2015. Thriving in an Increasingly Digital Ecosystem, in: MIT Sloan Management Review 56 (4), 27–34.

[6] Desai, V., Fountaine, T., Rowashankish, K., 2022. A Better Way to Put Your Data to Work, in: Harvard Business Review 100 (4), 100–107.

[7] Howaldt, J., Kopp, R., Schultze, J., 2017. Why Industrie 4.0 Needs Workplace Innovation - A Critical Essay About the German Debate on Advanced Manufacturing, in: Oeij, P.R.A., Rus, D., Pot, F.D., editors. Workplace Innovation: Theory, Research and Practice. Cham: Springer, 45–60.

[8] Lanza, G., Nyhuis, P., Ansari, S.M., Kuprat, T., Liebrecht, C., 2016. Befähigungs- und Einführungsstrategien für Industrie 4.0. Vorstellung eines reifegradbasierten Ansatzes zur Implementierung, in: Zeitschrift für wirtschaftlichen Fabrikbetrieb 111 (1-2), 76–79.

[9] Liebrecht, C., Krogmann, M., Stricker, N., Lanza, G., 2019. Methoden-Toolbox zur Einführung von Industrie 4.0. Identifikation und Bewertung von Industrie 4.0-Potenzialen in mittelständischen Unternehmen, in: wt Werkstatttechnik online 109(4), 216–222.

[10] Salvinetti, C., 2016. Entwicklung einer Methode zur Modellierung von Industrie 4.0 Anwendungen, sowie zur Identifikation von Potenzialen bei der Datennutzung in der Montage. Diplomarbeit an der TU Wien.

[11] Metternich, J., Meudt, T., Hartmann, L., 2022. Wertstrom 4.0. Hanser, Munich.

[12] Meudt, T., Rößler, M.P., Böllhoff, J., Metternich, J., 2016. Wertstromanalyse 4.0, in: Zeitschrift für wirtschaftlichen Fabrikbetrieb 111 (6), S. 319–323.

[13] Lai, N.J.G., et al. 2019. Industry 4.0 Enhanced Lean Manufacturing, in: 8th International Conference on Industrial Technology and Management, 206–211.

[14] Cifone, F.D., et al. 2021. 'Lean 4.0': How can digital technologies support lean practices? in: International Journal of Production Economics 241, 108258.

[15] Mayr, A., et al. 2018. Lean 4.0 - A conceptual conjunction of lean management and Industry 4.0, in: Procedia CIRP, 72, 622–628.
[16] Alieva, J., von Haartman, R., 2020. Digital Muda - The New Form of Waste by Industry 4.0, in: Operations and Supply Chain Management 13 (3), 269–278.
[17] Alieva, J., Powell, D., 2021. The Automation of Lean Practices: Digitalized or Digitally Wasted? in: Dolgui, A., et al. editors. Advances in Production Management Systems. Artificial Intelligence for Sustainable and Resilient Production Systems. Cham: Springer, 651–661.
[18] Hodapp, D., Hanelt, A., 2022. Interoperability in the era of digital innovation: An information system research agenda, in: Journal of Information Technology 37 (5) 407–427.
[19] Tropschuh, B., et al. 2021. Industrie 5.0 – ein menschzentrierter Ansatz, in: Zeitschrift für wirtschaftlichen Fabrikbetrieb 116 (6), 387–392.
[20] VDI 2860:1990-05, 1990. Assembly and handling; handling functions, handling units; terminology, definitions and symbols. VDI-Gesellschaft Produktionstechnik, Dusseldorf.
[21] DIN 8580:2022-12, 2022. Manufacturing processes - Terms and definitions, division. Deutsches Institut für Normung, Berlin.
[22] DIN 8593-0:2003-09, 2003. Manufacturing processes joining – Part 0: General; Classification, subdivision, terms and definitions, Deutsches Institut für Normung, Berlin.

Biography

Valesko Dausch (*1995) studied mechanical engineering at the University of Stuttgart. Since 2018, he has been working on his doctorate research as a research assistant at the Institute for Engineering Design and Industrial Design (IKTD) of the University of Stuttgart, focusing on digital transformation and methodical product development.

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.

Louis Huebser (*1993) studied mechanical engineering at RWTH Aachen University. 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 manual assembly.

Tobias Schulze (*1997) studied mechanical engineering at RWTH Aachen University. Since 2022, 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 model explainability.

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).

Matthias Kreimeyer (*1976) graduated from TU Munich and Ecole Centrale Paris in Mechanical and General Engineering and did his PhD in product development / complexity measurement at TUM. For about twelve years he worked in various roles for a major European commercial vehicle manufacturer before being appointed as a professor for product at the University of Stuttgart, with a research focus on the design.

5th Conference on Production Systems and Logistics

Comparison Of Sealing Methods For Polymer Electrolyte Membrane

Gregor Mueller[1], Rebecca Pahmeyer[1] Aleksandar Radlovic[2]
[1] *Fraunhofer Institute for Manufacturing Engineering and Automation, Stuttgart, Germany*
[2] *MAHLE Filtersysteme GmbH, Stuttgart, Germany*

Abstract

The use of flat membrane humidifiers increases efficiency and extends the lifetime of fuel cells by humidifying the inlet airstream. The conditions under which the membranes mainly operate are determined by humidity, temperature, and pressure. The flat membrane humidifier uses the cathode-outflow of the flue cell to humidify the inlet airstream. Commonly available PFSA sandwich membranes are not necessarily designed to suit these operational conditions. Delamination of PFSA and the reinforcement layers may occur due to weak connection between the different layers. A delamination may lead to leakage, which could result in a bypass and pressure loss of the in- and outflow of the fuel cell. As a consequence, delamination of the PFSA membrane may cause failures of the flat membrane humidifier operation. To avoid delamination under such thermal and humidified conditions, it is necessary to strengthen the membrane during preparatory production steps against delamination. This paper examines different methods to strengthen the sandwich membrane against delamination due to water intake. It compares the effect of different sealing processes, focusing on increasing resistance against delamination. The investigated methods can also find application in PFSA membranes used under similar conditions, such as fuel cells. The technology selection process is focused on technologies enabling the flat membrane humidifier mass production for the automotive supplier MAHLE.

Keywords

Polymer Electrolyte Membrane (PEM) Fuel Cells; humidifier membrane; PFSA; technology screening; technology selection; flat membrane humidifiers; automotive industry

1. Introduction

Proton-exchange membrane fuel cells (PEMFC) have emerged as clean power sources with broad applications. In PEMFCs, chemical energy is converted to electrical energy through an electrochemical reaction, primarily utilizing hydrogen as fuel. Maintaining optimal humidity levels within the fuel cell is crucial to ensure efficient and stable performance.

In recent years, flat membrane humidifiers have gathered significant attention as effective solutions for humidifying reactant gases in fuel cells. Higher humidity levels in the fuel cell lead to increased efficiency and extended service life. The function of flat membrane humidifiers is to separate outgoing used and incoming fresh air and pass the humidity of the outgoing air to the incoming air. [1] Therefore, the flat membrane humidifier consists of various layers of alternating membranes and spacer, which need to be joined. [1] One of the most promising joining technologies for the layers of the membrane/spacer-stack seems to be adhesive bonding.

Experiences by the automotive supplier MAHLE have revealed weaknesses in the membrane used for flat membrane humidifiers, particularly related to delamination of the membrane layers when exposed to water.

DOI: https://doi.org/10.15488/15243
ISSN: 2701-6277
publish-Ing.

As operational conditions for flat humidifiers involve high water intake, optimizing the membrane's resistance against delamination becomes vital. Enhancing resistance to delamination, especially during water intake, appears to be beneficial in improving lifespan during an operation.

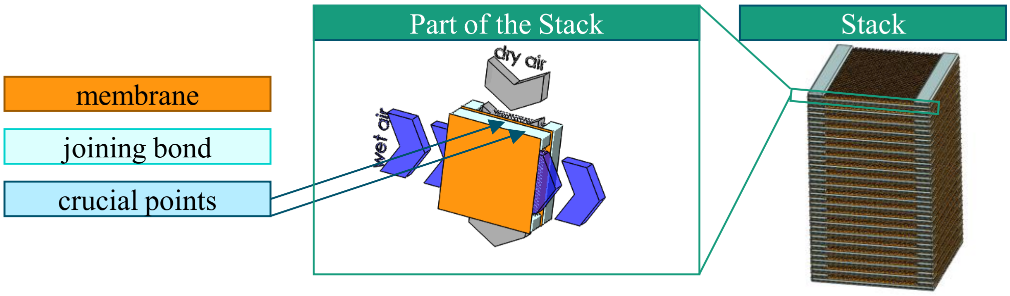


Figure 1: membrane stack for a flat membrane humidifier of a fuel cell system [1]

Delamination of the membrane of the flat membrane humidifier is critical, because it creates gaps and irregularities in the joining bond between the two membranes. Figure 1 shows these points as crucial points. When gaps or irregularities occur, dry and wet air can mix, leading to pressure loss and mixing air components This consequently results in a loss of functionality. A well-bonded membrane spacer stack is essential for the long-term durability of the humidifier. Delamination tendency of the membrane layers, ultimately reducing the membrane's lifespan and necessitating frequent replacements or maintenance.

Perfluorosulfonic acid (PFSA) membranes are considered the standard in PEMFC applications due to their superior thermal, mechanical, and chemical stability, as well as high proton conductivity. [2] This paper focuses on the production of a flat membrane humidifier by using a PFSA membrane as the active layer between the inlet and outlet airstreams. PFSA-based membranes are well-known for their exceptional water conduction properties. To enhance specific properties, such as mechanical strength and stability, the membrane is reinforced and built up as a "sandwich membrane".

The paper examines various approaches to preventing delamination in an existing PFSA sandwich membrane with non-woven reinforcement. The state of the art presents the properties of PFSA membranes. The methodology chapter investigates approaches to improve the mechanical properties of the PFSA membrane. At the end, the results are described and discussed. The paper concludes that conventional sealing methods are not helpful for increasing resistance against delamination during water intake.

2. State of the Art

The sandwich membrane of the flat membrane humidifier has two major functions, a structural/mechanical function (i.e., to serve as a chemically inert barrier to prevent bulk mixing of catholyte and anolyte solutions) and a chemical function (i.e., to selectively transport the specific ions from one solution to the other). [3]

To meet the requirements, PFSA polymers are used as membrane materials. The hydrophilic groups of the PFSA membrane act as proton-conducting pathways when hydrated and thus are responsible for the quality of proton conductivity. [4,5] The hydrophilic acid groups are agglomerated in clusters. Upon hydration, they take up water, which results in swelling of the clusters. Therefore, the clusters partially connect and build paths for hydrogen ions. [2]

Additional materials for PFSA membranes are non-woven materials. Non-woven materials are porous substrates that result in a higher membrane lifetime. [6] The membrane investigated in this paper is a sandwich membrane consisting of a non-woven reinforcement layer on the outside (Figure 2).

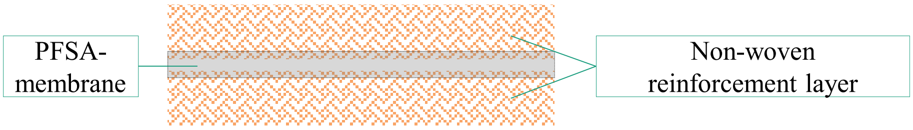


Figure 2: Schematic representation of the sandwich membrane

3. Methodology

Since delamination due to water intake was recognized through empirical experience in the usage test of the flat membrane humidifier, the behaviour of the membrane in humidified environments had to be analysed. Test conditions for humidified environments were achieved in a climatic chamber (95°C, 95 % rel. humidity). The conditions in the climatic chamber simulate the operating conditions during normal operation. Additionally, the samples were submerged in liquid water to model maximum water intake. The time out of water (ooW) before peel-off was defined as one of the main parameters.

The first step in this study was to inspect the structure of the sandwich membrane. An optical inspection of the sandwich membrane was done. Because of the fleece structure of the non-woven reinforcement, the bond between the reinforcement layer and the PFSA membrane is punctual (Figure 2). Different conventional sealing methods have been considered to improve the bonding quality between two layers.

Sealing technologies commonly used in the packaging industry are heat sealing (also called conduction sealing), high-frequency sealing, and ultrasonic (us) sealing [7]. Additionally, laser welding as a sealing technology has been considered. As laser welding resulted in smoke marks on the membrane, it is not described in the results. Since the membrane consists of non-metallic parts, high frequency sealing methods could not be applied. Additionally, adhesive bonding has demonstrated its potential as an effective joining technique, prompting investigation into its application for sealing purposes. The goal of the sealing technology was to improve the bonding strength of the layers of the sandwich membrane (non-woven layers and PFSA membrane), especially in humid environments.

In this paper, ultrasonic sealing, heat sealing and adhesive bonding experiments were carried out. Complementary, the authors applied a combination of heat sealing and adhesive bonding. Heat sealing and adhesive bonding, as the most promising sealing techniques, were tested under different stages of humidity.

4. Material, Machines, and Methods

The membrane is a sandwich membrane composed of a PFSA polymer and additional non-woven layers on the outside. A two-component polyurethane compound was used as an adhesive. Sealing experiments for ultrasonic sealing were carried out on the ultrasonic machine SonyTop from MS Ultrasonic Technology Group. The SonyTop machine uses a frequency of 20 kHz and 4 KW. The radius of the sonotrode is 2.5 mm, and the anvil has a radius of 1.5 mm. There are two linear sealing seams of ultrasonic sealing for each sample. Heat-sealing experiments were conducted using the laboratory-sealing device of SGPE HCT 320 Labormaster. The parameters that were used in the test are summarized in Table 1.

The tensile testing machine from ZwickRoell GmbH & Co. KG was used for testing. The tensile test was performed by delaminating a non-woven layer and clamping it onto the tensile testing machine. The tensile test was performed at 100 mm/min. All samples were conducted as strips with a width of 15 mm and a 10 mm wide sealing seam across the entire width for heat sealing and adhesive bonding, and two linear seams for ultrasonic sealing. Six samples of heat sealing and ultrasonic sealing and three samples of adhesive bonding were tested. The peel-off angle of the samples was at 180 degrees and the tests were conducted in a climate-controlled environment at 21.8°C and 64% relative humidity (r.h.).

For adhesive bonding experiments, the material was prepared in two different ways. First, the adhesive was applied to commercially available sandwich membranes, compressed to create a defined adhesive bead, and then dried for 24 hours at ambient temperature (Figure 3 left). Additionally, an adhesive was applied to the sealing bead of heat-sealed sandwich membranes (Figure 3 right).

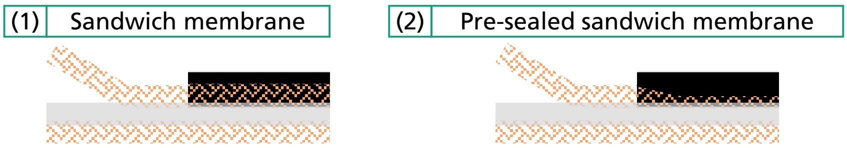


Figure 3: Schematic illustration of sample preparation

4.1 Optical inspection

The following chapter presents the results of the optical inspections, showing the actual structure of the membrane. To investigate the structure of the membrane, it was analysed under a scanning electron microscope (SEM). Additionally, the membrane was imbedded in resin and polished to examine the bond line with a light microscope (Figure 4).

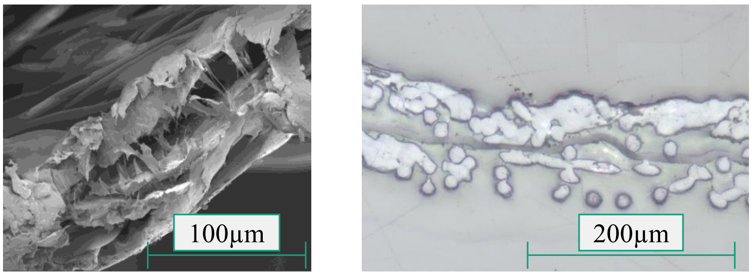


Figure 4: SEM (left) and micrographic inspection (right) of the sandwich membrane

As outlined in the state of the art, the sandwich-membrane consists of a continuous PFSA membrane, which is the active layer between two non-woven reinforcement layers. Due to the non-homogenous surface of the non-woven, the bond between PFSA and the non-woven layer only consists of single fibres enclosed with PFSA, as shown in Figure 4 on the right side. Consequently, adhesive forces between PFSA and the reinforcement layer cannot be as high as they would be if both materials had continuous surfaces. This results in decreased adhesion.

In further research, the process of delamination was examined optically. To this end, the different layers of the non-woven and the PFSA membrane were examined under the microscope and during delamination. It became apparent that one of the non-woven reinforcement layers can be peeled off more easily than the other one. Visually, this difference can not be explained.

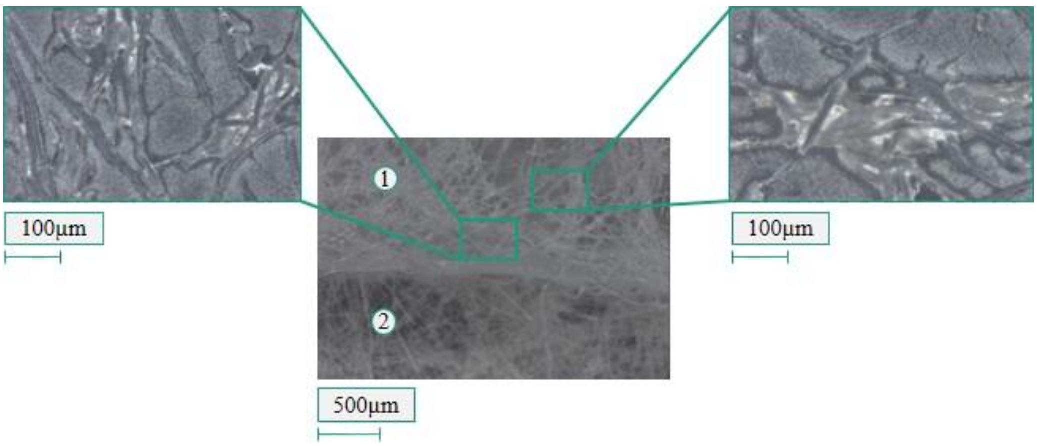


Figure 5: Microscopic image of the peel-off process (middle) and the peeled-off PFSA membrane (side))

Figure 5 shows the microscopic image of the sandwich membrane during the peel-off process. The middle figure illustrates the sandwich membrane. The area marked “2” depicts the peeled-off non-woven reinforcement layer. The upper part shows the remaining sandwich membrane consisting of PFSA membrane and a non-woven layer. The left and right images illustrate the PFSA membrane, once again in enlarged view. Peeled-off non-woven layers were also examined under the SEM. An EDX analysis was performed to obtain the type of material seen in the images.

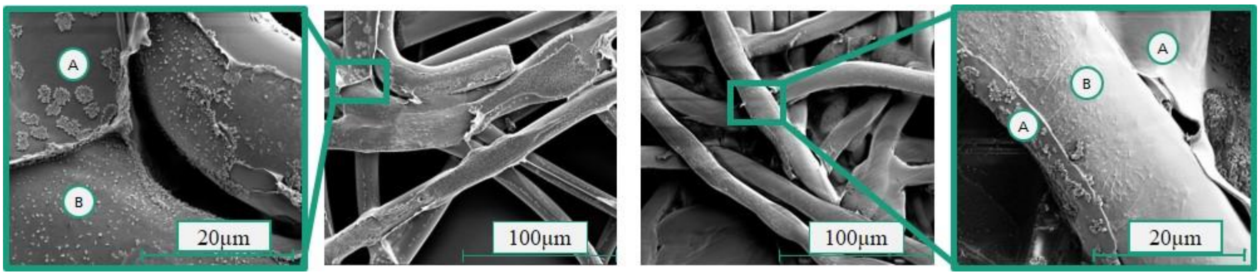


Figure 6: SEM of the dry (left) and wet (right) peeled-off non-woven membrane from the sandwich membrane

Figure 6 shows the peeled-off non-woven layer. In areas marked “A”, the EDX analysis detected mostly carbon and fluorine, leading to the assumption that those areas were PFSA. The SEM recognized carbon and oxygen only in areas marked “B”, mainly in the middle of the fibres. This indicates that those areas are non-woven fibres. There was no difference to be found between the dry peeled-off membrane (on the left side) and the wet peeled-off membrane (on the right side). The thickness of the layer of the PFSA around the fibres is smaller than 500 nm.

4.2 Results of Sealing Experiments

The following paragraph shows the results of the different sealing methods. Three sealing methods were investigated: Sealing by ultrasonic (us) sealing, sealing by heat sealing, and sealing by adhesive bonding. The results of ultrasonic sealing and heat sealing are shown in Figure 7

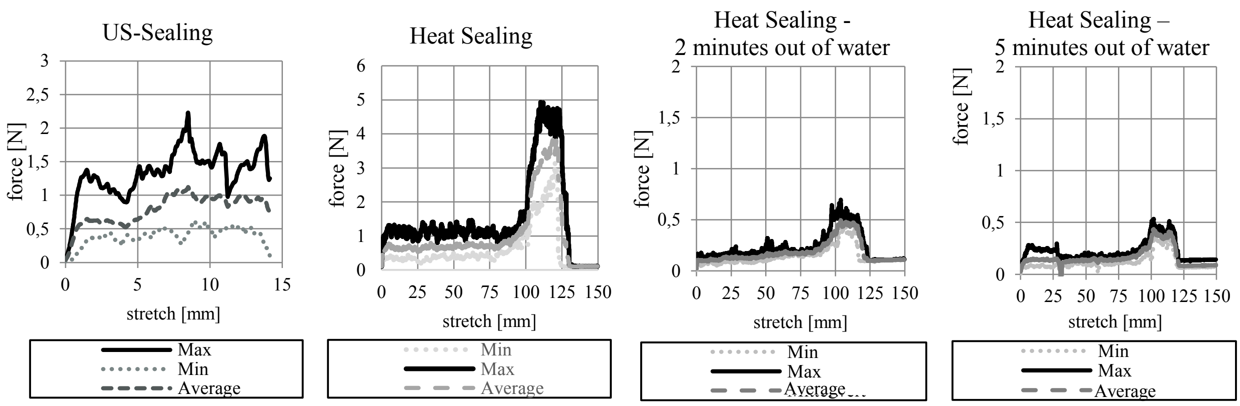


Figure 7: Comparison of tensile tests of ultrasonic sealing and heat sealing, and after water intake

Figure 7 shows that dry ultrasonic-sealed membranes reach a maximum peel strength of 2.23 N, which is significantly lower than the maximum peel strength of heat-sealed membranes (4.93 N). It also shows the difference between non-sealed and sealed areas. Thus, it can be concluded that sealing does in fact have an impact on the peel-off strength of dry membranes. Since heat sealing provided better results, it was chosen for the upcoming experiments. All results are summarized in Table 2.

With wet, heat-sealed membranes (after 2 or 5 minutes out of water), the resistance against delamination is drastically lower than in a dry state. It shows that the maximum peel-off strength of heat-sealed membranes that had been out of water for only 2 minutes is approximately the same as for the reference membrane (non-sealed). Measuring the peel-off strength every 15 minutes demonstrated that resistance against delamination rises with time out of water until it is back at the level of dry heat-sealed membranes. Figure 8 shows the peel-off strength of the sandwich membrane after the climatic chamber and after 30 minutes out of water.

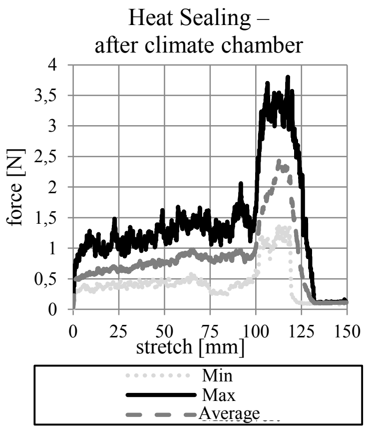


Figure 8: Tensile stress after climatic chamber and after drying process

Figure 8 shows that, after 30 minutes out of water, the resistance against delamination again reaches the level of dry, heat-sealed sandwich membranes. Likewise, the sandwich membrane outside of the climatic chamber is almost in no time at the level of a dry, heat-sealed sandwich-membrane.

To examine an additional non-conventional sealing process, adhesive bonding was investigated as a means to prevent delamination. The investigation assessed whether pre-sealing before adhesive bonding would improve resistance against delamination in the sandwich-membrane samples. The samples were pre-sealed using heat sealing before applying adhesive on the sealing seam. Figure 9 illustrates the results of these experiments.

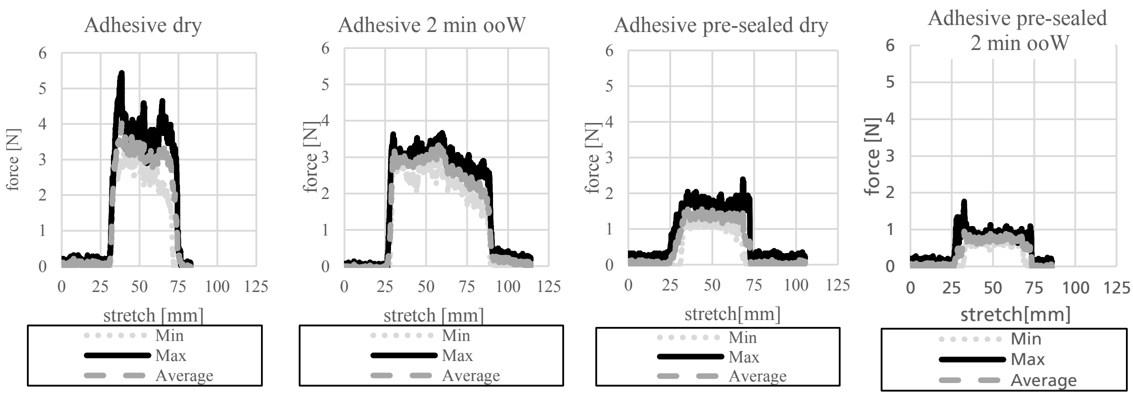


Figure 9: Comparison of tensile test of adhesive bonding as sealing with and without pre-sealing

The resistance against delamination of the dry adhesively bonded membranes is nearly equivalent to that of the heat-sealed membranes (5.43 N adhesive | 4.93 N heat-sealing). Even though the resistance against delamination decreases when submerged in water, the decrease is less pronounced compared to the heat-sealed membranes (3.60 N adhesive | 0.69 N heat-sealing | 2 min ooW). In general, non-pre-sealed membranes are able to sustain higher peel-off forces than pre-sealed membranes. When pre-sealed membranes are exposed to water, the decrease in peel-off strength is more substantial compared to non-pre-sealed membranes. Nevertheless, resistance is still higher than that achieved only by heat sealing. The results are summarized in Table 3.

5. Discussion

5.1 Optical investigations

Figure 5 presents the membrane after the peel-off process. The structure remaining on the PFSA membrane is cratered, resembling a negative imprint of the non-woven fibres. The SEM image in Figure 6 indicates that, typically, the PFSA is present around the fibres and subsequently torn off during the peel-off process. Consequently, the effect of wet delamination is not due to a lack of adhesion but due to lower cohesive forces within the PFSA. A decrease in mechanical strength of PFSA while humidified has been observed in past research [4,8,2] .

Additionally, it was found that one non-woven layer is easier to peel off than the other. This circumstance might be due to the manufacturing process of the sandwich-membranes. Due to the roll-to-roll manufacturing process, the non-woven layers may be applied at different points in time or at different stages in the process.

5.2 Sealing processes

Figure 7 and Figure 8 demonstrate that heat sealing and ultrasonic sealing enhance the pull-off force. This observation points to an adhesive effect. During sealing, the contact area between PFSA membrane and non-woven layers increases, increasing adhesive strength in those areas. Combined with mechanical interlocking, the overall strength of the bonding between PFSA membrane and non-woven layers increases.

Notably, heat sealing proves to be more effective than ultrasonic sealing, which could be expected since ultrasonic sealing uses only a small line contact for sealing. This effect seems to result from two impacts: the non-continuous nature of the non-woven results in pores within the layer. In those areas, melting material is less available (compared to solid materials), potentially leading to lower adherence between non-woven layer and PFSA. Heat sealing allows for sealing a more extensive area, so the probability of melting areas with more fibres is higher. Additionally, the intermittent contact between the non-woven layer and PFSA membrane in the line contact area can result in a non-continuous seam for ultrasonic sealing. Fibres may not be present in some areas along this line of contact. Consequently, ultrasonic sealing exhibits lower durability than heat sealing. In contrast, the seal seam of the heat-sealing process is broader, and by taking more time and pressure, ensures more material in the contact area.

In both cases, water intake weakens the strength of the seal seams. It can be attributed to a two-fold effect. Firstly, the difference in swelling due to water intake for PFSA and a non-woven layer could reduce the adherence between these two materials. [9] Secondly, the mechanical strength of PFSA decreases under humid conditions. [8] This effect is underpinned by the sandwich membrane exhibiting greater resistance against delamination when dry compared to when wet.

Noteworthy is that the effect of decreasing resistance against delamination seems to be reversible. As the membrane gradually dries, the resistance increases once again. Another notable observation is the marked disparity in the effect between the experiments conducted in humid air in the climate chamber and the membranes exposed to pure water. The effect appears to be significantly stronger when PFSA is exposed to pure water rather than humid air. Since water intake of PFSA is drastically higher when exposed to liquid water instead of saturated water vapour [10], it can be assumed that delamination is directly related to water intake of PFSA membranes. This suggests that heat sealing could provide a durable sealing seam during flat humidifier operations when the membrane is not exposed to liquid water.

5.3 Adhesive bonding as sealing

The resistance against delamination for dry adhesively bonded membranes is slightly higher than for heat-sealed membranes. This suggests that the adherence between PFSA membrane and adhesive is slightly stronger than the bonding between heat-sealed non-woven and PFSA membrane. The adhesive effectively fills the pores of the non-woven layer and adheres to PFSA. As a result, the contact area between PFSA and non-woven/adhesive increases, enhancing delamination resistance.

The adhesive bonding experiments did not point to significant differences in peel strength between the wet and dry state. Several explanations could account for this effect. Since the adhesive has an elongation at break of 210 %, it might compensate for the difference in swelling caused by water intake in non-woven fibres and PFSA. Thereby, the adhesive force is maintained. Another possibility is that the adhesive limits the absorption of water of PFSA, resulting in less swelling of PFSA.

When examining the pre-sealed adhesively bonded samples, the resistance against delamination is not equally strong. Pre-sealing the membranes melts the non-woven fibres and therefore closes the pores of the non-woven. Consequently, the adhesive cannot flow through the pores sufficiently and adhere to the PFSA. Hence, the positive effect of adhesive bonding is reduced when dealing with pre-sealed membranes.

6. Conclusion

The goal of this paper was to explore methods to enhance the resistance against delamination in humidified conditions for sandwich membranes during the operation of a flat membrane humidifier. Firstly, the structure of the PFSA membrane was optically analysed. Subsequently, different sealing methods, including ultrasonic sealing, heat sealing, sealing by adhesive bonding support, and sealing by adhesive bonding support with additional pre-sealing were investigated under both dry and wet conditions.

It was observed that conventional sealing technologies did not exhibit a strong positive effect against delamination in wet conditions. However, adhesive bonding support showed promising results, significantly increasing the resistance against delamination in both wet and dry conditions. Surprisingly, the combination of pre-sealing and adhesive bonding did not yield a positive effect. In the end, adhesive bonding as a support against delamination emerged as the most promising approach in this study.

Acknowledgements

The research activities presented in this paper have been supported by the German research project FLAMMi (Industrialisierung FLAchMembranbefeuchterModul). The project has received funding from the Federal Ministry for Economic Affairs and Climate Action.

Appendix

Table 1: Parameter of sealing techniques used (4. Material, Machines, and Methods)

Process	Force	Power	Sealing time	Amplitude
Ultrasonic sealing	500 N	200 W	0.3 s	0.04 mm
Process	Pressure	Temperature	Sealing time	-
Heat sealing	2 MPa	220°C	2 s	-

Table 2: Results of the sealing techniques (4.2. Results of Sealing Experiments)

Process	F_{max}	F_{min}	$F_{Ø}$	SD	SD/ $F_{Ø}$	sample width
Ultrasonic sealing	2.23	0.,96	1.42	0.47	0.33	15 mm
HS - dry	4.93	3.19	4.32	0.61	0.14	15 mm
HS – 2 min ooW	0.69	0.49	0.59	0.07	0.12	15 mm
HS – 5 min ooW	0.8	0.32	0.74	0.05	0.07	15 mm
HS – 10 min ooW	2.81	1.21	1.60	0.61	0.38	15 mm
HS – 20 min ooW	5.16	2.14	4.11	1.03	0.25	15 mm
HS – 30 min ooW	4.18	2.05	3.01	0.92	0.31	15 mm
HS – CC	3.8	1.55	3.25	0.43	0.13	15 mm
reference membrane	0.63	0.54	0.59	0.02	0.03	15 mm

Table 3: Results of sealing techniques (4.2. Results of Sealing Experiments)

Process	F_{max}	F_{min}	$F_{Ø}$	SD	SD/ $F_{Ø}$	sample width
Adhesive dry	5.43 N	3.60 N	4.56 N	0.75	0.16	15 mm
Adhesive 2 min ooW	3.67 N	3.60 N	3.63 N	0.03	0.01	15 mm
Adhesive pre-sealed dry	2.68 N	2.01 N	2.35 N	0.27	0.12	15 mm
Adhesive pre-sealed 2 min ooW	1.91 N	1.41 N	1.62 N	0.21	0.13	15 mm

References

[1] Kaiser, S.A., Baumann, M., Biba, S., Steurer, HU., 2019. Der Ladungswechsel und das Stack-Management von modernen Brennstoffzellen-Systemen, in: Liebl, J. (Ed.), Ladungswechsel und Emissionierung 2018. Im Spannungsfeld von Luftqualität, Klimaschutz und Elektrifizierung 11. MTZ-Fachtagung. Springer Vieweg, Wiesbaden.

[2] Kusoglu, A., Santare, M. H., Karlsson, A. M. Micromechanics Model Based on the Nanostructure of PFSA Membranes, in: , Journal of Polymer Science Part B: Polymer Physics,, 46(22), pp. 2404–2417.

[3] Penner, R.M., Martin, C.R., 1985. Ion Transporting Composite Membranes: I . Nafion-Impregnated Gore-Tex. J. Electrochem. Soc. 132 (2), 514–515.

[4] Choi, S.-Y., Ikhsan, M.M., Jin, K.S., Henkensmeier, D., 2022. Nanostructure-property relationship of two perfluorinated sulfonic acid (PFSA) membranes. Intl J of Energy Research 46 (8), 11265–11277.

[5] Peng, Z., Huguet, P., Deabate, S., Morin, A., Sutor, A.K., 2013. Depth-resolved micro-Raman spectroscopy of tri-layer PFSA membrane for PEM fuel cells: how to obtain reliable inner water contents. J. Raman Spectrosc. 44 (2), 321–328.

[6] Nguyen, H., Klose, C., Metzler, L., Vierrath, S., Breitwieser, M., 2022. Fully Hydrocarbon Membrane Electrode Assemblies for Proton Exchange Membrane Fuel Cells and Electrolyzers: An Engineering Perspective. Advanced Energy Materials 12 (12), 2103559.

[7] Bach, S., Thürling, K., Majschak, J.-P., 2012. Ultrasonic Sealing of Flexible Packaging Films - Principle and Characteristics of an Alternative Sealing Method. Packag. Technol. Sci. 25 (4), 233–248.

[8] Kirsten, W., Krüger, A., Neomagus, H., Bessarabov, D., 2017. Effect of Relative Humidity and Temperature on the Mechanical Properties of PFSA Nafion™-cation-exchanged membranes for Electrochemical Applications. International Journal of Electrochemical Science 12 (3), 2573–2582.

[9] Feng, C., Li, Y., Qu, K., Zhang, Z., He, P., 2019. Mechanical behavior of a hydrated perfluorosulfonic acid membrane at meso and nano scales. RSC advances 9 (17), 9594–9603.

[10] Shi, S., Dursch, T.J., Blake, C., Mukundan, R., Borup, R.L., Weber, A.Z., Kusoglu, A., 2016. Impact of hygrothermal aging on structure/function relationship of perfluorosulfonic-acid membrane. J. Polym. Sci. Part B: Polym. Phys. 54 (5), 570–581.

Biography

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. He studied production engineering at the RWTH Aachen University and is an Alumnus focusing on mechanical engineering and automation

Rebecca Pahmeyer (*1994) is a research associate at the Fraunhofer Institute for Manufacturing Engineering and Automation IPA. Rebecca Pahmeyer joined the Department lightweight construction in 2021. She finished her Masters in production engineering at University Bremen with a background in manufacturing engineering.

Aleksandar Radlovic (*1982) currently serves as a development engineer at MAHLE, specializing in the Product Development Fuel Cell Peripherals department. His journey with the company began in 2008 when he joined the predevelopment department at MAHLE BU2 Filter Systems GmbH. He possesses a degree in mechanical engineering (Dipl.-Ing.) from the University of Stuttgart.

CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
CPSL 2023-2

5th Conference on Production Systems and Logistics

Fixed Route Refueling-Strategy For Fuel Cell Trucks

Achim Kampker, Heiner Heimes, Fabian Schmitt, Maximilian Bayerlein, Philipp Scheffs
PEM/ RWTH Aachen University, Aachen, Germany

Abstract

Road logistics are essential to ensure the smooth flow of production and delivery of goods to their destination. Heavy-duty transportation places high demands on the power supply and driving range. Fuel cell electric powertrains appear to be the most suitable solution in the context of zero-emission targets for long-haul trucks. While several companies are working on the development of drivetrains and vehicle concepts, the supply of the required hydrogen remains a challenge. Many uncertainties in the logistics industry are caused by the lack of hydrogen fuel stations. This paper presents a concept to detect suitable hydrogen fuel stations along a planned route and select those that minimize hydrogen consumption. The concept is applied to a known set of fuel stations in Germany and a fixed route defined by the operational task of the truck. First, fuel stations that are relevant to the operational task are identified. Then, the energy consumption of the refueling strategy is minimized by solving the fixed-route vehicle-refueling problem (FRVRP), taking into account vehicle characteristics and unknowns such as the precise distance to the refueling station. An external application programming interface provides the route information. The optimization is then implemented as a mixed integer program (MIP). The resulting strategy indicates the sequence of fuel stations that need to be visited to reach the route destination in the most energy-efficient way. The implementation of the strategy shows that the operation of heavy-duty hydrogen vehicles in Germany is feasible with certain boundary conditions. Therefore, integrating the refueling strategy into the navigation task to avoid running out of fuel is a step towards reaching the zero-emission targets.

Keywords

hydrogen refueling strategy; hydrogen fuel stations; fixed-route vehicle-refueling problem; fuel cell; heavy-duty truck

1. Introduction

Compared to the refueling problem for vehicles with internal combustion engines or hybrid powertrains, fuel station planning for vehicles with fuel cell (FC) electric powertrains has different challenges. While fuel cost is of interest to operators of conventional trucks [1], keeping the vehicles in operation is an issue for alternative-fueled vehicles [2]. This is due to the lacking amount of fuel stations for alternative fuels and the limited range of vehicles [2]. Germany for example, has 91 operational hydrogen fuel stations, at 700 bar level, by May of 2023 [3]. Out of these, only about ten stations are accessible for trucks [4]. To ensure operability, it is compulsory to combine the navigation of the truck with its fuel planning. Otherwise, there is a risk of running out of fuel and not being able to reach a refueling station. To ensure operability and make FC trucks attractive for operators, an energy management system (EMS) that minimizes hydrogen consumption is developed. The EMS is designed to control the power supply from the FC to the powertrain of the truck. Therefore, it is integrated into an onboard system running in the truck. To ensure the operation of the system and prevent transmission errors, the amount of data transmitted should be as small as possible. The navigational data is supplied by a web API with a response with a high data load. Therefore, the number

DOI: https://doi.org/10.15488/15253
ISSN: 2701-6277

of these requests needs to be limited. Hence, it is an attractive approach to solve the refueling strategy to provide the required amount of hydrogen as an FRVRP.

In this paper, we present a method to solve the FRVRP for FC trucks, defining suitable fuel stations in the first step and deriving a policy, that considers the limited amount of fuel stations and the fuel consumption on the track afterward. First, an overview of the literature is given. Thereafter, the problem is introduced in detail and an approach to solve is presented. We show how an FC truck operation in an environment with fewer refueling stations can be ensured and where further improvements can be made.

2. Literature review

Vehicle routing problems (VRP) try to find a policy that either minimizes one or several route properties, those are e.g. travelled distance [5], fuel costs [5], [6], or aims to fit the routing into a time window [7]. These methods can solve the routing and refueling problem as a whole. To do so, a graph network is required. As this is not available, the “route-first, refueling-policy second” approach [8] is used. This approach solves the routing problem in the first step. Thereafter, the refueling problem is solved for the resulting fixed route. The fixed-route vehicle-refueling problem (FRVRP) divides the route into edge segments that are connected by nodes [9]. Depending on the model, the fuel stations are either assumed to be located on the route, represented by the nodes, or extra miles detouring from the route to the fuel stations are considered [10]. Usually, the edges contain travel distance, travel time, and fuel consumption, whereas nodes can be equipped with data regarding fuel prices and fuel levels [9]. Different approaches, models, and aims for solving the FRVRP are presented. [11] differentiates between heuristic, suboptimal, and exact approaches to optimize the cost function. Out of these, only the exact approaches deliver optimal results. These can be divided into mixed-integer programs (MIP) [11] and dynamic programs (DP) [12]. While most optimizers aim to minimize fuel costs by integrating fuel prices at gas stations [8], [9], [13] minimizing fuel consumption is less common [14], [15]. Besides assuming the fuel station to be located on the node, the impact of detouring to the station is considered. While, [8], and [16], assume a priori knowledge of the distance and the consumption from the route to the fuel station and back, [1] models the detour and retour with the possibility of different lengths. In addition to the cost function, the runtime of the FRVRP algorithms is investigated [17].

In literature, the fuel consumed while traveling the route is either assumed to be constant [8], [16], [17] per distance unit or derived from vehicle models [1], [18], [19]. The authors of [20] derive a cost-optimal refueling strategy from [21] and [8], that includes the compulsory rest periods of truck drivers. In [15] the fuel consumption within an FRVRP is reduced considering the additional fuel demand required when driving a full fuel tank uphill. To minimize the fuel cost of a hybrid electric truck, [18] solves the FRVRP using DP. There the vehicle operation is modelled assuming that the hybrid truck can be operated in four different driving modes. An approach to reduce the amount of considered gas stations is presented in [10], by removing the most expensive stations from the solution space, the computational speed is increased.

As presented above the FRVRP is commonly used to minimize fuel costs. Therefore, a constant fuel consumption per distance unit is assumed. Additionally, it is assumed that the amount of fuel stations is large enough to choose between several stations to reduce costs. To the author’s best knowledge, the FRVRP has never been used to derive an operation policy that enables truck operation for FC trucks. Therefore, a vehicle model will be integrated into the pre-processing to precisely estimate the hydrogen consumption.

3. Problem description

At the moment, the availability of refueling capabilities is one major issue, when operating a FC truck [4]. H2-Mobility [3], a platform to push hydrogen mobility, lists 91 hydrogen refueling stations in Germany that are in operation. Because of this low number, refueling needs to be considered when planning the operation. In the concept of the applied EMS, the refueling strategy is computed onboard the truck, and the "route first, refueling-policy second" [10] approach is implemented. This decision was made to reduce the data stream from and to the truck. The route the FRVRP is solved for is determined by an external, web navigation service. Starting from this 'base' route, two issues arise regarding the refueling policy of the hydrogen truck. First fuel stations along the planned route need to be determined. Second the refueling policy to enable the operation of the truck needs to be determined.

3.1 Bordering refueling stations

The base route the FRVRP is solved for is structured as a row of subsequent nodes and edges connecting starting point, waypoints, and destination. As discussed earlier in this work and shown in [4], the density of hydrogen refueling stations in Germany is sparse. It is obvious that there are regions with one refueling station in a radius of hundred kilometers. This issue requires the implementation of the refueling stations into the operation policy of the truck. After choosing a route, as discussed in [10], unqualified refueling stops, that enlarge the refueling problem, need to be removed. This prevents potentially long detours which would unnecessarily consume fuel. While most literature regarding the FRVRP assumes variable fuel prices in between refueling station, the hydrogen costs per kilogram is assumed to be the same at all stations, which meets the current market situation [3].

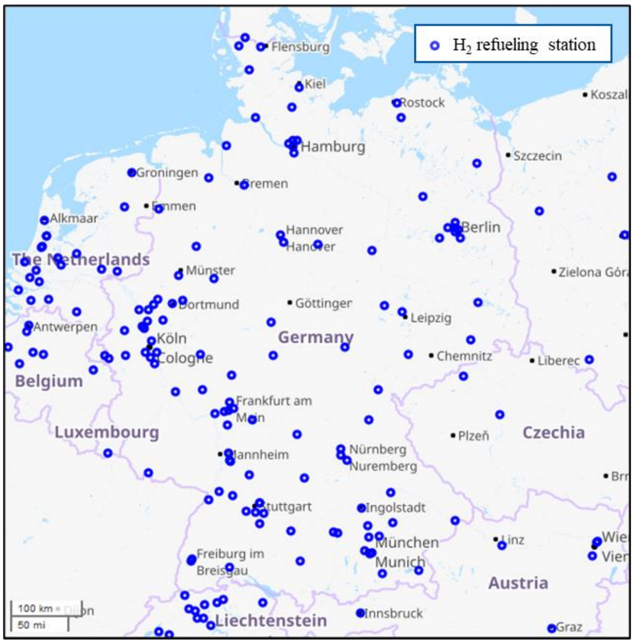


Figure 1: Density and location of hydrogen refueling stations in central Europe [3]

3.2 Refueling policy

After deriving the refueling stations that are located along the route, a policy needs to be found that enables the operation of the truck. FRVRPs operate in a way that the fuel level never falls below the minimum value before reaching a refueling station [9]. Their consumption is usually computed assuming a constant fuel demand per distance unit [1]. This concept is suitable for a policy that is aiming to reduce fuel costs in an environment with a high density of refueling stations, as it is the case for trucks with combustion engines. In that case, running out of fuel can be prevented by targeting a closer refueling station than planned. This leads to higher fuel costs but not to run out of fuel. In a network with a low density of refueling stations, this is not possible. Therefore, to ensure operability, fuel consumption needs to be calculated precisely.

As described above, the aim is to limit the amount of exchanged data. Due to this decision, it is unintentional to request the distance of the detours of all refueling stations that are located along the route from the web

API. Hence the distance between the node and the refueling station of the detour needs to be estimated. The quality of this estimation is afflicted with an error. The total distance and consumption error of the estimation of the detour correlates with its length. Therefore, determining the nearest refueling stations and thereby minimizing the detours reduces this error.

4. Model formulation

To derive the refueling policy the bordering refueling stations and their approximate distance to the route need to be calculated. Thereafter, the FRVRP with the truck model can be solved. The location of the refueling stations as well as the base route from start to destination are known. As described above, the base route is supplied by a web navigation service, that returns the route as a sequence of subsequent nodes and edges attached with meta information regarding distance, travel time, gradients, and location of the nodes.

4.1 Deriving bordering refueling stations

The route, which the refueling problem should be solved for, is defined by a starting point (s), waypoints that should be visited in a predefined order, and a destination (e). The route is given by a sequence of nodes ($n_{s \le i \le e}$) that are separated by the exact same distance. Besides the distance (d) between the nodes, the gradient (g), the assumed travel speed (v), and its specific longitude ($long$), as well as its latitude (lat), are attached to the node. The data containing these values is supplied by the web API. Each node is structured as follows: $\overrightarrow{n_i} = \{d, g, \mathrm{v}, \mathrm{long}, \mathrm{lat}\}$.

Since fuel costs per kilogram are the same for nearly all refueling stations, the stations that are closest to the route are of relevance. Each station that is not bordering the route would lead to unnecessary fuel consumption. Therefore, they are removed. A bordering fuel station is defined as the station that is nearest to a least one node of the route. To determine those stations, the beeline between each node and each station is computed as shown in Figure 2. On the left side of Figure 2, these bordering stations are marked by blue lines. The information on the closest station and the distance are attached to the node. As one station is the closest one in a particular area, it is the closest one to all nodes in the area. Out of these consecutive nodes, one is the closest to the station. Since the route information is known, while the precise detour information is not, minimizing the detour distance reduces the error in the detour approximation. In the following step, the node that is the closest one to a refueling station within a pattern of consecutive nodes is determined. This allows for transforming the route into a sequence of nodes that are the closest to the refueling stations and edges that represent the route from the start via these nodes to the destination. The right side of Figure 2 illustrates the result of calculating the nodes that are the closest to a station of each pattern of nodes. This data set allows solving the FRVRP with a truck model to determine the hydrogen consumption.

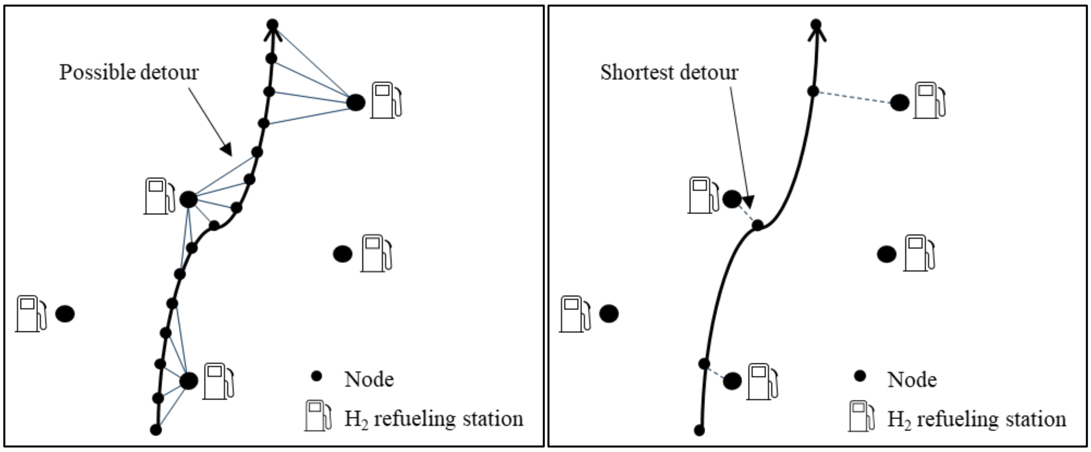


Figure 2: Determination of the closest refueling stations to each node of the route (left); closest node to a refueling station of a pattern of nodes (right)

4.1 Modell of the FC truck

Approaches that solve the FRVRP as presented in [8] and, [11] try to minimize fuel costs in environments with variable fuel costs. Solving the FRVRP with fuel spending as the optimizations cost function minimizes hydrogen consumption as well. To include a precise model of hydrogen consumption into the model, the required energy of the truck and therefore, the power by the engine is determined. The nodes (n) supply the data to compute the forces acting on the truck. Those are the air drag (1), the rolling resistance (2), the slope force (3), and the inertia of the truck.

$$F_{air} = \frac{1}{2}\, \rho\, c_w\, A\, v^2 \tag{1}$$

The air density (ρ), the air drag factor (c_w) as well as the front surface (A) of the truck are constant. This means the air drag (F_{air}) is mainly a function of the velocity (v) that is predicted along the complete route and stored in n.

$$F_{rr} = m\, g\, c_{rr}\, cos(\alpha); \qquad w. \qquad \alpha = arctan(g) \tag{2}$$

The rolling resistance (F_{rr}) is a function of the gradient (g). The vehicles mass (m), the free fall acceleration of the earth (g) and the rolling resistance factor (c_{rr}) are constant.

$$F_{slope} = m\, g\, sin(\alpha); \tag{3}$$

The drag due to inclines is concluded by the slope force (F_{slope}).

$$F_a = m\, a; \qquad w. \qquad a = \dot{v} \tag{4}$$

The inertia force (F_a) is a function of the vehicle acceleration (a), that is the change in the vehicle's velocity ($\dot{v}$) and therefore a function of the velocity.

$$P = \left(F_{air} + F_{rr} + F_{slope} + F_a\right) v \tag{5}$$

The power (P) required to operate the truck is defined by the sum of all the forces Equations (1 – 4) multiplied by velocity. Following these equations, including the efficiencies of the electric motor, gearbox, and inverter, the actual power required at each node is computed. Integrating this power over the travelled distance, to respect the spatial gradient values, and dividing it by the velocity to transform the spatial values, allows us to determine the energy that is required to pass each edge. Dividing the required amount of energy by the FC efficiency, that is depending on the operational strategy, the hydrogen demand is derived. That way the specific amount of hydrogen required for each edge, considering the assumed velocity and the precise gradients, is computed. These edges consecutively connect the start with the nodes closest to the refueling stations, and the destination. The derived hydrogen demand is added to each of the edges, resulting in a sequence of hydrogen demands in between approachable refueling stations.

To include the energy that is required on the route and to reach the refueling stations the concept of [11] is adapted as suggested. Information on the detours is not determined using navigational methods to reduce the data stream as mentioned before. Therefore, the velocity and distance approaching the refueling station need to be approximated. To do so, the distance is assumed to be approximated by the beeline between a node and its corresponding station, multiplied by a safety factor. This allows us to estimate and include the uncertain length of the detour. The speed of the truck on the detour needs to be approximated as well. There, the truck is assumed to constantly travel with the maximum allowed speed on lower-level roads. The detour is assumed to be of zero gradients. Since the detours, to which this estimation is applied, are those closest to the route, the error is assumed to be small compared to the total power demand.

4.2 The modified FRVRP

The data determined in the previous steps are required to determine the truck's hydrogen demand. Based on that information regarding the refueling stations bordering the route, the refueling strategy is planned. The concept is based on the MIP approach presented in [11]. The constraint regarding the minimum amount purchased is removed since the main target is to enable operation. Additionally, the fuel demands are known. The problem consists of the starting node (s), the nodes (r_i) closest to the determined bordering refueling stations, and the destination (d) derived in the previous step. The index (i) references the nodes from start ($i = 1$) to destination ($i = d$). Each node allows a detour to its corresponding refueling station, that requires (fl_i) fuel. There the amount (ref_i) can be refueled. The decision to take the detour and refuel is based on the variable dec_i. dec_i equals one if the detour is made, otherwise, it equals zero. Each edge connecting the nodes requires (f_i) hydrogen, while the fuel level of the truck at each node is given by (l_i). The minimum hydrogen level (l_{min}) allows to have some reserves to counteract errors and compensate for possible unplanned detours. The maximum hydrogen level (l_{max}) is defined by the dimensions of the hydrogen tanks. Since the consumption of each edge and each detour is known explicitly, the MIP writes as follows:

$$min \sum_{i=1}^{d} ref_i \tag{6}$$

With the constraints:

$$l_{min} \leq l_i + fl_i * dec_i - ref_i \tag{7}$$

$$0 \leq ref_i \leq (l_{max} - l_{min}) * dec_i \tag{8}$$

$$l_{max} \geq ref_i + l_{i-1} - f_i - fl_i * dec_i \tag{9}$$

$$l_i = l_{i-1} - f_{i-1} - 2 * fl_i * dec + ref_i \tag{10}$$

$$f_1 + fl_1 \leq l_s \leq l_{max} \tag{11}$$

$$l_d \geq l_{min} \tag{12}$$

$$dec_d = ref_d = 0 \tag{13}$$

Objective (6) minimizes the refueled amount of hydrogen. That way the time and distance of the detours while enabling vehicle operation in minimized also. Constraint (7) ensures that the fuel level does not fall below the minimum allowed. Constraint (8) limits the refueling capacity of the truck relative to the tank volume and defines it as a positive integer. The refueling capacity based on the previous consumption is defined in constraint (9). The fuel level after potential refueling is calculated in equation (10). Constraint (11) defines the fuel level required at the start of the trip. While constraint (12) limits the fuel level when arriving at the destination. The destination constraint (13) prevents potential refueling at the destination node and defines the decision variable and the refueled amount of hydrogen as zero. Refueling for a potential upcoming route is not considered.

If solving the MIP is possible, hydrogen trucks can be operated on the route using the resulting stations of the problem solution. Assuming that the travel speed on the predefined route is higher than the speed on the detours, solving the MIP also minimizes the required time for truck operation. If the MIP is infeasible, operation on the route with the defined minimum hydrogen level and the total fuel capacity of the truck is not possible. In that case either a truck with a larger tank volume needs to be used or the route needs to be changed.

5. Results

The refueling strategy is developed in the SeLv project. The project aims to develop a modular FC electric drivetrain for heavy-duty trucks. The key parameters of the truck are concluded in Table 1. Regarding the network of hydrogen fuel stations at $700\ bar$ level in Germany, some assumptions were made. First, it is assumed that each fuel station can supply the requested amount of hydrogen at any time. Second it is assumed that the stations are accessible for a $41\ tons$ truck. Third, fuel stations under construction are included in the computation. In the following section, the influence and density of the bordering fuel stations are reviewed. Thereafter, the power demand along the route and on the detours is computed. The results of the combined method including the solution of the MIP are discussed in conclusion. There the necessity of a refueling policy for areas with a low density of refueling stations is discussed as well. The policy is reviewed along the testing route of [22] in southern Germany at a length of 342 km. To demonstrate the concept of refueling policy tank capacity was reduced to a fiction value of 12 kg.

Table 1: Key parameters of the SeLv FC truck

Characteristic	Value
Mass	41 tons
Front area	9,94 m^2
Gearbox efficiency	0,95
Electric engine efficiency	0,95
Inverter efficiency	0,95
Auxiliary power demand	15 kW
Tank capacity	68 kg

5.1 Bordering fuel stations

Starting with the route information in a first step the distances between all refueling stations and each node are computed. This step is visualized in the very left map of Figure 3. There the refueling stations closest to each section of the route are marked by a Roman numeral. The areas of the route where a specific refueling station is bordering are marked by a Roman numeral in a white circle. In the specific example, the number of refueling stations that needs to be considered reduces to 7 stations. These have a strongly varying distance to the route. While some stations are in direct proximity to the route, the distance to the closest station reaches values up to 37 km in some sections. In this example, station II is the closest one to a section of the route at a beeline of around 35 km as visualized at the right map of Figure 3.

5.2 Computation of hydrogen demand

After determining the nodes for the potential detours, the hydrogen required for the edges and the detours is computed. This is done by solving the vehicle dynamics equations with information regarding velocity and gradients. The hydrogen demand per edge reaches up to 8 kg while the total trip requires ca. 33 kg of hydrogen. Additional to the edges, up to ca. 2 kg of hydrogen is scheduled to reach refueling station II. The hydrogen consumption to reach each node and the potential refueling station is summarized in Table 2. There the hydrogen demand required to travel an edge is presented in the second column. The additional demand that is consumed when choosing to refuel is summarized in the third column.

5.3 Refueling policy

The MIP is applied to the values of Table 2. Minimizing the overall hydrogen consumption, the MIP schedules three refueling stops. The resulting overall refueling strategy is visualized in the right map of

Figure 3. The detour to refueling station IV is easy to identify, while the detours to stations III and V are difficult to recognize as they are very close to the route.

Table 2: Hydrogen demand of the route and the potential detours

Node closest to	Hydrogen demand from the previous node	Hydrogen demand to station
Station I	0 kg	0,04 kg
Station II	3,11 kg	1,88 kg
Station III	3,53 kg	0,02 kg
Station IV	8,43 kg	0,32 kg
Station V	8,10 kg	0,04 kg
Station VI	6.04 kg	0,68 kg
Station VII/Destination	4,24 kg	0,51 kg

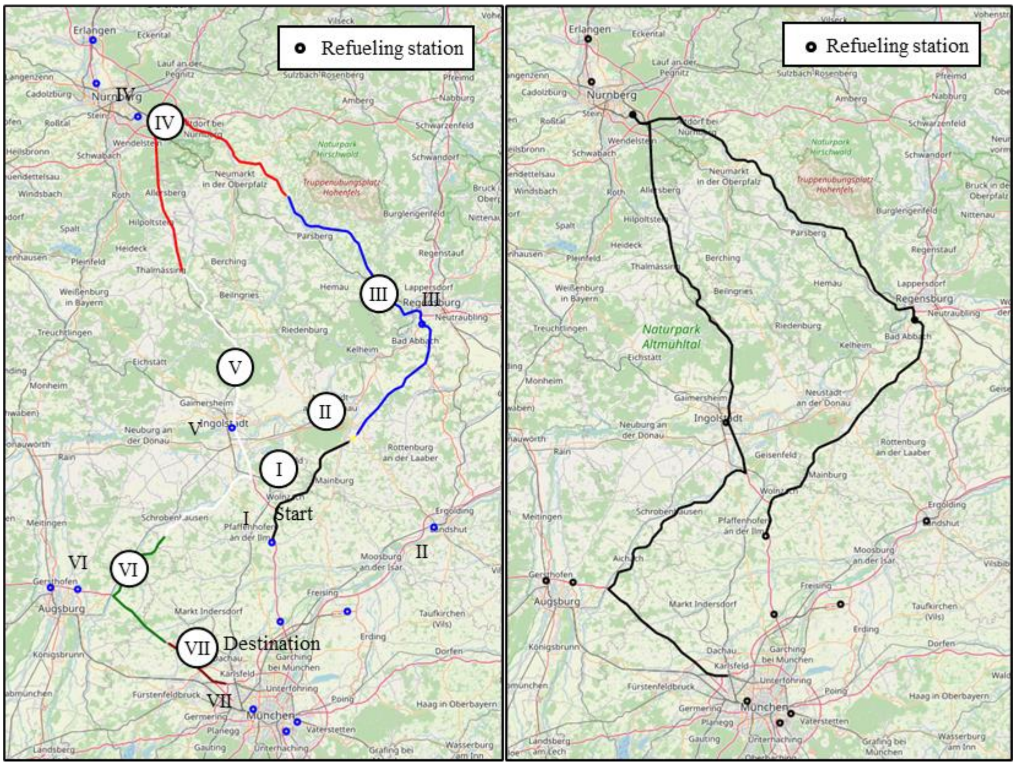


Figure 3: Process of deriving the refueling strategy; deriving the closest refueling stations (left); the overall refueling policy integrating hydrogen consumption (right)

6. Discussion

Applying the policy allows for a potential reduction of hydrogen demand by avoiding long detours to refueling stations. Drivers and fleet operators are provided with a strategy that gives them certainty about the existing supply of hydrogen, visualized by an HMI in the truck, and thus enables smooth and hassle-free operation. Integrating the hydrogen demand from the FC operation strategy into the policy returns a precise estimation of the fuel consumption and therefore supports a qualitative selection of the optimal refueling station. Determining the refueling stations closest to the route allows for the selection of the optimal station possible as well. We can show, that by implementing the presented method it is possible to operate FC trucks all over Germany as the gaps between the refueling stations can be overcome easily with knowledge of the station’s locations. As discussed before the derived refueling stations need to be targeted to ensure operability in the sparse network of hydrogen refueling stations. Overall, this policy and the generated strategy will help enable hydrogen truck operation on German roads.

7. Conclusion

In this paper, the issue of operating FC trucks in an environment with a sparse refueling station density is addressed. It is shown that most research focuses on diesel trucks with a high density of refueling stations and that predominantly the fuel consumption is assumed to be constant per distance unit. The problems of the bordering refueling station and the subsequent refueling policy are discussed. To determine the closest station to the route, the beeline between each node and each refueling station is computed. Based on the set of bordering refueling stations the optimal refueling strategy is derived, solving the refueling problem as an MIP. This way it is shown that it is possible to operate FC trucks on German highways when considering the locations of the refueling stations.

Acknowledgments

The presented results have been developed under the scope of the research project SeLv as part of the realization of the Federal Government's Mobility and Fuel Strategy ("Mobilitäts- und Kraftstoffstrategie"; MKs) by the Federal Ministry for Digital and Transport (BMDV, former BMVI). The funding measure is coordinated by Now GmbH.

References

[1] Bernhardt, A., 2019. Decision support in international long-haul freight transportation for the planning of rest periods breaks and vehicle refueling. Universität Bremen; FB7 Wirtschaftswissenschaften.

[2] Jeong, I.-J., Illades Boy, C.A., 2018. Routing and refueling plans to minimize travel time in alternative-fuel vehicles. International Journal of Sustainable Transportation 12 (8), 583–591.

[3] H2 MOBILITY Deutschland GmbH & Co. KG, 2023. www.h2.live. https://h2.live/. Accessed 5 March 2023.

[4] Heimes, H., Kampker, A., Kehrer, M., Hagedorn, S., Biegler, S., Hausmann, J., 2023. Strategien zur Erreichung der Emissionsziele im Nutzfahrzeugsektor. https://www.pem.rwth-aachen.de/cms/PEM/Der-Lehrstuhl/~hwpp/Aktuelle-Downloads/. Accessed 8 June 2023.

[5] Neves-Moreira, F., Amorim-Lopes, M., Amorim, P., 2020. The multi-period vehicle routing problem with refueling decisions: Traveling further to decrease fuel cost? Transportation Research Part E: Logistics and Transportation Review 133, 101817.

[6] Suzuki, Y., Dai, J., 2012. Reducing the Fuel Cost of Motor Carriers by Using Optimal Routing and Refueling Policies. Transportation Journal 51 (2), 145–163.

[7] Solomon, M.M., 1987. Algorithms for the Vehicle Routing and Scheduling Problems with Time Window Constraints. Operations Research 35 (2), 254–265.

[8] Suzuki, Y., 2008. A generic model of motor-carrier fuel optimization. Naval Research Logistics 55 (8), 737–746.

[9] Lin, S.-H., Gertsch, N., Russell, J.R., 2007. A linear-time algorithm for finding optimal vehicle refueling policies. Operations Research Letters 35 (3), 290–296.

[10] Suzuki, Y., 2014. A variable-reduction technique for the fixed-route vehicle-refueling problem. Computers & Industrial Engineering 67, 204–215.

[11] Schulz, A., Suzuki, Y., 2022. Bounds and valid inequalities for the fixed-route vehicle-refueling problem. Computers & Industrial Engineering 170, 108340.

[12] Aubeck, F., Peter, T., Birmes, G., Savelsberg, R., Pischinger, S., 2019. Refueling and Battery Charging Driver Assistance System for Online Operation Optimization of Connected Vehicles, in: IV19. 30th IEEE Intelligent Vehicles Symposium : 9-12 June 2019, Paris. Piscataway, pp. 606–613.

[13] Hong Lin, S., Gertsch, N., Russell, J.R., 2007. A linear-time algorithm for finding optimal vehicle refueling policies. Operations Research Letters 35 (3), 290–296.

[14] Suzuki, Y., 2011. A new truck-routing approach for reducing fuel consumption and pollutants emission. Transportation Research Part D: Transport and Environment 16 (1), 73–77.

[15] Suzuki, Y., Lan, B., 2018. Cutting fuel consumption of truckload carriers by using new enhanced refueling policies. International Journal of Production Economics 202, 69–80.

[16] Suzuki, Y., 2009. A decision support system of dynamic vehicle refueling. Decision Support Systems 46 (2), 522–531.

[17] Khuller, S., Malekian, A., Mestre, J., 2011. To fill or not to fill. ACM Trans. Algorithms 7 (3), 1–16.

[18] Aubeck, F. Modular strukturierte Optimierung des Energiemanagements in Hybridfahrzeugen: Modulary structured optimization of the energy management in hybrid vehicles, Aachen.

[19] Xiao, Y., Zhao, Q., Kaku, I., Xu, Y., 2012. Development of a fuel consumption optimization model for the capacitated vehicle routing problem. Computers & Operations Research 39 (7), 1419–1431.

[20] Aubeck, F., Birmes, G., Pischinger, S., 2019. V2G Connected Battery Recharging and Refueling Driver Assistance System to Optimize Long Distance Operation, in: The 2019 IEEE Intelligent Transportation Systems Conference - ITSC. Auckland, New Zealand, 27-30 October 2019. IEEE, Piscataway, NJ, pp. 4425–4430.

[21] Bernhardt, A., Melo, T., Bousonville, T., Kopfer, H., 2017. Truck driver scheduling with combined planning of rest periods, breaks and vehicle refueling. Schriftenreihe Logistik der Fakultät für Wirtschaftswissenschaften der htw saar 14. Saarbrücken: https://www.econstor.eu/handle/10419/175088.

[22] Burgdorf, J., 2022. Trucker Supertest: Strom im Tank! 2022/1 1. Springer Fachmedien München GmbH.

Biography

Achim Kampker (*1976) is head of the chair "Production Engineering of E-Mobility Components" (PEM) of RWTH Aachen University and is known for his co-development of the "StreetScooter" electric vehicle. Kampker also acts as a 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. From March 2019 to 2023, he was PEM's Executive Chief Engineer before being appointed Professor.

Fabian Schmitt (*1980) is the division manager responsible for the zero-emissions trucks projects at the Chair of Production Engineering of E-Mobility Components (PEM) at RWTH Aachen University. He is co-developer of the electric vehicle "StreetScooter".

Maximilian Bayerlein (*1997) is a research associate at the Chair of Production Engineering of E-Mobility Components (PEM) at RWTH Aachen University. He studied mechanical engineering at the Technical University of Munich (TUM) with a specialization in automotive engineering.

Philipp Scheffs (*1999) is a student assistant at the Chair of Production Engineering of E-Mobility Components (PEM) at RWTH Aachen University. There he is currently studying industrial engineering.

CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
CPSL 2023-2

5th Conference on Production Systems and Logistics

Design and Analysis of Mechanical Gripper Technologies for Handling Mesh Electrodes in Electrolysis Cell Production

Martin Römer[1], Benjamin Winter[1], Edgaras Mazeika[1], Klaus Dröder[1,2]

[1]*Institute of Machine Tools and Production Technology, Technische Universität Braunschweig, Braunschweig, Germany*

[2]*Fraunhofer Institute for Surface Engineering and Thin Films IST, Braunschweig, Germany*

Abstract

As climate change accelerates, the demand for green energy is increasing significantly. Due to the intermittent nature of renewable energy, the necessity of long-term storage is growing at the same rate. Hydrogen presents itself as a promising option for long-term storage, the demand for electrolysis plants is therefore increasing significantly. Solutions for scaling up alkaline electrolysis production are currently lacking, particularly in the handling of the conventionally used large mesh electrodes. Therefore, new gripping concepts and technologies have to be developed to enable precise and automated handling of these electrodes, as established handling methods have failed due to the porous, limp and weak magnetic material properties. The present research therefore demonstrates two new ingressive gripping systems in the form of individual gripping elements, which can be combined to form a gripper. The technologies identified here are based on threaded or spiral-like structures. Depending on the handled mesh geometry, the gripper elements are designed accordingly. In order to grip the wire mesh, the gripping element is moved translationally and rotationally synchronized. As a validation, sample gripper elements were tested for a range of mesh geometries. The individual gripper elements were produced using the Selective Laser Melting process (SLM), as the fine structures would be exceedingly challenging as well as very costly to produce using conventional manufacturing methods. The gripper elements were tested for three aspects of the handling process: Reliability, retention force and precision. The results exhibit a high holding force for fine meshes with the spiral structures, while the results with the examined screw structures demonstrate the possibility for a very high positioning accuracy. Consequently, potential use cases can be derived for both structures for the handling of mesh electrodes enabling new possibilities for the automated assembly of wire meshes for electrolysis cell production.

Keywords

Electrolysis cell production; Handling; Meshes; Selective Laser Melting; Robotics

1. Introduction

To meet the growing demand for hydrogen in Germany, estimated for 2023 at 90-110 TWh, the installed electrolysis capacity has to be increased significantly [1]. Since alkaline electrolysis (AEL) is considered the most developed technology to meet this demand, the production capacity of AEL manufacturing must be substantially expanded [2]. The most promising increase in production capacity is expected from an automation of the currently predominantly manual assembly of AEL cells. A major challenge for the automation of these processes is the lack of handling and gripping technologies for AEL electrodes, which consist of regular nickel-based mesh structures in order to provide a large surface area. A wire mesh is often used for the electrodes [3–6], consisting of regularly woven metal wire, usually in plain weave. They can be

DOI: https://doi.org/10.15488/15297
ISSN: 2701-6277

described geometrically by the mesh size w_m and the wire diameter d_m (Figure 1). Accordingly, the mesh height is twice the wire diameter $2\ d_m$ [7].

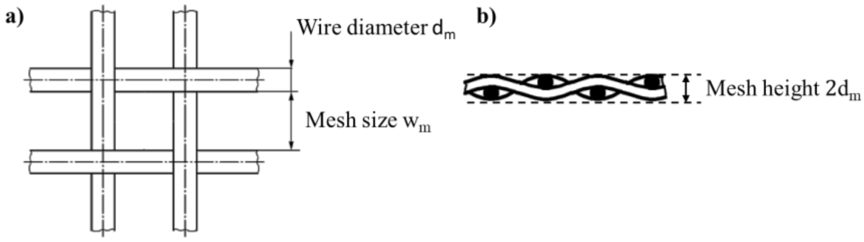


Figure 1: Structure of wire meshes according to DIN ISO 9044 in top view (a) and side view (b) [7]

The high permeability of the mesh structure restricts an implementation of vacuum and Bernoulli grippers. Conventional mechanical handling systems such as yaw grippers are also not feasible in the majority of cases, as it is only possible to grip the edges of the mesh, which would lead to fraying of the wires at the edges and negatively affect the assembly process. The utilization of magnetic grippers is complicated by the almost tenfold lower relative magnetic permeability of nickel compared to steel (material weakening) and by the geometrically low mass filling degree in the magnetic field (geometric weakening) [8]. Therefore, almost the entire surface of the wire mesh would have to be covered with magnetic grippers, making this solution economically unattractive. Currently, there are very few studies on automated wire mesh handling, therefore solutions for the handling of similar structures is briefly discussed. The handling of porous and permeable materials with limited leakage, such as textiles, is often attempted with classical vacuum handling by increasing the suction volume flow, e.g. with Coanda ejectors [9]. Larger wire meshes, such as those used to reinforce concrete structures, can be handled with simple yaw grippers due to large wire diameters of several millimetres and large mesh size. However, as the components of the AEL cells are fine wire meshes (i.e. mesh size and wire diameter $\approx$ 0.5 mm), these solutions are not suitable for this case. One possibility is to use ingressive grippers, which create a holding force through a penetration of the component. This principle is used, for example, in the handling of organic sheets or textiles with needle grippers [10,11]. The use of conventional needle grippers has already been tested in preliminary trials. However, the penetration of various needle sizes caused unacceptable damage to wire meshes of various mesh sizes in the form of elongation and displacement, affecting the deposition accuracies as well as overall geometry tolerances. Thus, new gripper technologies have to be developed. The concept of an ingressive spiral gripper has been shown by Tilli et al. [12] as a possible solution for handling heavy, deformable components. This concept is transferred for the handling of lighter but also flexible wire meshes in the following chapters. For this, the development of innovative approaches is discussed in this study with the following goals:

- Design and development of ingressive grippers for the handling of fine wire meshes
- Prototypical manufacturing and testing of various dimensions and designs of the gripper
- Experimental analysis of reliability, retention force and handling accuracy

2. Materials and Methods

2.1 Design of the gripper elements

In the following, two new gripping principles for the handling of electrode meshes are presented. The principle of the two gripper designs is based on rotating a helix-shaped structure into a single mesh opening create a force and form fit. The first structure investigated in the present study is designed as the simplest form of this principle, a spiral. The second structure is a screw-like design, reinforcing the stability of the spiral with a central axis. For larger electrode meshes in the range up to 14 m^2, which are common for AEL

[13], the gripping system must consist of a larger number of these elements in order to enable a stable handling during the entire assembly process.

2.1.1 Spiral gripper concept

In order for the spiral to fit through the mesh and develop a reliable retention force without damaging it, its geometry must be matched to the wire mesh. Therefore, a specific gripper geometry has to be developed for each mesh. To describe the geometry of the spiral the diameter d_{sp}, the outer diameter D_a, and the pitch P_{sp} have to be determined. The spirals diameter d_{sp} should be selected as large as possible to achieve the highest possible rigidity, especially for fine wire meshes. However, too large diameters will make impede the penetrability of the mesh. Therefore, the mesh size itself is the boundary condition for the spiral diameter d_{sp}. Therefore for the following calculations, a limit of $d_{sp} \leq 0.75\ w_m$ has been set. Furthermore, the outer diameter D_a of the spiral must cover the diagonal of a mesh (Figure 2a).

$$D_a \geq \sqrt{2}(w_m + d_m) \tag{1}$$

To simplify the pitch calculation, the mesh wires between two crossing points are assumed to be straight and resemble an oval rod with aspects d_m and $2\ d_m$ (Figure 2b). Therefore, the outer diameter of the spiral must cover the diagonal of a mesh (Figure 2).

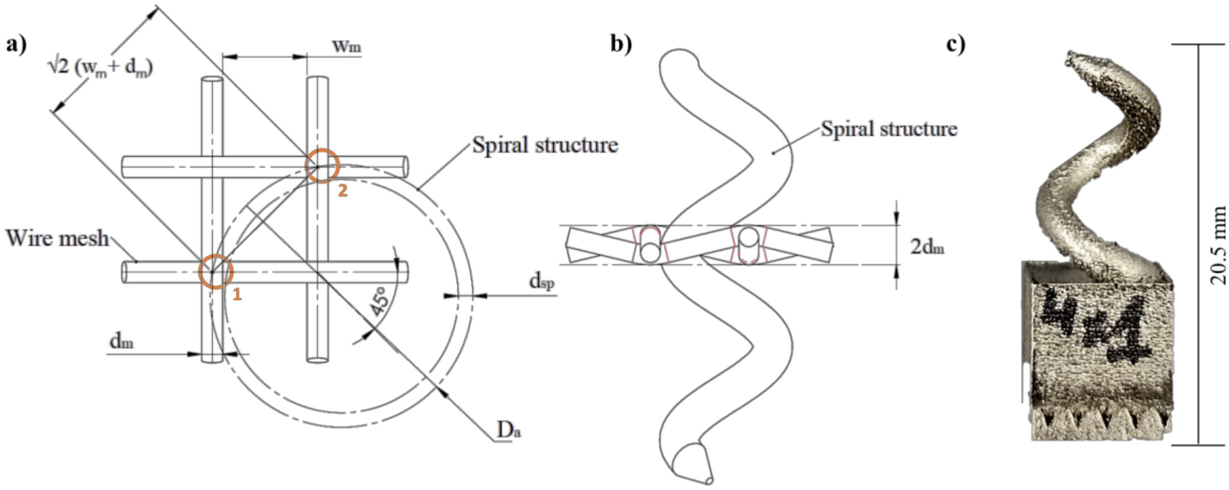


Figure 2: Contact points of the spiral structure with the mesh (a) and side view of spiral structure passing the mesh (b); gripping element produced with SLM (c)

Within the distance of the two points drawn (1 to 2), the pitch must be at least large enough to bridge the path of the mesh height $2\ d_m$ and the spiral diameter d_{sp}. Depending on the selected outer radius, the following formula applies:

$$P_{sp} \geq \frac{\pi}{\arcsin\left(\frac{\sqrt{2}(w_m+d_m)}{D_a}\right)} \cdot (2d_m+d_{sp}) \tag{2}$$

2.1.2 Screw gripper concept

As an enhancement of the spiral to increase stiffness, a central axis was added to create a screw like structure which is based on the design of auger core drills [14]. When the gripper element is rotated into the wire mesh, the axis of rotation must be eccentric to the centre of the single mesh, resulting in three points of contact with the mesh (Figure 3a). Two lateral contact points (1, 2) define the position of the screw to the mesh. The third contact point below the mesh wire (3) creates the form fit and is critical to the gripper element load carrying capacity. To achieve the three contact points, the screw geometry must be matched to the mesh geometry in terms of axis diameter d_s, the bar height h_s and the screw pitch P_s.

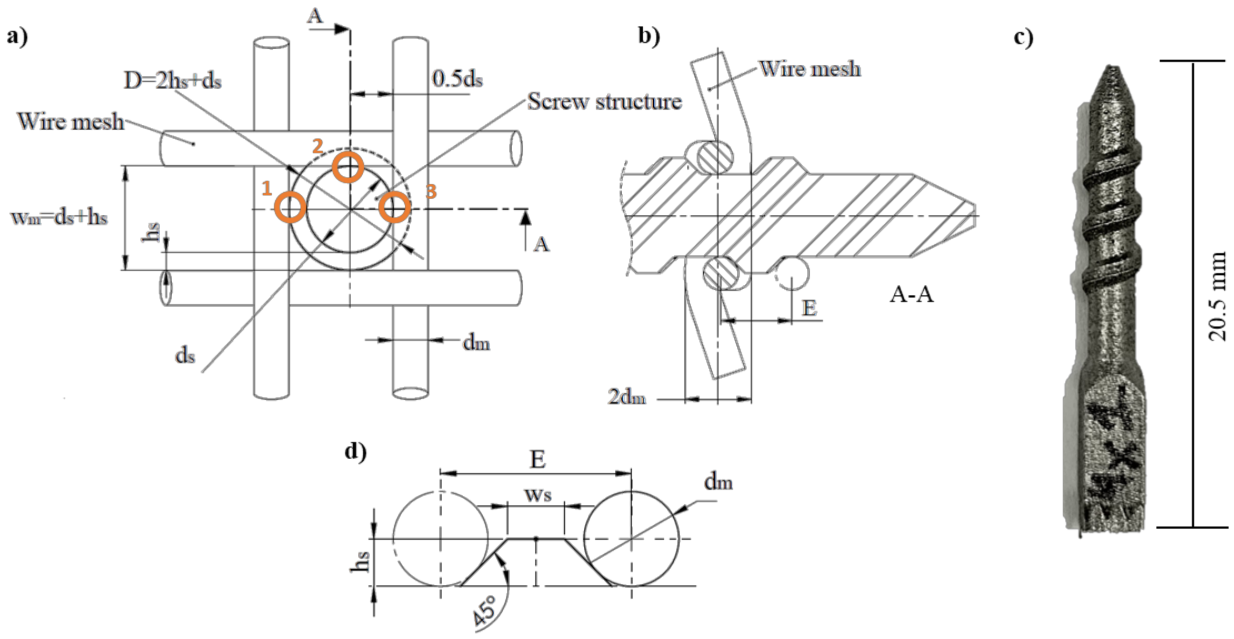


Figure 3: Geometric illustration of the screw gripper element in top view (a), and side view (b); gripping element produced with SLM (c), close-up to screw rod (d)

In order to pass the mesh, the axis diameter d_s and the bar height h_s must not be greater than the mesh size. To maximize the strength of the gripping element, the axis diameter must be as large as possible, but the bar height must be sufficient to provide a good contact surface so that the mesh does not slip under load. In this case, a bar height of at least half the wire diameter is recommended.

$$d_s = w_m - h_s \quad \text{with} \quad h_s \leq 0.5\, d_m \tag{3}$$

To reach the required contact points and be able to grip the wire mesh, the screw must reach the mesh height of $2\, d_m$ within three quarters turn (Figure 3a contact points 2 and 3) and bridging the height of the screw rod E (Figure 3c). Therefore, the pitch is calculated as follows:

$$P_s \geq \frac{4}{3}\left[2h_s + w_s + d_m\left(1+\sqrt{2}\right)\right] = \frac{4}{3}\, E \tag{4}$$

The variable w_s describes the thickness of the bar. While it is freely selectable, it must be considered in relation to the achievable precision of the manufacturing process. For the manufacturing of the gripper element specimens, w_s was selected as 1.0 mm. At the minimum allowable pitch, the mesh is additionally clamped between two screw flanks. However, the increased stability of the gripping leads to a smaller tolerance window in the gripping process and thus lowers gripping reliability.

2.2 Gripper geometry manufacturing

Due to the geometrical freedom and the manufacturability of delicate structures, the gripper elements were generated using the SLM process. Compared to other additive processes for metals, this process enables a high mechanical strength with a material density of almost 100% [15]. A SLM125 from SLM Solutions Group AG is used for manufacturing the grippers, which are generated using the martensitic stainless steel 15-5PH with a powder grain size of 15 – 45 µm with the process parameters shown in Table 1.

Table 1: Process parameters used to generate the gripper geometries

Laser power	Laser focus	Scanning speed	Layer thickness	Hatching distance
248 W	66.4 µm	840 mm/s	50 µm	120 µm

2.3 Analysis of handling properties

To determine the suitability of the gripping principles on mesh components, three aspects of the gripping process - reliability, retention force and handling accuracy - are evaluated. The grippers are investigated on a set of nine wire meshes with various mesh sizes and wire diameters (see Appendix 1). As described in the previous sections, the gripper geometry has to be developed specifically for each wire mesh. Two gripping elements are used for the test, since the use of a single gripping element can lead to unwanted rotation of the mesh sample. These gripper elements are clamped in a gripping jig, which is mounted on a KUKA KR6 industrial robot with a repeatability of ± 0.05 mm. To pick up the wire mesh, the gripper elements are synchronously inserted into the mesh. For the gripping process the gripper elements are rotated by 360°, in order to enable a reliable releasing process, the elements are rotated backwards by 380° for releasing the meshes. The rotation speed of the gripping element was set to 60°/s. The feed rate is set according to the respective thread pitch. Tilting can be assumed to be negligible due to the three contact points per element.

The reliability is tested by successfully gripping, holding and releasing. A total of ten repeated handling operations are carried out for each tested wire mesh. For this experiment, the wire mesh is gripped from a flat surface and held at a defined height of 100 mm for 10 s before releasing it on that surface again. Reliability is determined for each of the three steps separately. Gripper elements whose reliability in any of the operations is less than 50%, or which are damaged during the test, are not included in the retention force and handling accuracy analysis. To determine the maximum retention force of the gripper element, a common scenario is used, where a robot is used to pull vertically on a clamped component, while measuring the force the applied force [16,17]. The force is measured with a K6D40 200 N load cell from ME Messsysteme GmbH, which is mounted between the robot and the gripping device. This experiment is repeated five times with a pull-off-speed of 1.2 mm/s and stopped at a maximum force of 50 N to avoid damaging the wire mesh or gripper elements. The obtained value therefore represents the retention force of two gripper elements.

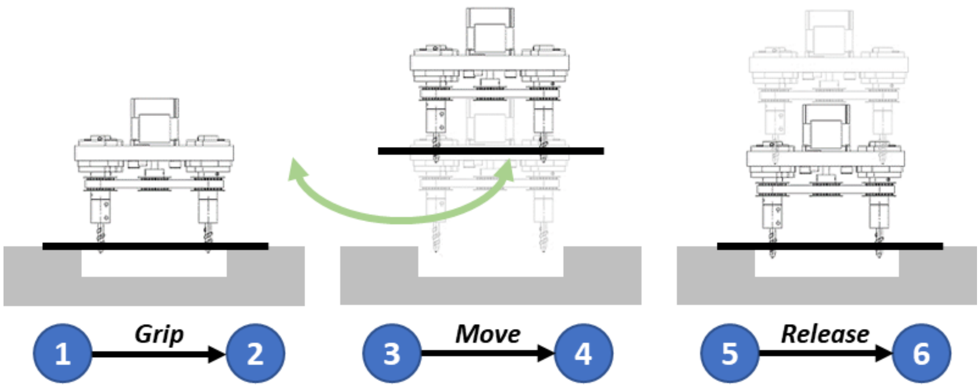


Figure 4: Illustration of the six measurement points implemented during experiments for the determination of the handling accuracy

The achievable precision is determined in a three-step process of *gripping*, *moving* and *releasing* (Figure 4). The displacement of the wire mesh after each of the three steps is calculated by comparing the position before and after the respective action. A 20 MP camera is used to measure the positions. The wire mesh is placed on a flat surface. Firstly, the gripping accuracy is measured by comparing the start position and the position after gripping (1 to 2) and calculating the displacement in X, Y and rotation around the Z-axis (RZ).

Secondly the wire mesh is lifted and a lateral handling trajectory is performed with a distance of ≈1 m each way on a section of a circular path (radius ≈580 mm) at a maximum speed of 2.5 m/s and maximum acceleration of the robot to simulate the effects of lateral process forces. The move accuracy is then calculated by comparing the wire mesh position before and after the simulated trajectory (3 to 4). Finally, the release accuracy is again calculated from the displacement before and after the mesh is released back onto the surface (5 to 6). Additionally, the total displacement of the wire mesh after the handling operation is determined by the difference between the positions of (1) and (6).

2.4 Determination of the manufacturing-related reproducibility

The gripper elements described are manufactured in various dimensions down to a minimum cross-section of 0.31 mm. Due to the high thermal loads during processing, thermal distortion and inhomogeneity can occur in the component, which can increase the risk of gripper elements breaking. This raises the question of the manufacturing-related influences on the geometries and the mechanical properties. This issue is investigated using tensile tests and CT scans. The tensile tests are carried out according to DIN EN ISO 6892-1:2019 [18], using non-standardized specimens. The gripper elements are extended by two clamping bases on each side for clamping in a Zwick Roell Z50 testing machine. A strain controlled test speed of 0.00025 1/s is used. The aim is to measure the forces in order to derive a statement about the maximum possible retention force of each gripper element. In addition, the geometric dimensional accuracy and reproducibility of the CT scan are also investigated. For reconstruction and measurement, the geometries were scanned using the FF35 CT from Comet Yxlon GmbH.

3. Results

3.1 Handling properties

All gripper elements studied achieved 100% reliability during holding; therefore these values are not discussed further. For wire meshes with a wire diameter equal and above 2 mm, the spiral gripper elements achieve 100% reliability during gripping and, with one exception, also during release (see Figure 5). For finer meshes, reliability depends on the ratio of mesh size and wire diameter. Wire meshes with larger diameters and the same mesh size (therefore higher rigidity) lead to a reduction in reliability and an increased risk of damage to the gripper elements. This is observable with the combination 1 x 0.28 / 1 x 0.63 mm and the 0.5 x 0.14 / 0.5 x 0.32 mm combinations. Therefore, for fine mesh structures with larger wire diameter the gripper is not suitable in its current design. Also the reliability for gripping is slightly higher than for releasing.

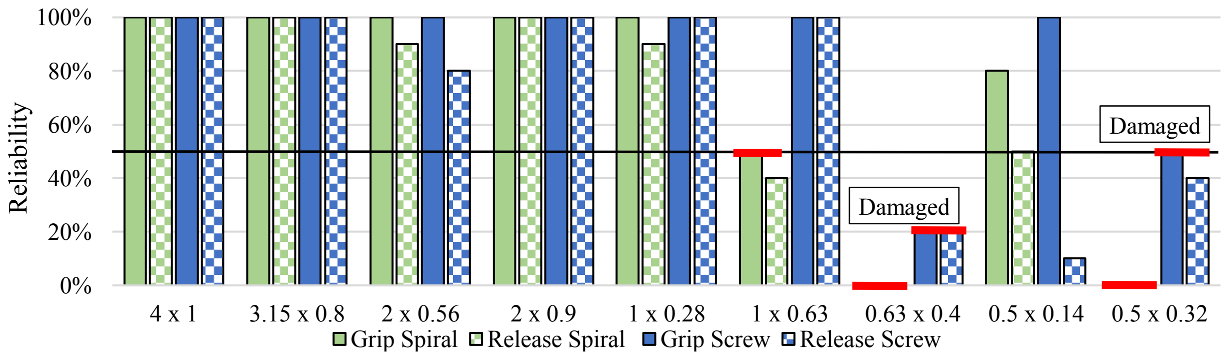


Figure 5: Reliability of the spiral gripper with different wire mesh geometries with sample size ten, experiments resulting in damage to the gripper are highlighted in red

The screw gripper achieved a consistent high reliability even for finer meshes. A difference in gripping and releasing similar to the spiral gripper does not occur. A clear exception is the 0.5 x 0.14 mm wire mesh. It is assumed, that the rough surface of the fine screw resulting from the manufacturing process negatively impacts the releasing process. This surface roughness can also be detected on the CT scans. Particularly in the case of smaller screw geometries with a core diameter of less than 0.75 mm, rough and partially undefined screw flanks can be detected (see Appendix 2). Due to the damage to the gripper during reliability tests, the gripper elements of spiral and screw concept were excluded for the 0.63 x 0.4 mm and 0.5 x 0.32 mm wire meshes and the spiral gripping element for 1 x 0.63 mm wire mesh for the retention test. For the spiral gripper, with the exception of the 4 x 1 mm wire mesh, a decreasing retention force can be observed as the mesh size decreases. Under load, the finer spirals stretch earlier and allow the wire mesh to slip accordingly. The values for the screw geometry do not show a regular progression. In comparison, the spiral geometry achieves a higher force than the screw geometry, with the exception of the 2 x 0.9 mm wire mesh (Figure 6). The reason for the higher retention force, especially in fine structures, is considered to be the improved form fit of the spiral geometry. On the one hand, the bearing surface of the spiral is higher than the screw, even for finer structures. On the other hand, the screw structures in the range of core diameters smaller than 0.75 mm have an undefined structure due to the manufacturing process, which hinders a form fit (see Appendix 2).

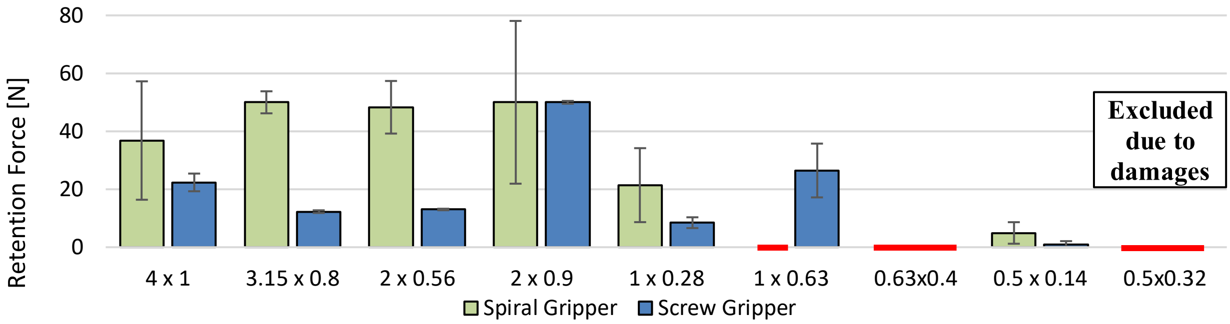


Figure 6: Average retention forces of spiral and screw gripper on wire mesh geometries with a sample size of five

A major disadvantage of the spiral geometry can be seen by comparing the component displacement during the handling. Comparing the precision results of the two gripping elements, the spiral element shows both a higher average deviation and an increased scattering of the position deviations. An exception is the wire mesh 2 x 0.9 (Figure 7). This may be due to the more favourable position of the contact points and the central axis of the screw, which, unlike the spiral geometry, stabilize the wire mesh. Although the displacements during the gripping and releasing process are comparably high with the geometry of the screw, but the total displacement remains small. This results in a reversible displacement of the component. This effect is not observed with the spiral geometry. The screw geometry can therefore be described as more precise in comparison. The individual values of all precision tests are given in Appendix 3.

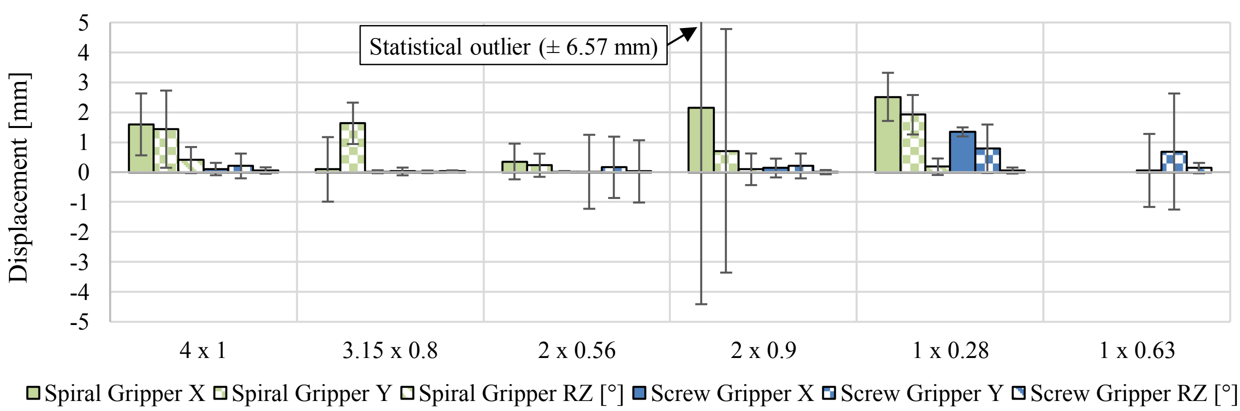


Figure 7: Average overall displacement of wire meshes handled with spiral and screw gripper with sample size 10 subdivided into X, Y and RZ

3.2 Geometrical and mechanical properties of the gripper geometries

The correlation of the wire meshes and the gripper geometries with the mean values of the maximum retention force is shown in Figure 8. While the spirals are under torsion, bending and tensile stress, the screws are only loaded by tensile stress. As a result, the spirals generally achieve lower maximum retention forces across all the wire meshes studied. In comparison, a larger number of spiral grippers must be used to handle a wire mesh than screw grippers. Furthermore, compared to the spiral geometries, the calculated standard deviations indicate a higher reproducibility of the screw geometries. As the core diameters of the screw geometries become smaller, the standard deviations of the maximum holding force increase, indicating less reproducibility of the geometries through the manufacturing process. The CT scans supports this assumption. Various defects are visible as interconnected material dots and inaccurate screw geometries for these sizes. For core diameters of 0.75 mm and above, accurately defined screw geometries are possible, which also reflect the higher handling properties in the experiments. The spiral grippers showed significant thermal distortion in the smallest dimension with a core diameter of 0.31 mm. This specimen geometry consequently deviated strongly from its nominal geometry and could not be tested more accurately due to instability. Therefore, no values are given for a 0.5 x 0.32 mm wire mesh. The spiral gripper for 0.63 x 0.4 mm wire mesh failed to record data as the structures broke immediately when clamped. This supports the theory spiral grippers are not suitable for smaller wire meshes.

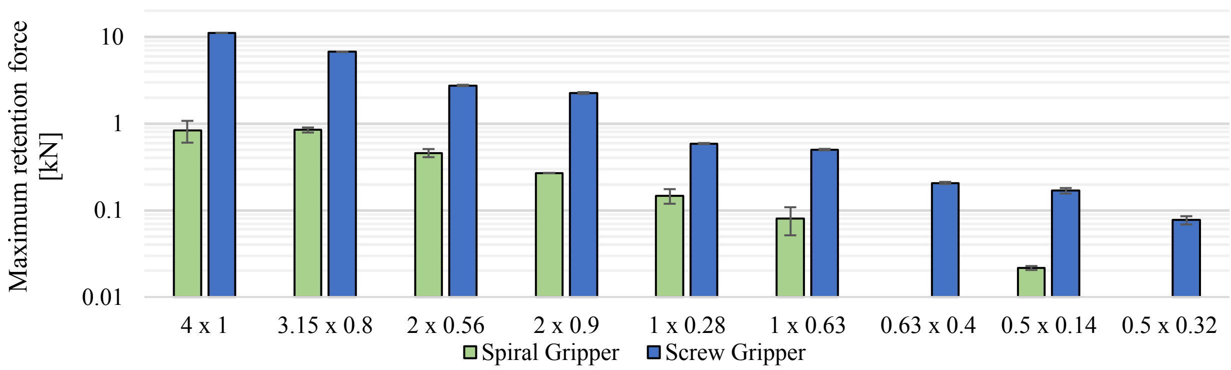


Figure 8: Mean values of maximum retention force of investigated spiral and screw gripper geometries

4. Conclusion and Outlook

A major challenge in the automation of alkaline electrolysis cell production is the handling of mesh electrodes. Due to the failure of established gripping technologies, the objective of this research was to develop and verify concepts for the safe and precise handling of these components. For this purpose, the two concepts of spiral and screw grippers were presented as well as the design guidelines in order to match them to individual wire mesh geometries. In order to verify the concepts, gripper elements for nine different mesh specimens were manufactured using the SLM process and tested for reliability, retention force and handling accuracy. The screw geometry demonstrated a comparably higher overall reliability. Both concepts showed weaknesses up to a damaging of the gripper with very fine meshes and correspondingly very filigree gripper elements. In terms of retention force, the spiral geometry achieved a consistently higher value in comparison. Inaccuracies at the transition from the centre axis to the mesh resulted in a reduced contact surface for the screw gripper and thus to an increased slip of the mesh under load, especially with fine mesh structures. In contrast, the central axis and the three contact points with the mesh created a stable contact with the mesh, which led to a high overall handling accuracy. Based on the geometry and material studies, it was possible to identify the manufacturing constraints in terms of dimensioning in the Selective Laser Melting process. In summary, the screw geometry has great potential for use in handling mesh electrodes, as it combines a high reliability and handling accuracy with a reliable and widespread manufacturing process. With the basis created with this research, a selection and assessment of screw and spiral grippers for implementations with various wire meshes is possible. This establishes these gripping principles as a possible future solution for the damage-free, precise and automated handling of metal grids, therefore increasing the viability and efficiency of an automated production of electrolysis cells.

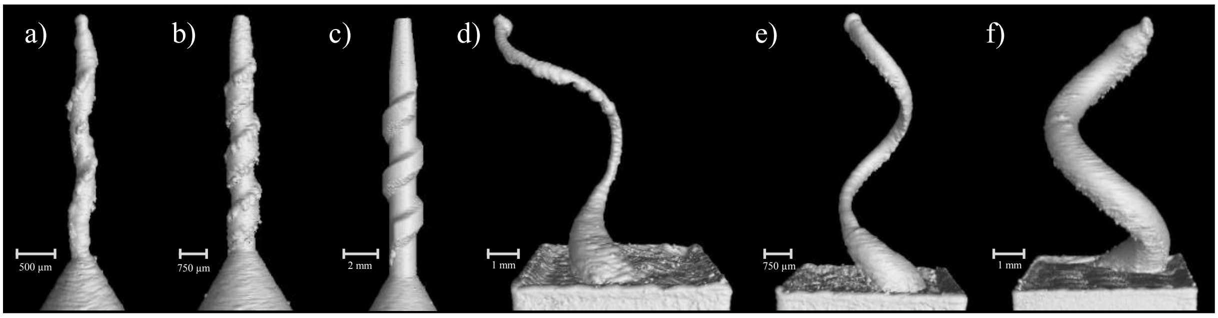
Acknowledgements

The authors gratefully acknowledge the financial support by the German Federal Ministry of Education and Research (BMBF) via grant number 03HY119D (project acronym: 'INSTALL AWE - H2NRY').

Appendix 1: Geometric dimensions of the mesh samples used

No.	Mesh size w_m [mm]	Wire diameter d_m [mm]
1	4	1
2	3.15	0.8
3	2	0.56
4	2	0.9
5	1	0.28
6	1	0.63
7	0.63	0.4
8	0.5	0.14
9	0.5	0.32

Appendix 2: CT scan of screw grippers with core diameters of a) 0.31 mm b) 0.75 mm c) 1.60 mm and of spiral grippers with core diameters of d) 0.31 mm e) 0.35 mm and f) 1.25 mm



Appendix 3: Average measured values of the displacement of the different meshes in the precision test according to sub-processes

Gripper	Wire Mesh (mesh size x wire diameter) [mm x mm]	(1-2) Grip-Displacement RZ [°]	(1-2) Grip-Displacement X [mm]	(1-2) Grip-Displacement Y [mm]	(3-4) Move-Displacement RZ [°]	(3-4) Move-Displacement X [°]	(3-4) Move-Displacement Y [°]
Screw	4 x 1	-0.414	0.138	1.344	0.168	0.115	-0.258
Screw	3.15 x 0.8	-0.027	0.597	1.998	0.029	1.116	0.773
Screw	2 x 0.56	-0.297	-0.367	0.735	0.000	0.210	0.124
Screw	2 x 0.9	-0.038	0.344	0.402	-0.013	0.067	0.048
Screw	1 x 0.63	-0.038	-0.287	1.539	-0.001	-0.010	-0.115
Screw	1 x 0.28	-0.067	0.000	-0.471	0.476	0.878	-0.353
Spiral	4 x 1	0.261	-0.884	0.999	0.126	-0.668	-0.143
Spiral	3.15 x 0.8	-0.026	-1.206	0.241	0.015	1.269	0.468
Spiral	2 x 0.56	0.012	-1.252	-0.299	-0.037	1.737	0.124
Spiral	2 x 0.9	0.755	-4.191	-0.402	-0.145	2.281	0.811
Spiral	1 x 0.28	0.141	-0.517	0.103	0.343	0.019	-0.363

Gripper	Wire Mesh (mesh size x wire diameter) [mm x mm]	(5-6) Release-Displacement RZ [°]	(5-6) Release-Displacement X [mm]	(5-6) Release-Displacement Y [mm]	(1-6) Overall Displacement RZ [°]	(1-6) Overall Displacement X [mm]	(1-6) Overall Displacement Y [mm]
Screw	4 x 1	0.411	-0.276	-1.504	0.054	-0.103	-0.207
Screw	3.15 x 0.8	0.013	-1.194	-1.895	-0.027	-0.023	0.011
Screw	2 x 0.56	0.373	0.310	-0.896	0.025	-0.011	-0.161
Screw	2 x 0.9	-0.014	-0.379	0.023	0.000	-0.138	0.207
Screw	1 x 0.63	0.036	-0.769	-0.448	-0.054	-1.344	0.781
Screw	1 x 0.28	0.010	-0.402	1.137	-0.135	0.057	0.689
Spiral	4 x 1	-0.029	0.448	0.138	0.403	-1.596	1.435
Spiral	3.15 x 0.8	0.027	-0.494	1.596	0.014	-0.092	1.631
Spiral	2 x 0.56	0.062	-0.080	-0.896	0.012	-0.356	-0.230
Spiral	2 x 0.9	-0.853	3.169	-0.115	-0.096	2.159	0.712
Spiral	1 x 0.28	-0.061	2.825	1.091	-0.181	2.515	1.918

References

[1] Stiftung Arbeit und Umwelt der IG BCE, 2021. Wasserstoffbasierte Industrie in Deutschland und Europa., Berlin.

[2] Smolinka, T., Wiebe, N., Sterchele, P., Palzer, A., Lehner, F., Jansen, M., Steffen Kiemel, Robert Miehe, Sylvia Wahren, Fabian Zimmermann, 2018. Studie IndWEDe Industrialisierung der Wasserelektrolyse in -Deutschland: -Chancen und Herausforderungen für nachhaltigen Wasserstoff für Verkehr, Strom und -Wärme, Berlin.

[3] Gannon, W.J.F., Warwick, M.E.A., Dunnill, C.W., 2020. Woven Stainless-Steel Mesh as a Gas Separation Membrane for Alkaline Water-Splitting Electrolysis. Membranes 10 (5).

[4] Hu, X., Tian, X., Lin, Y.-W., Wang, Z., 2019. Nickel foam and stainless steel mesh as electrocatalysts for hydrogen evolution reaction, oxygen evolution reaction and overall water splitting in alkaline media. RSC advances 9 (54), 31563–31571.

[5] Phillips, R., Edwards, A., Rome, B., Jones, D.R., Dunnill, C.W., 2017. Minimising the ohmic resistance of an alkaline electrolysis cell through effective cell design. International Journal of Hydrogen Energy 42 (38), 23986–23994.

[6] Schalenbach, M., Kasian, O., Mayrhofer, K.J., 2018. An alkaline water electrolyzer with nickel electrodes enables efficient high current density operation. International Journal of Hydrogen Energy 43 (27), 1–7.

[7] Deutsches Institut für Normung e. V. Industriedrahtgewebe – Technische Anforderungen und Prüfung. Beuth Verlag, Berlin.

[8] Edwards, T.C., Edwards, T.C., Steer, M.B., Steer, M.B., 2016. Foundations for microstrip circuit design, Fourth edition ed. Wiley IEEE Press, Chichester, West Sussex.

[9] Natarajan, E., Onubogu, N.O., 2011. Application of Coanda Effect in Robots – A Review. International Conference on Mechanical Engineering and Technology, London 2011.

[10] Bruns, C., Bohne, F., Micke-Camuz, M., Behrens, B.-A., Raatz, A., 2019. Heated gripper concept to optimize heat transfer of fiber-reinforced-thermoplastics in automated thermoforming processes. Procedia CIRP 79, 331–336.

[11] Ebraheem, Y., Drean, E., ADolphe, D.C., 2021. Universal gripper for fabrics – design, validation and integration. International Journal of Clothing Science and Technology 2019 (33), 643–663.

[12] Tilli, J., Brando, A., Fantoni, G., 2014. Gripping Device for Heavy and Deformable Materials Handling: Concept, Design, Selection and Test. Procedia CIRP 21, 373–378.

[13] Prout, N.M., 1990. Modern Chlor-Alkali Technology : Volume 4. Elsevier Applied Science, London.

[14] Hong, J., Talalay, P., Sysoev, M., Fan, X., 2014. DEM modeling of ice cuttings transportation by electromechanical auger core drills. Ann. Glaciol. 55 (68), 65–71.

[15] Armstrong, M., Mehrabi, H., Naveed, N., 2022. An overview of modern metal additive manufacturing technology. Journal of Manufacturing Processes 84, 1001–1029.

[16] Gabriel, F., 2022. Methodenentwicklung zur Energieeffizienzsteigerung in der vakuumbasierten Handhabung. Dissertation, Braunschweig.

[17] Straßer, G., 2011. Greiftechnologie für die automatisierte Handhabung von technischen Textilien in der Faserverbundfertigung. Dissertation. Utz, München.

Biography

Martin Römer (*1991) is a research associate at the Institute of Machine Tools and Production Technology (IWF) at TU Braunschweig in the field of handling and automation. He is currently working on automated assembly technologies for electrolysis cell assembly. He studied mechanical engineering at the TU Braunschweig, specialising in production and systems engineering.

Benjamin Winter (*1993) is a research associate at the Institute of Machine Tools and Production Technology (IWF) at TU Braunschweig in the field of tool development and additive manufacturing. He is currently working on the implementation of additively manufactured components in primary and forming tools. He studied mechanical engineering at the TU Braunschweig

Edgaras Mazeika (*1997) studied mechanical engineering at the TU Braunschweig. In his final thesis, he worked on the verification of the suitability of grippers for wire mesh.

Klaus Dröder (*1968) is the head of the Institute of Machine Tools and Production Technology (IWF) at TU Braunschweig. Prof. Dr.-Ing. Klaus Dröder is a member of the German Academic Association for Production Technology (WGP) as well as the International Academy for Production Engineering (CIRP). In addition to his activities as professor and institute director, he is also a member of the board of the Automotive Research Centre Niedersachsen (NFF) and the Open Hybrid Lab Factory (OHLF).

CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
CPSL 2023-2

5th Conference on Production Systems and Logistics

Deficits Of Innovation Management In The Application To The Disruptive Battery Industry

Achim Kampker[1], Heiner Heimes[1], Jessica Schmied[1], Paul Lingohr[1], Henning Clever[1], Benjamin Dorn[1]

[1]*Chair of Production Engineering of E-Mobility Components (PEM) of the RWTH Aachen University; Aachen, Germany*

Abstract

With the electrification of the automotive industry and the resulting demand for batteries, Gigafactories are increasingly established by battery cell manufacturers or new players, especially in Europe, and North America. When planning Gigafactories, there are various planning challenges due to the high and long-term investments. In particular, the variety of innovations and short innovation cycles creates uncertainty in the planning process. Reviewing the background provided, the application of existing approaches from innovation management to the current battery industry was assessed in this paper. For this, the environment of battery production was first examined in more detail, resulting in the identification of the relevant requirements for an innovation management method. Based on this, standard methods of innovation management were examined and evaluated based on the derived requirements. The evaluation showed that standard methods of innovation management only partially fulfil some of the requirements, highlighting the necessity of a dedicated method for the battery industry. In conclusion, the deficits and potential levers for successful innovation management are discussed.

Keywords

Battery Production; Electrification; Innovation Management; Disruptive Industry; Planning Methods

1. Navigating market demand and technological innovation

The battery industry is highly dynamic and evolving rapidly, driven by a growing demand for sustainable technologies, especially in Europe, where electrification of the automotive sector is surging [1]. To meet diverse customer needs like longer range, faster charging, and enhanced safety, constant innovation is essential. Yet, with innovations and advancements like dry coating and laser cutting emerging, the planning of costly Gigafactories is a long-term and challenging process [2, 3]. Market demand and technological advancement interact, creating a dynamic and uncertain environment for technology selection. To navigate this uncertainty, a strategic approach to innovation management is crucial. This involves identifying and managing risks, as well as ensuring the right resources are available [4, 5].

This paper aims to explore the various innovation management approaches and assess their suitability for the dynamic battery industry, along with the necessary requirements for successful implementation. Overall, the battery industry requires careful management and planning to thrive. By adopting a strategic approach to innovation, companies can stay at the forefront of technological advancements and meet evolving customer demands [4]. This paper offers a scientific perspective on the importance of effective innovation management in battery production. It contributes to our understanding of ongoing and potential developments in the battery production field. While Gigafactories and global competition, especially from economically competitive Chinese facilities, pose significant challenges for European companies, the

DOI: https://doi.org/10.15488/15299
ISSN: 2701-6277
publish-Ing.

imperative for further research in this field remains evident. Research efforts are currently constrained, given the early stages of the European industry, which has announced a capacity of 2,014 GWh, a notable increase compared to the existing 120-150 GWh production capacity in Europe [6,7].

2. Structure of the paper reviewing innovation management

Following the methodological structure of a literature review, this paper performed the steps: *Definition of the research topic, identification of relevant literature, analysis, and synthesis, as well as presentation of the results and discussion* [8, 9].

This paper reviews standard methods of innovation management in battery production. Conventional methods were analysed and reviewed for their suitability. Relevant articles on innovation management were considered, with a focus on established approaches. The current state and challenges of battery production are examined in detail, leading to the identification of criteria for successful implementation of innovation management. In total, 14 methods were analysed and evaluated based on the criteria. The applicability of each method to battery production was determined, highlighting specific deficits and potential areas for improvement. The conclusion summarizes the results and outlines future research plans.

3. Deriving evaluation criteria from the dynamic battery industry

In this following section an overview of current market trends and their direct and indirect effects on battery production management are compiled. Furthermore, five criteria for a possible method to effectively manage future battery production were derived.

3.1 A global pivot towards e-mobility creates growing demand

The transition to electric transportation relies on electric batteries, a key driver of global mobility [10]. Electric vehicle performance depends on battery technology, leading to increased demand. To meet this demand, global battery production capacity is expected to increase by over 50% by 2030 [11], with a focus on mobility applications [10]. However, European and United States (US) battery manufacturers must reduce costs to compete. As of 2021, production costs were approximately \$177/kWh and \$155/kWh in Europe and the US, respectively, which is around 60% and 40% higher than their Chinese counterparts [12]. This cost difference could significantly impact the market share of European and US manufacturers in the battery industry, particularly considering the growing importance of batteries in the global mobility transition.

3.2 High innovation rate for both product and production

In today's rapidly evolving market, characterized by a high innovation rate in both product and production, companies face significant challenges. Traditional decision-making processes like the product development process are too slow to keep up with Industry 4.0's mid-term uncertainty and the rapid substitution of existing technologies with innovations [12]. Innovation spans materials and products, like fourth-gen batteries and metallic Li-Anodes, and process-level improvements, such as dry-mixing, laser drying, and separator-lamination [13]. As these innovations mature, manufacturers must quickly adapt to realize cost and performance benefits [13]. New entrants, particularly OEMs, contend with the substantial capital requirements, technology complexity, and uncertainty associated with building Gigafactories.

To address these challenges effectively, companies must adopt a strategic and flexible approach to innovation management, prioritizing agility, and adaptability to navigate the dynamic market to maximize the leveraging of emerging opportunities, it is crucial to engage in calculated risks and undertake assertive actions. In conclusion, in the context of the high innovation rate in both product and production, forward-thinking innovation management is vital for staying competitive, fostering risk-taking, agility, adaptability, and embracing emerging technologies and production methods. This positions companies as industry leaders poised to seize opportunities in the rapidly changing market [10].

3.3 Production complexity creates increased planning difficulties

The manufacturing of batteries is a complex process that involves a diverse range of technologies, which can make effective management a challenging task [12]. The battery production process consists of multiple steps, from electrode manufacturing to cell assembly and finishing, each requiring specialized technologies and innovations [13, 14], as depicted in Figure 1. In Figure 1, a subset of the innovation examples presented in Chapter 1 is depicted to enhance clarity. The primary emphasis of this paper centers on delineating methods for managing innovations, rather than delving into the innovations themselves. With the increasing diversity of technologies involved, there is an increased likelihood of bottlenecks and inefficiencies, which can adversely affect the overall production process. To address these challenges and improve the efficiency and effectiveness of battery production, different strategies have been employed. However, due to the complexity of the process, it is difficult to optimize all parameters simultaneously. For instance, reducing the duration of a specific operation could potentially lead to increased idle times of other machines [15]. Thus, managing the entire production process in a holistic manner becomes crucial. However, the increasing diversity of technologies involved in battery production makes it challenging to develop a standardized approach that can be applied to all manufacturing processes. As new technologies emerge, they may require modifications to existing production processes, which can result in additional costs and delays.

Furthermore, advancements in a particular technology can render certain process steps, like dry mixing, unnecessary, potentially making all technological developments in the drying process, such as laser drying, redundant [5]. To manage this complexity effectively, battery cell manufacturers need a management tool that can guide their decision-making by considering the interdependencies of technologies along the production line.

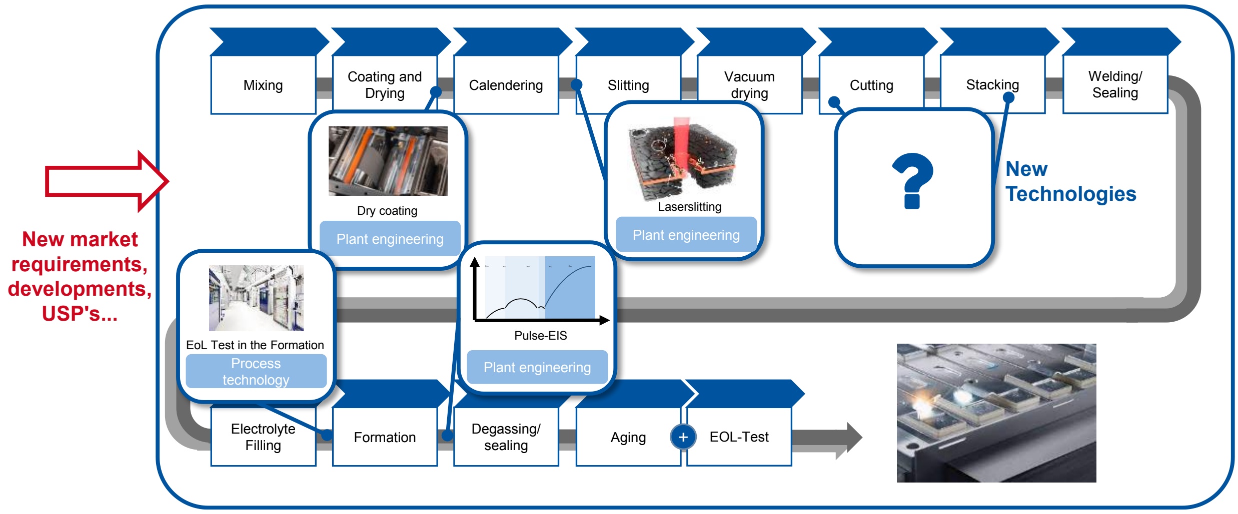


Figure 1: Battery production process chains and exemplary innovations [5]

3.4 The critical need to implement Industry 4.0

Industry 4.0 adoption and readiness is a recommended strategic focus point for most companies in the general manufacturing industry [16], and the same should apply to battery cell manufacturers. However, while most companies fail to move beyond the pilot phase when investing in big data analytics, AI, or 3D printing, a select group of leading organizations is showcasing how to generate new value when deploying advanced manufacturing at scale [17]. Despite the difficulties in scaling up digital transformations, it can provide significant cost and energy reductions, throughput increase, and quality improvements [16, 17] all of which are helpful to meet the before-mentioned increase in demand. Manufacturers must avoid the pitfall of implementing the latest technological advances by default, and instead be value-driven in their decision making [16]. In conclusion, digitalization measures offer promising cost, energy and quality improvements for battery cell manufacturers [18] while simultaneously generating their own challenges in deployment.

3.5 Resulting criteria for innovation management methods

Addressing the market dynamics and the intricate manufacturing processes in battery production (see chapters 3.1-3.4), it is essential to establish clear criteria for effective innovation management. The following qualitative characteristics have been identified to gauge the success of innovation management methods following the previously mentioned challenges:

Bifocal technology foresight: This involves performing simultaneous technology foresight for both process and product innovations. By doing so, companies can effectively evaluate and plan for the latest advancements, ensuring that they remain competitive and stay ahead of the curve, especially in battery production process for electric vehicles. Keeping track of the latest product and process technological advancements, particularly those related to sustainability, energy efficiency, and safety is crucial.

Complexity management: The innovation management method should be capable of handling multi-technology evaluation to effectively manage the complexity of battery cell manufacturing and its potential for factory-scale use.

Industry 4.0 relevance: The innovation management method should emphasize awareness of the latest digital advancements, particularly those related to automation, data exchange, and artificial intelligence. These advancements differ from the first criterion (bifocal technology foresight) in that they are only relevant at the factory level (and not on a single-process or product specific level). Embracing Industry 4.0 technologies allows battery cell manufacturers to enhance efficiency, quality, and safety while reducing costs and waste.

Flexibility and adaptability: The method should facilitate later changes in production processes and the introduction of newer technologies. Given the rapid evolution of the battery production industry, a rigid approach may hinder growth and competitiveness. Flexibility and adaptability are essential for remaining agile and responsive to changing market needs and technological advancements.

Implementation planning: Effective implementation planning should be a core aspect derived from the methodology, encompassing both long and short-term considerations while aligning with the identified criteria. Implementation planning plays a pivotal role in ensuring that the battery production process remains efficient, cost-effective, scalable, and socially responsible.

4. Results: Identification and evaluation of relevant approaches from innovation management

As mentioned in chapter 2, a thorough literature review has been performed. In total, 14 methods addressing the mentioned topics in chapter 3.2 were selected and analysed in detail in regards to their compatibility for battery production. The selected methods can be categorized in four clusters: 1) General methods, 2) Assessment methods, 3) Portfolio methods and 4) Roadmaps.

4.1 General approaches for innovation management

In the context of this paper the Patent-/ and Publication analysis, Scenario analysis and S-Curve Analysis, can be assigned to the application area of general methods on the basis of their overarching function. The underlying assumption is that the number of publications in a given research area is indicative of the level of research activity in that field. For applied research areas, patent data is utilized, whereas publication data is used for basic research areas. The approach is limited by data availability, but nonetheless enables the identification of general manufacturing or product (criterion bifocal technology foresight) as well as Industry 4.0 and digitalization trends and research priorities in the field of battery production [20]. The second general method is the scenario analysis. The overarching goal of this analysis is to generate prescriptive action recommendations for the present by analysing several potential future scenarios that are both flexible and resilient, while accounting for a diverse range of possible outcomes. This process involves identifying potential future risks and opportunities, aligning with the primary objective of early technology identification [21, 22]. Accordingly, scenario analysis is an appropriate method for informing decisions related to (battery) technology strategy but lacks the application towards complexity management and implementation planning since these are mostly out of scope of the method. The S-curve concept describes the development course of a technology's performance as a function of the cumulative R&D expenditure [23]. The concept follows the principle that technologies inevitably reach their technological performance limits during constant advancement. Recognizing the right time to replace one technology by a superior technology is essential for companies. The comparison of several technology developments in this S-curve concept can sensitize and support assessments regarding the remaining further development potential of existing technologies and the development of new technologies [19, 24] and is therefore suited in terms of the bifocal technology foresight and relevant for Industry 4.0 solutions. This methodology allows for a certain degree of foresight in flexibility and adaptability; however, this method does not map the interactions of the various technologies or the complexity of battery cell manufacturing.

4.2 Evaluation-based methods for innovation management

The next section includes the return on investment (ROI) ratios, cost-benefit analysis, argument balance, utility analysis and checklist method. The method of ROI figures, which calculates the financial return of an investment, can be used to compare different technologies from a financial perspective [25]. However, it is not an appropriate innovation management method in the field of battery production because it focuses solely on financial gains and may not account for other important factors, such as technical feasibility, market demand, and complexity management. The cost-benefit analysis compares the costs for the realization of the project with the future benefits achieved [26]. An attempt is made to make non-monetary variables (e.g. reliability) comparable by converting them into monetary values. With the cost-benefit analysis, the net benefit can be used to evaluate different alternatives. This is calculated from the difference between the monetary benefit and the costs of the investment project. The choice should then be made for the alternative with the highest net benefit [19, 27]. One of the biggest challenges of the cost-benefit analysis is the often difficult transformation of benefits into monetary values [26]. For this reason, the practical benefit is often lower than it appears theoretically possible. For qualitative assessments the argument balance, checklist method, and utility value analysis can be used. The argument balance represents a simple method for comparing the advantages and disadvantages of alternative technologies in list form. It can be used especially in early consideration of innovations [28]. However, this allows only a qualitative comparison of one technology without quantifying the effects. The checklist method offers another tool for qualitative comparison of multiple technologies based on predefined criteria and therefore enables complexity management on a small scale [29], but also lacks the quantifiability. The utility value method allows for the evaluation of soft criteria, which are standards that are difficult to measure. The method allows the quantified comparison of various alternatives and the assessment of their advantageousness. For this, a set of target criteria are defined and weighted by pairwise comparison. For each of these criteria the performance of the various alternatives is evaluated using an absolute conversion function. Finally, the multiplication of the criteria weights and the sum of the partial utility value generates a total utility value for each alternative allowing their comparison [19, 29]. The utility value analysis offers a structured approach comparing alternatives but is limited to identification of the optimal alternative.

4.3 Portfolio-based methods for innovation management

As part of strategic technology management, technology portfolios are used to systematically evaluate technologies and derive investment decisions. A variety of portfolio approaches exist in the literature, and each of them addresses different characteristics and dimensions. The most relevant portfolios from ARTHUR D. LITTLE, PFEIFFER, and MCKINSEY are examined in more detail below.

The portfolio approach from ARTHUR D. LITTLE aims to derive a technology strategy, considering the different technology and business unit life cycles [19, 30]. It is based on an analysis of the technology and competitive positions of the strategic business areas and the life cycles of the technologies and the respective industry. In one dimension the technology life cycle curve provides an estimate of future technology potential. The second dimension of the relative technology position indicates, in comparison to competitors, which qualifications, such as patents and production technology, the company has [30, 31]. Considering the Research and Development (R&D) risk, the portfolio approach from ARTHUR D. LITTLE is particularly suitable for deriving directions (see criterion implementation planning) for action based on the consistency of technology and market strategy. In the context of battery production innovation management, such portfolio approaches can serve as a basis for evaluating technology readiness and aligning it with market dynamics. Specifically, the 'Bifocal technology foresight' and 'Flexibility and adaptability' criteria can be assessed by leveraging the technology life cycle curve to identify emerging battery technologies with the potential for sustainability, energy efficiency, and safety. The relative technology position dimension can help gauge a company's competitive edge in these areas.

The technology portfolio by PFEIFFER considers both the generation cycle preceding the market cycle and the observing cycle for the strategic analysis process via the two dimensions of technological attractiveness and resource strength [31]. The attractiveness of the technology describes the economic and technological advantages that can be strategically achieves by further developing a particular field. The resource strength compares the company's resources to realize the technological potential with those of the competitors. When considering the 'Complexity management' criterion in battery production innovation management, PFEIFFER's approach can be adapted to evaluate the resource strength needed for implementing complex manufacturing technologies. Based on the positioning in the portfolio the approach recommends to invest or disinvest in certain technologies to achieve an innovator positioning assuming that the innovator generates more revenue than the imitator [19, 31, 32]. Nevertheless, the PFEIFFER's approach only derives R&D priorities and is limited to the technology portfolio, as detailed planning and implementation is not specified.

The integrated market and technology portfolio by MCKINSEY offer an analysis option to target the investment of internal resources. The basis of the MCKINSEY portfolio is the S-curve concept [33]. The technology and market portfolio provide a mapping of the relevant technologies comparing the company's position with the market and technology attractiveness. The following comparison and subsequent integration of the technology and market portfolio into an integrated portfolio with the dimensions market and technology priority enables the analysis of technology-strategic factors [19, 33]. Regarding 'Industry 4.0 relevance' and 'Flexibility and adaptability' criteria in battery production innovation management, MCKINSEY'S integrated portfolio can be used to assess the alignment of technology priorities with Industry 4.0 advancements. It provides a structured approach to incorporate digital technologies like automation, data exchange, and artificial intelligence into the innovation management strategy. Moreover, it can help in identifying the flexibility and adaptability needed to respond to changing market dynamics and technological advancements. However, MCKINSEY's portfolio serves primarily as a formal instrument for structuring the strategic planning process and for visualizing the strategic position and problems of business areas.

4.4 Roadmapping methods for innovation management

The technology roadmap visualizes technologies and their links over time. The roadmap illustrates the path from a current state to a future targeted status, which ensures that the required resources for fulfilling the targeted objectives are deployed at the right time. Thereby, the technology roadmap serves as a tool for the specification of the technology strategy and implementation [34, 35]. Nevertheless, the main benefit of the technology roadmap is the time-based and graphical representation for the development, representation, and communication of strategic plans regarding the coevolution a development of technology, products, and markets. The roadmap enables continuous support of the technology planning process and the alignment of planning levels. As a variant, explorative technology roadmaps offer the consideration of scenarios and forecasts about technological developments. As a procedure for creating the roadmap, a future scenario is defined and broken down to the current status quo through intermediate scenarios [34]. To translate technology roadmaps into operational measures, balanced innovation scorecards (BIC) can be used. It uses the strategy captured in roadmaps, concretises it in its four perspectives and thus translates the roadmap into clear and measurable goals, key performance indicators, measures, and the persons responsible [35]. In the context of evaluating innovation management methods for battery production, all considered roadmapping methods are especially effective in 'Implementation planning', providing suitable frameworks for translating innovation strategies into actionable plans. When assessing their performance in other criteria, roadmaps integrated with balanced innovation scorecards emerge with a slight advantage due to their ability to combine foresight with performance measurement, manage complexity, and integrate digital advancements makes them slightly more advantageous for addressing the multifaceted challenges of innovation in battery production.

4.5 Summary and evaluation of approaches

In summary, none of the methods presented fully meet all the evaluation criteria. In particular, there are still major deficits in the areas of implementation planning and flexibility and adaptability in production. The evaluation results are shown in Figure 2.

	Existing approaches / Evaluation-criteria	Bifocal technology foresight	Complexity manage-ment	Flexibility and adapt-ability	Industry 4.0 relevance	Implemen-tation planning
General	Patent / Publication analysis	●	○	◑	◑	○
	Szenario analysis	◕	◔	◑	◕	◔
	S-Curve analysis	◑	◔	◔	◔	◑
Evaluation	Key return figures	○	◔	○	◑	○
	Cost-benefit analysis	○	◔	○	◑	○
	Argument balance	○	○	◑	◔	○
	Utility analysis	○	◔	○	◑	○
	Checklist method	○	◑	◑	◔	○
Portfolios	Portfolio method (A. D. LITTLE)	◑	◔	◑	◑	◑
	Integr. portfolio (MCKINSEY)	◑	◔	◑	◑	◔
	Tech. portfolio (PFEIFFER)	◑	○	◑	◑	◔
Roadmap	Roadmapping (general)	◔	◔	◔	◑	●
	Expl. Technology-Roadmaps	◕	◑	◑	◕	●
	BIC with Roadmaps	◑	◑	◔	◑	●

Degree of consideration : Full consideration ● ◕ ◑ ◔ ○ No consideration

Figure 2: Evaluation of existing approaches in innovation management assessed by criteria from battery industry

Summarizing, the general approaches such as the scenario technique or patent analyses mainly offer possibilities for early technology identification, but only insufficiently fulfil the simultaneous evaluation of different technologies and the planning of implementation. The evaluation methodologies primarily enable the prioritization of individual technologies or various technology alternatives, but do not consider aspects such as implementation or bifocal technology foresight. The portfolio approaches are mainly used for visualization and support the derivation of strategic measures. However, implementation and complexity management are only considered superficially. The roadmap approaches, such as the explorative technology roadmaps, fulfil the criteria to a certain extent, but have deficits in the multi-technology evaluation and in the consideration of flexibility and later adaptability of the planning. The results show that the application of the respective standard innovation methods to battery production addresses only a fraction of the problems. For this review standard methods from innovation management were focused and assessed for their applicability to battery production. These methods are established in industry and are generally applied for solving specific tasks. However, the review also showed that a combination of all approaches does not meet the requirements of the current battery industry. This highlights the lack of a holistic method addressing the current innovation challenges in battery production.

5. Conclusions and Outlook

The assessment of innovation management methods within the context of battery production indicates that existing approaches have their limitations. None of these methods offers a comprehensive solution to the multifaceted challenges in this field. Each method demonstrates strengths in certain aspects while falling short in others. Future research aims to address these limitations, develop a holistic method, and expand the scope of approaches through an extended literature review. This will enable successful innovation management in battery production. Achieving this goal requires understanding the unique challenges and opportunities in the battery industry, collaborating across disciplines, and considering factors like regulations, market trends, and societal expectations. By adopting a multidisciplinary approach and holistic method, the battery industry can navigate its dynamic landscape and ensure long-term success.

Nevertheless, there are several critical considerations and promising opportunities for future investigation. One such consideration is the development of a tailored innovation framework that specifically addresses the complexities of battery production. This framework should be capable of effectively handling issues related to implementation and adaptability. Additionally, exploring the potential advantages of integrating multiple innovation methods and customizing them to better suit the industry's requirements is essential. Such an approach could yield more comprehensive and holistic solutions. Interdisciplinary collaboration among experts from diverse fields is also of paramount importance. Experts in materials science, engineering, and business management, among others, must work together to generate new perspectives and innovative solutions. Lastly, the potential benefits of knowledge transfer and best practices from related industries, such as energy storage or semiconductors, should not be overlooked. Adopting these insights could help overcome current limitations and accelerate progress.

In conclusion, as battery technology continues to advance, the role of innovation management remains critical in shaping the future of sustainable energy solutions and in harmonizing the integration of product and process advancements in battery production. Innovation will drive progress, efficiency, and sustainability in this dynamic field.

Acknowledgements

This paper is based on the research results of the projects "FoFeBat" [03XP0256, 03XP0416, 03XP0501A]. The projects are funded by the German Federal Ministry of Education and Research. The authors of this publication thank the ministry and their partners from the Fraunhofer Research Institution for Battery Cell Production FFB for the funding.

References

[1] Chudy, A., Mazurek, P. A., 2019. Electromobility – the Importance of Power Quality and Environmental Sustainability. Journal of Ecological Engineering, Volume 20, Issue 10, November 2019, pages 15–23, DOI: https://doi.org/10.12911/22998993/112713

[2] Aykol, M., Herring, P. & Anapolsky, A. 2020. Machine learning for continuous innovation in battery technologies. Nat Rev Mater 5, 725–727. https://doi.org/10.1038/s41578-020-0216-y

[3] Liu, Y., Zhang, R., Wang, J., Wang, Y. 2021. Current and future lithium-ion battery manufacturing. IScience, 24(4).

[4] Hardman, S., Steinberger-Wilckens, R., van der Horst, D., 2013. Disruptive innovations: The case for hydrogen fuel cells and battery electric vehicles. International Journal of Hydrogen Energy Volume 38, Issue 35, 22 November 2013, Pages 15438-15451. https://doi.org/10.1016/j.ijhydene.2013.09.088

[5] Kampker, A., Heimes, H., 2024. Elektromobilität. Eine Fortschrittstechnologie. Dritte Auflage, Berlin, Springer-Verlag. https://doi.org/10.1007/978-3-662-65812-3

[6] Battery News, 2023. Battery Atlas, Battery Cell Production. https://battery-news.de/en/europe-battery-cell-production/

[7] Fraunhofer ISI., 2022. Europäische Batteriezellfertigung: Verzehnfachung der Produktionskapazitäten bis 2030, https://www.isi.fraunhofer.de/de/presse/2022/presseinfo-17-Batteriezellfertigung-Verzehnfachung-2030.html

[8] Linnenluecke, M. K., Marrone, M., Singh, A. K., 2020. Conducting systematic literature reviews and bibliometric analyses. Australian Journal of Management, 45(2), pp. 175–194. https://doi.org/10.1177/0312896219877678

[9] Denyer, D., Tranfield, D., 2009. Producing a systematic review. In D. A. Buchanan & A. Bryman (Eds.), The Sage handbook of organizational research methods pp. 671–689.

[10] Breiter, A., Horetsky, E., Linder, M., Rettig, R., 2022. Power spike: How battery makers can respond to surging demand from EVs

[11] Volta Foundation, Annual Battery Report 2021

[12] Michaelis, S.; Rahimzei, E.; Kampker, A.; Heimes, H.; Offermanns, C.; Locke, M.; Löbberding, H.; Wennemar, S.; Thiel-mann, A.; Hettesheimer, T.; Neef, C.; Kwade, A.; Haselrieder, W.; Blömeke, S. Roadmap Batterie-Produktionsmittel, Update 2020, VDMA, 2020

[13] Heimes, H.; Kampker, A.; Wennemar, S.; Plocher, L.; Bockey, G.; Michaelis, S.; Schütrumpf, J., Produktionsprozess einer Lithium-Ionen Batteriezelle, 2023. PEM der RWTH, VDMA

[14] Mauler, L., Duffner, F., Leker, J., 2021. Economies of scale in battery cell manufacturing: The impact of material and process innovations

[15] Silva, G. V., Thomitzek, M., Abraham, T., Herrmann, C., 2021. Bottleneck reduction strategies for energy efficiency in the battery manufacturing

[16] Gregolinska, E., Khanam, R., Lefort, F., Parthasarathy, P., 2022. Capturing the true value of Industry 4.0. by McKinsey & Company

[17] Betti, F., Giraud, Y., Manna, F., Torti, F., 2021. Reimagining Operations for Growth by Global Lighthouse Network, World Economic Forum.

[18] Wanner, J., Bahr, J., Full, J., Weeber, M., Birke, K.P., Sauer, A., 2020. Technology asessment for digitalization in battery cell manufacturing

[19] Schuh, G., Klappert, S., 2011. Technologiemanagement. Zweite Auflage, Berlin, Springer-Verlag. https://doi.org/10.1007/978-3-642-12530-0

[20] Ensthaler, J., Stübbe, K., 2006, Patentbewertung. Ein Praxisleitfaden zum Patentmanagement. 1.Auflage Springer Berlin Heidelberg New York

[21] Mietzner, D., 2010, Strategische Vorausschau und Szenarioanalysen. Methodenevaluation und neue Ansätze. Gabler Verlag Wiesbaden. https://doi.org/10.1007/978-3-8349-8382-4

[22] Regis, S., 2019. Sustainability Balanced Scorecard und Szenarioanalyse – Instrumente des Risikomanagements im Hinblick auf Identifikation, Bewertung, Steuerung und Überwachung von Nachhaltigkeitsrisiken. Technische Universität Chemnitz

[23] P. Asthana, 1995. Jumping the technology s-curve, IEEE Spectrum, vol. 32, no. 6, pp. 49-54, June 1995, doi: 10.1109/6.387142]

[24] Gochermann, J., 2020. Technologiemanagement: Technologien erkennen, bewerten und erfolgreich einsetzen. 1. Auflage Springer Gabler Wiesbaden https://doi.org/10.1007/978-3-658-28799-3

[25] Hicking, J., Heimes, P.,2022. Technologiebewertung. In: Schuh, G., Zeller, V., Stich, V. (eds) Digitalisierungs- und Informationsmanagement. Springer Vieweg, Berlin, Heidelberg. https://doi.org/10.1007/978-3-662-63758-6_14

[26] Kim, H., Jee, S., Sohn, S., 2021 Cost–benefit model for multi-generational high-technology products to compare sequential innovation strategy with quality strategy. PLoS ONE 16(4): e0249124. https://doi.org/10.1371/journal.pone.0249124

[27] Heina, J., 1999. Variantenmanagement, Kosten-Nutzen-Bewertung zur Optimierung der Variantenvielfalt. Deutscher Universitätsverlag Wiesbaden. https://doi.org/10.1007/978-3-663-09093-9

[28] Witte, F., 2020. Strategie, Planung und Organisation von Testprozessen, Planungsrisiken und Unvorhersehbares. Springer Fachmedien Wiesbaden https://doi.org/10.1007/978-3-658-31228-2

[29] Zangemeister, C., 2014. Nutzwertanalyse in der Systemtechnik: eine Methodik zur multidimensionalen Bewertung und Auswahl von Projektalternativen, 5. Auflage, Zangemeister

[30] Schimpf, S., Faerber, M., Heubach, D., Korell, M., Lang-Koetz, C., Masior, J., Rettinger, A., Rummel, S., Schloen, J., Schmitz, M., Sieber, V., Wichert, P., Wohlfart, L., 2015. Technologien frühzeitig erkennen, Nutzenpotenziale systematisch bewerten.

[31] Buchholz, L., 2019. Strategisches Controlling, Grundlagen – Instrumente – Konzepte. Springer Gabler Wiesbaden https://doi.org/10.1007/978-3-658-26662-2

[32] Karagiannis, D., Moser, C., Helmes, A., 2020. Benutzerzentrierte Unternehmensarchitekturen: Ein portfolio-orientierter Ansatz zur Geschäftstransformation mit ArchiMate ®, Springer Fachmedien Wiesbaden https://doi.org/10.1007/978-3-658-30537-6

[33] Kaufmann, T., 2021. Branchenattraktivitäts-Wettbewerbsstärkenportfolio (McKinsey) In: Kaufman, T., Strategiewerkzeuge aus der Praxis. Springer Berlin Heidelberg https://doi.org/10.1007/978-3-662-63105-8_23

[34] Mörhle, M., Isenmann, R., 2008. Technologie-Roadmapping, Zukunftsstrategien für Technologieunternehmen, Springer Berlin, Heidelberg https://doi.org/10.1007/b138871

[35] Phaal, R., Farrukh, C.J.P., Probert, D.R., 2004. Technology roadmapping – A planning framework for evolution and revolution. Technological Forecasting and Social Change, Volume 71 https://doi.org/10.1016/S0040-1625(03)00072-6

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. From March 2019 to 2023, he was PEM's Executive Chief Engineer before being appointed Professor.

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.

Paul Lingohr (*1993) is research associate at the Chair of Production Engineering of E-Mobility Components (PEM) at RWTH Aachen University. He studied industrial 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 was group lead for the research group Battery Production Management from 2021-2023. He studied mechanical engineering specializing in production engineering at the 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.

CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
CPSL 2023-2

5th Conference on Production Systems and Logistics

Mini-Environments In Lithium-Ion Battery Cell Production: A Survey On Current State, Challenges And Trends

Lorenz Plocher[1], Marius Heller[2], Benedict Ingendoh[1], Hasibe Turhan[2], Matthias Burgard[3], Sarah Wennemar[1], Achim Kampker[1,2], Marc Kissling[4]

[1]*Production Engineering of E-Mobility Components (PEM), RWTH Aachen University, Aachen, Germany*
[2]*Fraunhofer Research Institution for Battery Cell Production (FFB), Münster, Germany*
[3]*Fraunhofer Institute for Manufacturing Engineering and Automation (IPA), Stuttgart, Germany*
[3]*Fraunhofer Institute for Solar Energy Systems (ISE), Freiburg, Germany*

Abstract

The demand for lithium-ion batteries increases rapidly. Possible improvements of the production technology are seen as key lever to improve sustainability and cost. The production of lithium-ion battery cells is complex and highly influenced by the production environment. Large parts of the production processes must take place in so-called clean and dry rooms to strictly control particles, temperature, and humidity. Especially the dehumidification of air for dry room conditions requires significant amounts of energy. Moreover, contaminants are emitted in certain processes that must not interfere with operational safety. A possible improvement is given with so-called mini-environments. This concept, roughly described as encapsulation of the individual process step, offer numerous theoretical benefits such as improved process control, enhanced product quality, increased worker safety and reduced energy consumption. The concept of mini-environments in battery cell production is not yet established. This paper presents the findings of an industry and institute survey with key stakeholders from the battery machinery, clean- and dry room, and encapsulation industries. The results show that while the potentials of mini-environments in battery cell production are recognised, many hurdles must be overcome before successful implementation. For example, adapted holistic production systems and new logistic measures must be developed.

Keywords

Mini-Environments; Battery Cell Production; Production Environment; Industry Survey; Sustainable Production

1. Introduction to mini-environments in battery cell production

The manufacturing of lithium-ion battery cells requires to strictly control particles, temperature, and humidity of the production environment [1]. Among other negative influences, moisture leads to the decomposition of the electrolyte which results in shortened lifetime and reduced capacity of the battery cell [2,3]. Airborne or process emitted molecular and particulate contamination can also lead to defects and thus high reject rates [4,5]. Figure 1 gives an overview of the process steps in the production of lithium-ion battery cells, which can be divided into three stages: electrode production, cell assembly and cell finishing. Depending on the materials, dimensions and cell format, not only the process chain but also the individual process steps can differ significantly. In electrode production, anodes and cathodes are produced from the

DOI: https://doi.org/10.15488/15301
ISSN: 2701-6277

input materials. Both electrodes are then assembled with a separator, electrolyte, and a housing. In cell finishing, cells are electrochemically activated, checked, and packed. [6]

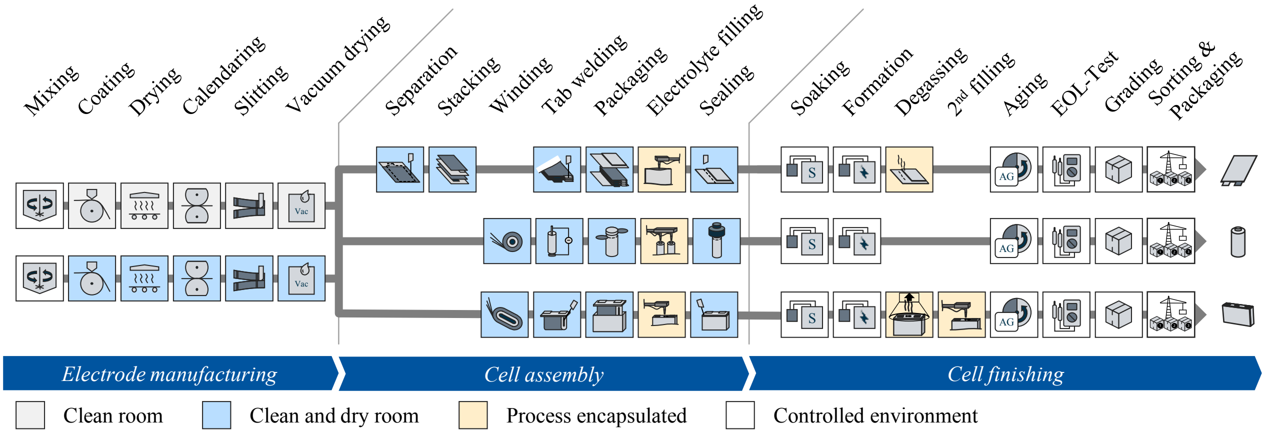


Figure 1: Generic process chain and necessary production environment to produce a lithium-ion battery cell [6]

As seen in Figure 1, the processes are currently placed in facility-integrated clean and dry rooms which are used to control particles, temperature and humidity. Those rooms must be tailored to meet the requirements of individual materials, processes and production characteristics. [7,1,8] Only the electrolyte-processing steps are additionally encapsulated in low-pressure or inert atmosphere due to the electrolyte's high reactivity with moisture. Conventional clean and dry rooms account for 26% to 53% of the overall energy consumption depending on the use case and production conditions [9–11]. At the same time, the sensitivity of future battery materials towards the influence of the production environment will continue to increase [12–14].

One possibility to reduce energy consumption and improve the condition of the production environment is given with so-called mini-environments. Figure 2 illustrates the concept of mini-environments compared to conventional clean and dry rooms. According to the ASSOCIATION OF GERMAN ENGINEERS, a mini-environment is a limited, separated product environment to protect the product from contamination [15]. Applied to battery cell production, this means that particle, temperature and humidity control does not (purely) take place on a room level but within a limited volume around the process. Currently, mini-environments are not established in industrialized battery cell production due to multiple reasons (see chapter 3). In the semiconductor industry on the other hand, mini-environments are already fully developed and integrated, with the key differences to battery cell production being very high degree of standardization and low requirements on ambient humidity. Only very few publications exist in the context of mini-environments for battery cell production. [16] KIM YU GON and EBERHARDT et al. published patents that describe the state of the art of mini-environments in battery cell manufacturing [17,18]. Furthermore, HELLER et al. discussed various terminologies regarding new airtight housing or encapsulation concepts for battery production [19].

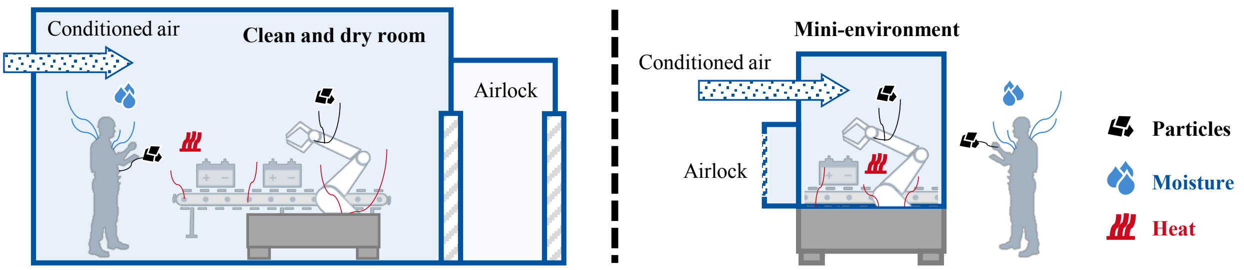


Figure 2: Schematic illustration of a conventional clean and dry room (left) and a mini-environment concept (right) for battery cell production

2. Survey

A comprehensive industry and institute survey was conducted to identify the current status of mini-environments in battery production. The survey was conducted in April and May 2023 and therefore reflects the status on given matter at this time.

To prepare the survey, a comprehensive literature and patent research was conducted. An extensive questionnaire with 76 questions divided into 13 clusters (matching subchapters in chapter 3) was formulated. For each cluster, 4-8 questions were asked divided into quantifiable questions e.g., “at what dew point and particle cleanliness requirement does a mini-environment make sense?” and qualitative questions e.g., “how should a logistic interface look like?”. Forty-five relevant companies and institutions with focus on the European market were identified and contacted to inquire survey participation. In the end, the authors conducted twenty-six digital face-to-face interviews. Figure 3 shows the number of companies and institutes that participated in the survey divided by company profile and origin. The share of participating companies in comparison to the inquired/existing companies is approximately the same in each category.

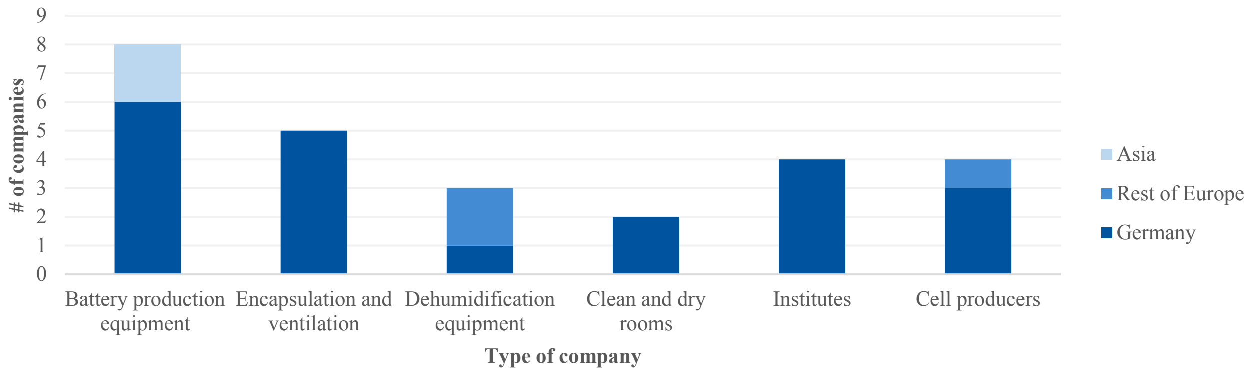


Figure 3: Survey participants divided by type of company and origin (of mother company)

3. Results

The results of the survey are presented below, broken down into the 13 survey clusters. It turned out that only very few of the participating companies already have experience with mini-environments in general. Most of the companies that have experience come from the glovebox or semiconductor industry. Only few companies have developed initial mini-environment prototypes specifically for battery cell production. Thus, the results of the survey rather represent a comprehensive aggregation of knowledge, experiences, opinions, and expectations. Quantifiable answers could only be retrieved by very few participants.

3.1 Concept understanding and definition

Based on the statements of the interviewees, two conceptual approaches exist:

C1. Mini-environment as technically tight enclosures similar to currently available gloveboxes. It can be set up in a grey room and thus aims to replace large clean and dry rooms. Reconditioning upon opening is a key concern. Inert gas may be used.

C2. Mini-environment as an extended machine enclosure concept in comparison to current machine housings, aiming to increase or improve isolation of the process and exclude humans. In this case, some sort of clean and dry room with lower requirements are still necessary. A precise concept vision does not exist yet.

The dimensions of mini-environments are considered to match current machine housings. Mini-environments are seen as an intermediate step towards even smaller process enclosures like micro-environments.

3.2 Application scenarios

Mini-environments are predominantly seen for use in cell assembly. The critical step of electrolyte filling already uses glovebox-like enclosures (C1) today. Implementing mini-environments is generally considered easier for processes with smaller footprint than for those with larger equipment.

The assessment of potential mini-environment application scenarios varies significantly based on the two described concepts as outlined in 3.1:

1. Glovebox-like mini-environments (C1) are already implemented in research laboratories and small-scale production. This concept is predominantly seen limited to this production scale.
2. The yet broadly undefined extended machine enclosure concept (C2) is considered useful for high-volume production with extensive automation. The prevailing opinion is that this concept is most effective when coupled with high automation and precise process control.

3.3 Quality and measurement

The improvement/stabilization of environmental conditions is seen as one of the top three potentials of mini-environments. Especially the advanced separation of operators from the process reduces possible negative influences and therefore increases quality consistency. All types of contamination (humidity, particles, temperature) are considered easier to remove in mini-environments than in larger rooms, mainly due to better and more controlled airflow, which can be simulated in advance. Based on improved/stabilized environmental conditions, a potential scrap reduction during operation was deemed realistic but could not be quantified because of possible contrary effects by necessary enclosure openings.

With regards to measurement, participants stated that temperature, humidity, and particle detection can be inline. Currently used particle traps should be reconsidered as they necessitate openings of the mini-environment. In comparison to current sensor placements to monitor environmental conditions, sensor placement moves closer to the process with shrinking encapsulation volume. Therefore, environmental product requirements can be monitored more precisely. On the other hand, higher complexity applies for data collection and processing, especially regarding frequent mini-environment openings and the resulting variety of states. Almost all respondents stated that the costs for testing humidity, particles, and temperature would not significantly differ from conventional clean and dry room concepts.

3.4 Accessibility

Accessibility is perceived as one of the top three challenges for implementing mini-environments. Companies in the semiconductor industry tend to view the challenges as somewhat lower. Cases that require mini-environments to be opened are given with emergencies, cleaning, maintenance, malfunctions and partially for logistic processes. Overall, accessibility for material supply and logistics are seen as not yet resolved but potentially solvable (see 3.5). A lack of concepts for maintenance, cleaning, etc., is considered critical. Placing mini-environments in a clean and dry room is a straightforward option to minimize negative impact when opening is necessary. Innovative approaches like mobile protective tents were mentioned.

One of the top three challenges in implementing mini-environments in battery production is seen with reconditioning times after enclosure opening. To reduce reconditioning times, smart opening mechanisms and boost modes have been suggested, but detailed concepts are yet to be developed. Reconditioning times between 3 minutes (mainly C2) and 8 hours (mainly C1) can be achieved today and are dependent on:

- The difference between inside and outside conditions during the time of opening. General rule: the larger the difference between those conditions, the longer the reconditioning times.
- The maximum achievable air exchange rate of the mini-environment. General rule: the higher the air exchange rate, the shorter the reconditioning times.

While not all companies consider standardizing accessibility components necessary, most see some level of standardization as desirable. Developing a singular functional accessibility concept is perceived as more important than a universally applicable standard.

3.5 Interconnection and interfaces

The interconnection of multiple processes with mini-environments is perceived as more complex compared to conventional clean and dry room setups. Physical interfaces are seen as one of the top three challenges for implementing mini-environments in battery production. Unresolved issues primarily relate to airlock concepts between individual mini-environments. The semiconductor field provides valuable know-how, including (partially) standardized load ports for material infeed. Here, challenges are mainly seen in roll-to-roll processes.

Airlock concepts become challenging, especially when trying to standardize interfaces across different process sections e.g., from electrode manufacturing to cell assembly. Standardization is considered less important in this area than for accessibility. Nevertheless, many companies express a desire for standardization in mini-environment interconnection. Custom interfaces are estimated to be technically feasible today.

Airlocks should be designed as compact as possible to minimize the needed conditioned air. It is assumed that interconnecting airlocks between two mini-environments do not require separate ventilation systems but are ventilated with conditioned air from the mini-environments itself. With increasing interconnecting airlock volume, survey participants see higher likelihood of separate ventilation systems. Discontinuous airlock operations are not seen as a difficulty for mostly continuous working dehumidifiers. Pressure relief and pressure retention valves can be employed for compensation.

3.6 Energy and costs

Costs are categorized in investment costs and operational costs, with the latter primarily depending on energy costs.

Overall investment costs are estimated to increase for mini-environment concepts that additionally require a clean and dry room (mainly C2). Overall investment costs are estimated to decrease for mini-environment concepts that can operate without an additional clean and dry room (mainly C1).

Operational cost is believed to decrease significantly with mini-environments with energy saving potentials from reduced dehumidified process volume. This is seen as one of the top three potentials of mini-environments. The amount of energy saving potential is significantly dependent on the production environment requirements. The higher the requirements the higher the possible energy saving potentials are assessed. With lower production environment requirements, the expected energy saving potential also decreases. That leads up to the point where mini-environments have no advantage over conventional clean and dry rooms. A quantification of the requirements at this point could not be made due to a general lack of existing business case calculations and prototypes.

Although acknowledging the theoretically benefit of reducing energy cost, most companies noted that other factors such as yield rate have a much higher impact on operational cost of current battery productions.

3.7 Enclosure and air handling

The assumed requirements for enclosure vary significantly depending on the mini-environment concept. While the glovebox-like concept (C1) involves technically tight enclosures, other mini-environment concepts (mainly C2) mention currently unquantifiable but in the future to be defined leak rates. Pressure induced flow direction of air due to a leakage rate of the housing is considered to be more relevant for particles than for humidity. Here, the flow direction is mainly based on the partial pressure differences of water inside and outside the housing. In battery production, glovebox gloves are only used in positive pressure concepts, which are found only in the glovebox-like concepts (C1). For large-scale applications, gloves are generally considered impractical.

According to company statements, the smaller volume of mini-environments allows for process-oriented airflow patterns in comparison to conventional clean and dry rooms. There is no standardized rule for air handling in mini-environments, and each concept needs to be individually designed in terms of e.g. air flow, ventilation and filtration. Participants are uncertain whether air from the mini-environment needs to be fully exhausted or can be recirculated after treatment. For safety reasons, most concepts currently involve exhausting all air.

It is believed that not every mini-environment requires its own air conditioning/dehumidification unit. Several mini-environments can be supplied by a single unit to enhance overall system efficiency. However, this increases the piping complexity. Employing more units to supply fewer mini-environments could enhance flexibility. Most survey participants consider moisture accumulation non-existent in mini-environments due to partial pressure of water and corresponding immediate distribution of humidity in the small environment.

3.8 Safety

Better separation of the operator from the process is seen as one of the top three potentials of mini-environments. General consensus is that the use of mini-environments can increase occupational safety in battery cell production. This is primarily due to the physical barrier provided by the mini-environment between the worker and the product. Generally, safety requirements and resulting measures can vary depending on the mini-environment concept.

It is expected that the occupational safety standard will not increase with the use of mini-environments if they are designed in a positive pressure principle (mainly C1) because contaminants could be pushed out of the mini-environment towards the operator. A safety-beneficial concept is primarily seen in negative pressure concepts (mainly C2) where contaminants are contained inside the mini-environment. Additionally, mini-environments open up the possibility of filtering polluted exhaust air (e.g. NMC exhaust and VOCs) and feeding it back into the enclosure. Thus, the proportion of recirculated air and consequently the energy efficiency potentially increases. Concrete concepts for this aspect are yet to be developed. Even with possible higher occupational safety of mini-environments, it is assumed that the use of personal protective equipment (PPE) is still required.

With the possibility to achieve ultra-low dew points inside and higher dewpoints outside of the mini-environment, mitigated health risks for operators are also considered advantageous.

3.9 Monitoring and control

The participants assessed that the measurement technology used to monitor environmental conditions in mini-environments will not differ significantly from the current technology used in clean and dry rooms. However, the positioning of sensors will be adjusted. Proposed measurement points include the exhaust air of the mini-environment and critical points in the process. Sensor placement in mini-environments will be closer to the point of interest than it is currently customary, enabling more precise measurements. To ensure occupational safety, it is anticipated that more mobile measurement technology will be required, and sample measurements will also need to be taken at various points outside the mini-environments more frequently. For this purpose, e.g., wearable measurement systems can be attached to the operator's clothing.

Participants are unsure whether mini-environments will lead to sensor cost savings. Nevertheless, sensor costs are not considered particularly relevant. A peculiarity of mini-environment sensor technology could be that, upon opening, larger ranges of fluctuations may need to be covered than currently usual.

3.10 Factory integration

Opinions regarding the integration level of mini-environments vary significantly depending on the concept. Generally, mini-environments must be considered in comprehensive factory safety concepts, including emergency exits and fire protection measures. Companies aiming for a glovebox-like approach (C1) tend to believe that mini-environments can be used in a standard production environment and therefore fewer integration effort into the production facility is necessary. With concepts that still rely on clean and dry room (mainly C2), the number of interfaces would increase and the integration into the production facility is assumed to get more complex. In high-volume production scenarios (mainly C2), redundancy e.g., for dehumidifiers should be considered to reduce equipment downtime resulting in increased integration and interface complexity.

Today clean and dry rooms are considered to belong to the building or battery specific infrastructure with close interfaces to the production equipment. In contrary, companies see mini-environments rather belong to the production equipment than as part of the infrastructure. As a result, there is also a responsibility shift for the production environment towards the process equipment manufacturer which is viewed very critically by them.

3.11 Flexibility

Generally, mini-environments are considered to reduce production flexibility due to higher overall complexity of the plant compared to conventional clean and dry rooms.

Initial ramp-ups are also estimated to be more challenging with mini-environments resulting in longer ramp-up times and higher costs. Subsequent starting facilities with the same mini-environment concepts should then require a similar timeframe to current ramp-ups.

In addition, implementing alternative technologies (upgradability) are considered to be more challenging with mini-environments. However, upgradability is generally deemed almost irrelevant in battery cell manufacturing.

Contrary, the smaller air volumes of mini-environments also lead to two factors that could be beneficial for flexibility. Firstly, it is expected that scenarios like night or weekend stand-by operation will be easier and more efficient to implement. Secondly, by separating the process into smaller steps that are separated by mini-environments instead of integrating many process steps into one housing, there is potential for simplified troubleshooting and minimized contamination during openings.

3.12 Future outlook

The current Technology Readiness Level (TRL) of mini-environments in battery production is assessed with varying degrees. TRL ratings ranged from 3 to 9, with most respondents estimating the TRL to be between 4 and 7. While few initial concepts have been successfully demonstrated, near-series testing campaigns have not been conducted and market-ready systems are not yet available. Challenges to improve the TRL are particularly seen in the areas of automation (integration), maintenance and standardization, and in a mindset change required by various stakeholders to implement a new (riskier) concept.

Opinions diverge on the necessary time duration until mini-environments can be utilized in mass production of battery cells. Estimates range from approximately 2 to 3 years as a minimum to 5 years or more as a maximum. It is considered crucial that the mini-environment concept is first implemented and validated in a small series and then in large-scale production.

Regarding the further development of mini-environments, companies pursue two approaches:

- Companies develop concepts and validate them through demonstrators.
- Development is carried out by universities and research institutions and transferred to the industry.

3.13 Industry landscape

The survey results show that in the development of mini-environment concepts on the one hand equipment manufacturers often wait for a specific inquiry from producers and on the other hand producers expect fully developed and tested concepts from equipment manufacturers. Equipment manufacturers are particularly concerned about the possibility to be pushed into more responsibility by the producers when jointly delivering the process equipment and the equipment for process environment.

For this reason, concept development and hardware demonstration from research institutions were seen as valuable. In general, deeper cooperation and partnerships between stakeholders, especially between producers and equipment suppliers, were considered desirable.

Currently, leading companies in the mini-environment field are primarily considered to be traditional glovebox manufacturers and companies from the semiconductor industry.

4. Discussion and recommendations for action

It can directly be concluded that the concept of mini-environments for battery cell production is still in an early phase. Few companies have experience in the field of battery production in an industrial scale at all. This is also demonstrated by the fact that no quantifiable evaluation is possible for this broad-based industry survey. Holistic knowledge of current battery production processes is still limited and uncertainty about future improvements high. While some experiences from other industries and early-stage concepts exist, there is no uniform understanding of the topic across the industry.

The following recommendations for actions are derived from the results of the survey:

- Development of holistic mini-environment concepts (C2) for each process step individually paired with an industry wide discussion about concepts to interlink the mini-environment concepts for each process step into a complete mini-environment process chain. Uncertainty can even be more reduced if authorities are part of the discussion e.g., regarding occupational safety and standardization.
- Cooperations between multiple companies e.g., equipment manufacturer and enclosure specialists or research institutes and producers should be stimulated to ensure a transfer from requirement definition, over development into implementation.
- Funding of application-oriented research in the field of mini-environments for battery production to do preparatory work that the industry can use to decrease risk of own investment by e.g., a business case calculator that is able to compare capex and opex of different mini-environment concepts to conventional clean and dry rooms for different environmental requirements.

5. Conclusion and outlook

Mini-environments are a promising concept to reduce energy consumption and to increase product quality and operational safety in battery cell production. Currently, only few research publications and industrial concepts exist. Therefore, a comprehensive industry and institute survey was conducted to identify the current status of mini-environments in battery production. With this paper, for the first time, not only individual sub-topics of mini-environments like housing or material transfer are discussed but a comprehensive aggregation of knowledge, experiences, opinions, and expectations are covered with all involved players from process to building. The survey revealed that there is little and no uniform understanding of the topic across the industry. Simultaneously, the potential of mini-environments is recognised and interest in further developments is high. Derived from the results, recommendations for action were given that directly imply a need for further application-oriented research in the field of mini-environments for battery cell production.

Acknowledgements

We would like to thank the German Federal Ministry of Education and Research (BMBF) for funding our research. The results presented in this paper were developed within the project FoFeBat3 – Energy and resource efficient battery cell production (funding code: 03XP0501).

References

[1] Pinho, J., 2021. Dry Rooms: Why They Are Needed and a Review of the Complex Issues Associated With Building Them - Particularly the Large Ones Required to Mass Produce Lithium Batteries. A123, Watertown MA, 3 pp. https://www.scs-usa.com/docs/ABT_John_Pinho_Technical_Report_October_2010.pdf. Accessed 4 August 2023.

[2] Eser, J.C., Wirsching, T., Weidler, P.G., Altvater, A., Börnhorst, T., Kumberg, J., Schöne, G., Müller, M., Scharfer, P., Schabel, W., 2020. Moisture Adsorption Behavior in Anodes for Li-Ion Batteries. Energy Technol. 8 (2), 1801162.

[3] Stich, M., 2019. Wasserverunreinigungen in Lithium-Ionen-Batterien. Dissertation, Ilmenau.

[4] Grabow, J.; Klink, J.; Benger, R.; Hauer, I.; Beck, H.-P., 2023. Particle Contamination in Commercial Lithium-Ion Cells - Risk Assessment with Focus on Internal Short Circuits and Replication by Currently Discussed Trigger Methods. Batteries 9 (1), 9.

[5] 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.

[6] Plumeyer, J.F., Menebröker, N., Clever, H., Kokozinski, L., Wessel, S., Heimes, H.H., Kampker, A., 2023. A Review of Process Innovations in the Cell Finishing of Lithium-Ion Batteries in Large-Scale Production. Hannover: publish-Ing.

[7] Heimes, H.H., Kampker, A., Wennemar, S., Plocher, L., Bockey, G., Michaelis, S., Schütrumpf, J., 2023. Production Process of a Lithium-Ion Battery Cell, Frankfurt am Main. https://www.pem.rwth-aachen.de/global/show_document.asp?id=aaaaaaaabyilawq. Accessed 9 August 2023.

[8] Vogt, M., Koch, K., Turetskyy, A., Cerdas, F., Thiede, S., Herrmann, C., 2021. Model-based energy analysis of a dry room HVAC system in battery cell production. Procedia CIRP 98 (1), 157–162.

[9] Dai, Q., Kelly, J.C., Gaines, L., Wang, M., 2019. Life Cycle Analysis of Lithium-Ion Batteries for Automotive Applications. Batteries 5 (2), 48.

[10] 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.

[11] Yuan, C., Deng, Y., Li, T., Yang, F., 2017. Manufacturing energy analysis of lithium ion battery pack for electric vehicles. CIRP Annals 66 (1), 53–56.

[12] Bi, Y., Li, Q., Yi, R., Xiao, J., 2022. To Pave the Way for Large-Scale Electrode Processing of Moisture-Sensitive Ni-Rich Cathodes. J. Electrochem. Soc. 169 (2), 20521.

[13] Busà, C., Belekoukia, M., Loveridge, M.J., 2021. The effects of ambient storage conditions on the structural and electrochemical properties of NMC-811 cathodes for Li-ion batteries. Electrochimica Acta 366, 137358.

[14] Xin, F., Zhou, H., Zong, Y., Zuba, M., Chen, Y., Chernova, N.A., Bai, J., Pei, B., Goel, A., Rana, J., Wang, F., An, K., Piper, L.F.J., Zhou, G., Whittingham, M.S., 2021. What is the Role of Nb in Nickel-Rich Layered Oxide Cathodes for Lithium-Ion Batteries? ACS Energy Lett., 1377–1382.

[15] Verein Deutscher Ingenieure e. V., 2021. Cleanroom technology – Barrier systems - Minienvironments (VDI 2083 Blatt 16.2). VDI Verlag, Düsseldorf.

[16] Korea Air Cleaning Association, 2002. Clean Technology and Management for Indoor Air. Proc. Int.Symp.

[17] Eberhardt, K., Hubalek, K., Handte, J., 2021. Method for cleaning exhaust air produced during a machining process in a clean room/dry room and system for carrying out the method B01D46/42; B01D53/26; F24F7/003; F24F8/10;. https://worldwide.espacenet.com/patent/search/family/080266800/publication/DE102021004571A1?q=DE102021004571A1. Accessed 4 August 2023.

[18] Kim, Y.G. Multi-stage dehumidification system for local area dehumidification of dry room B01D53/26; F24F3/14; F24F9/00;. https://worldwide.espacenet.com/patent/search/family/077926778/publication/US2022373199A1?q=US%202022%2F0373199. Accessed 4 August 2023.

[19] Heller, M., Turhan, H., Holöchter, N., Miggelt, M., Niggestich, M., Schöne, N., Janning, F., Wessel, S., Tübke, J., 2023. Energieeffiziente und qualitätsorientierte Anlagenkonzepte für die Batteriezellfertigung.

Biography

Lorenz Plocher (*1994) has been research associate at the chair of "Production Engineering of E-Mobility Components" (PEM) of RWTH Aachen University since 2020. He studied mechanical engineering with a specialization of vehicle engineering at RWTH Aachen University and power engineering and engineering thermophysics at Tsinghua University, China. His research focus is on holistic production planning approaches.

Marius Heller (*1992) has been research associate at the "Fraunhofer Research Institution for Battery Cell Production FFB" in Münster since 2020. He received his M.Sc. degree in mechanical engineering from RWTH Aachen University. His research interests include sustainable and innovative production technologies.

Benedict Ingendoh (*1998) has been research associate at the chair of "Production Engineering of E-Mobility Components" (PEM) of RWTH Aachen University since 2022. He studied mechanical engineering with a specialization in production engineering and business administration with a focus on corporate strategy development at RWTH Aachen University.

Hasibe Turhan (*1981) has been research associate at the "Fraunhofer Research Institution for Battery Cell Production FFB" in Münster since 2020. She is in the Product and Production Technology department of Dr. Saskia Wessel and leads the project planning of a 21700 round cell production with mini-environments.

Matthias Burgard (*1975) studied Microsystem Technology at the University of Freiburg. He is working at the Fraunhofer Institute for Manufacturing Engineering and Automation IPA in the Department for Ultraclean Technology and Micromanufacturing since 2002. As a project manager he has led numerous projects in the field of battery cell assembly and micromanufacturing.

Sarah Wennemar (*1995) studied mechanical engineering and business administration with focus on power engineering at RWTH Aachen University. Since 2020 she has been research associate and since 2022 the group lead of the Battery Production Technology Group at the chair of "Production Engineering of E-Mobility Components" (PEM) of RWTH Aachen University.

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.

Marc Kissling (*1991) studied Renewable Energy Systems with focus on energy storage technologies at the Technical University Dresden (TUD). Since 2017 he has been research associate and since 2023 the group lead of the Battery Cell Production and Technology Assessment Group in the Department for Electrical Energy Storage at the Fraunhofer Institute for Solar Energy Systems (ISE).

CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
CPSL 2023-2

5th Conference on Production Systems and Logistics

Interoperable Architecture For Logical Reconfigurations Of Modular Production Systems

Sebastian Behrendt[1], Marco Wurster[1], Matthias Strljic[2], Jan-Felix Klein[3], Marvin Carl May[1], Gisela Lanza[1]

[1]*wbk Institute of Production Science, Karlsruhe Institute of Technology*
[2]*Institute for Control Engineering of Machine Tools and Manufacturing Units, University of Stuttgart*
[3]*Institue for Material Handling and Logistics, Karlsruhe Institute of Technology*

Abstract

Individualisation of products and ever-shorter product lifecycles require manufacturing companies to quickly reconfigure their production and adapt to changing requirements. While most of the existing literature focuses on organisational structures or hardware requirements for reconfigurability, requirements and best practices for logical reconfigurations of automated production systems are only sparsely covered. In practice, logical system reconfigurations require adjustments to the software, which is often done manually by experts. With the ongoing automation and digitisation of manufacturing systems in the context of Industry4.0, the need for automated software reconfigurations is increasing. However, heterogeneous and proprietary technologies in the field of industrial automation pose a hurdle to overcome for generally applicable approaches for logical reconfigurations in the industrial domain. Therefore, this paper reviews available technologies that can be used to solve the problem of automated software reconfigurations. For this purpose, an architecture and a procedure are proposed on how to use these technologies for automatic adaptation and virtual commissioning of control software in industrial automation. To demonstrate the interoperability of the approach, collective cloud manufacturing is used as a composing platform. The presented approach further includes a domain-specific capability model for the specification of software artefacts to be generated, allowing jobs to be described and matched on the platform. The core element is a code generator for generating and orchestrating the control code for process execution using the reconfigurable digital twin as a validator on the platform. The approach is evaluated and demonstrated in a real-world use case of a modular disassembly station.

Keywords

Logical Reconfiguration; Production Control; Industry4.0; Modular Production Systems; Reconfigurable Manufacturing Systems

1. Introduction

Today's rapid and dynamic business environment, characterised by trends like individualised products and shorter product life cycles, is forcing manufacturing companies to adapt their production systems frequently and efficiently [1, 2]. In addition, volatile and uncertain material supply and customer demand [3] require the deployment of adaptive production systems that can swiftly respond to changing circumstances. Reconfigurability proves to be a key capability to enable manufacturers to provide production processes and resources on demand [4].

DOI: https://doi.org/10.15488/15270
ISSN: 2701-6277

Industry4.0 and Cloud Manufacturing (CM) are driving the integration of cyber-physical systems (CPS) into the production environment to create cyber-physical production systems (CPPS) [5]. The seamless convergence of software and hardware forms the backbone of adaptive production systems, with software becoming an integral part [6]. Although the extension of hardware with software comes at the cost of increased complexity, it also enables digital planning, deployment and control of manufacturing operations [7]. The Software-defined Manufacturing (SDM) paradigm promises to enable orchestration and management of large CPS by using abstraction and encapsulation to reduce complexity when interacting with heterogeneous hardware and software infrastructure [8, 9].

While there exist many frameworks that provide design guidelines for software and hardware of flexible and reconfigurable production systems, their concrete implementation raises many questions given the wide range of technologies used in industrial practice. Reference architectures for CPS, such as RAMI4.0 or IIRA, provide conceptual and abstract frameworks but their usefulness for realisation of CPPS is limited due to their lack of technical depth, according to Wang et al. [10]. In fact, changing the logic of CPPS by reconfiguring software, e.g. by changing sequencing and parametrisation of control code, is still a highly manual task in practice, which increases cost of reconfigurations and limits the useable potential of reconfigurable hardware [11–13].

Heterogeneity of communication protocols, proprietary software interfaces and complicated planning tasks challenge the general applicability of more technical approaches for logical reconfigurations, especially with respect to the integration and automation of software systems [10]. In the following, we will explore existing approaches that contribute the reconfigurability of production systems and evaluate their suitability (Section 2). With reference to ElMaraghy [1], Wiendahl et al. [4] and Monostori [5], we propose the following requirements to evaluate existing approaches for realising reconfigurable production systems:

R1 Automation: Automated adaptation of the control code to suit individual hardware configurations.

R2 Abstraction: Individual software modules are encapsulated according to their associated hardware, abstracting the hardware and its capabilities in a service-oriented manner.

R3 Generalisation: The architecture is generic and can be implemented with various tools and technologies, thus promoting interoperability.

R4 End-to-End: Continuous approach from the gathering of the customer requirements to the physical execution of processes.

R5 Virtual Validation: The feasibility of the sequenced processes should already be predicted virtually with a high quality.

R6 Integration: The integration of additional hardware/software modules and their deployment in the existing infrastructure should be possible with little effort.

Based on the findings of this analysis, we present a framework and an architecture that uses state-of-the-art technologies and the concepts of CM and SDM to overcome existing limitations (Section 3). Section 4 demonstrates and validates the applicability of this approach in a case study of a reconfigurable and automated assembly station. Finally, Section 5 discusses the potentials and limitations of the proposed approach and gives directions for research in the field of reconfigurable production systems.

2. State-of-the-Art

Several approaches aim to provide a framework for designing production systems that can better adapt to changing requirements through flexibility and changeability [4]. While both flexibility and changeability specify the ability to adjust the operating point of production systems, changeability goes beyond flexibility by covering more fundamental changes to the production system, such as reconfigurations [14].

Existing approaches in the literature for manufacturing system paradigms have in common that they aim to have universal production resources that can be equipped with different processes, thus allowing simple reconfigurations of the production capacity. Bionic, fractal and holonic manufacturing systems [15, 16] follow the idea of having universal entities that can act autonomously, change their configuration and interact with each other to enable an adaptive system. Another paradigm, i.e. reconfigurable manufacturing systems (RMS), provides a more tangible approach by providing design principles for reconfigurability [17]. Reconfigurability specifies the ability to adapt the physical or logical structure to implement a different functionality, both at the resource level and at the system level [18].

More recent paradigms, in particular Smart Manufacturing Systems and Advanced Manufacturing Systems, focus more on the IT infrastructure required for logical reconfigurations, but the literature lacks generally applicable approaches for implementing these paradigms in practice [10, 19, 20]. Existing approaches use proprietary solutions that are not generally applicable due to technical barriers such as different programmable logic controller (PLC) manufacturers or proprietary protocols. For example, Talkhestani et al. [12] adapt PLC control code for logical reconfigurations by using a direct but proprietary PLC interface.

Besides the field of manufacturing system's paradigms, there are many approaches in the field of smart manufacturing, Industry4.0 and CM that present concepts and architectures to manage and operate CPS. The integration of generated software artefacts is a core element of model-based systems engineering and has been striving for generated and reusable software within automation technology since the 1990s, as presented by Eppinger and Steven [21]. The concept is being revived in current topics such as the asset administration shell of the reference architecture model RAMI4.0 [22] and the concept of SDM by Verl et al. [23] for autonomous program parameterisation. As described by Wymore [24], the concept of generated control code is used in systems engineering and could be applied more broadly in automated capability-based systems to generate digital twins for process validation, according to Madni et al. [25]. Exemplary approaches already exist, such as a cloud-based evaluation platform for real-time applications within SDM [26]. However, there is still a lack of software tools that validate and generate control code regarding a uniform process description in a neutral process model. For example, Brovkina [27] specifies a process model with a focus on assembly sequences, but this is part of a holistic tool for automated layout design and control code generation with a clearly specified methodology. For example, several studies on general [28], additive [29] and CNC (Computerised Numerical Control) [30] CM platforms show that manufacturing processes for individual components and assemblies can be realised. However, there is a limitation to geometrical and material-related properties that can be covered. The lack of uniform task and process descriptions as well as generally applicable tools for control code generation hinders to provide control code as a service to allow manufacturing machines to be operated adaptively with frequent logical reconfigurations. Industrial architecture models in CM provide metamodels for domain-specific modelling of digital twins to approximate the production capabilities of a service provider [31]. Yet, do not provide additional tools to realise these capabilities by generation of associated control code.

Considering related research in the field of virtual commissioning [32], Martinez et al. [33] present a digital twin demonstrator that adapts the control code based on production orders and resource configurations. After a successful adaptation phase, a digital twin is used to validate the system by simulation.

In the area of process sequence orchestration, Pfrommer et al. [34] present a skill-based framework for reconfigurable manufacturing systems. Here, executable actions can be generated from a high-level description of the capabilities, which are orchestrated as services in the next step, similar to the approach of Backhaus und Reinhart [35]. As noted by van de Ginste et al. [36], the transformation of high-level skills to executable skills remains a research gap. First approaches to automate code generation and constraint checking are provided by Kocher et al. [37].

In summary, there exist many approaches that aim to increase the flexibility and reconfigurability of production systems by considering new design paradigms, especially with regard to CPS and CM. However, there seems to be no approach in the literature that satisfies all requirements presented in section 1. The analysis showed that approaches from the field of manufacturing systems paradigms and reference architectures for digital manufacturing promote Abstraction (R2) and Generalisation (R3) but lack details considering Automation (R1) and Integration (R6). More technical approaches, on the other hand, demonstrate Automation (R1) and Integration (R6) but lack general applicability (R3) and their continuity (R4). In the following, we will present a framework and architectures that aim to combine insights from the reviewed literature to satisfy requirements R1-R6 and to enable automatic deployment of logical configurations in production systems.

3. Approach

The resulting approach consists of two subsequent steps: the development of a code generator (CG) and its embedding in the architecture and system model of the Collective Cloud Manufacturing (CCM). The embedding into the CCM is explained first, followed by the structure and functionality of the CG. Figure 1 serves as a high-level architecture and flow diagram, with numerical steps within the CCM platform and alphabetical steps for domain-specific steps of code generation and validation.

For CCM, the two required components are a domain-specific capability model and an encapsulating analysis container of integration patterns [38]. Thus, individual process steps and system capabilities can be freely defined according to Brovkina's process model [27] and receive the design guideline to be enriched with a standardised position node via a start and end pose. A sequence of process steps is realised via a concatenation of such process steps via a "next" relation. For example, this could represent a sequence of handling tasks from a robot where the start pose specifies the pickup of a workpiece and the end pose specifies the target of the handling task itself. In this context, handling tasks are non-value-adding processes that do not need to be noted explicitly for higher abstraction. Relevant process step parameters can be attached directly to a process step node or as sub-elements via their own relationships. The definition of the domain-specific process steps with a process model forms the basis of the execution flow (step 1 - step 10) of the CCM platform.

For individual processes or sub-process, their configured CG are encapsulated as a simulation service according to Strljic and Riedel [38] within an analysis container. This is annotated with the previously defined domain-specific process step parameters, i.e. the process step model. The process steps represent in their union the entire bundle of required manufacturing capabilities to be executed. The annotated analysis container is registered on the CCM platform in step 1).

Using previously created process step models, users can specify individual production process requirements to be realised by a plant, a manufacturing system or a production resource in step 2). According to the CCM-concept, these can be own plants or a mixture of service providers. The requirements are summarised by created digital assets for each step in the process sequence, which are made available downstream to the CG.

In step 3), a completed requirement description can be uploaded to the CCM platform as a project request, and in step 4), the matching process is initiated with the help of a subgraph search for compatible CGs, as described in [39]. The most suitable candidate of the matching process is instantiated on the CCM platform and starts with step 5): the analysis of digital assets for their requirements of manufacturing capabilities. For this purpose, interfaces from the CCM platform are made available to the CG to provide information about the requirements responsible for matching a process step to a production resource. The core of the instantiation is the execution of the CG as well as providing requirements.

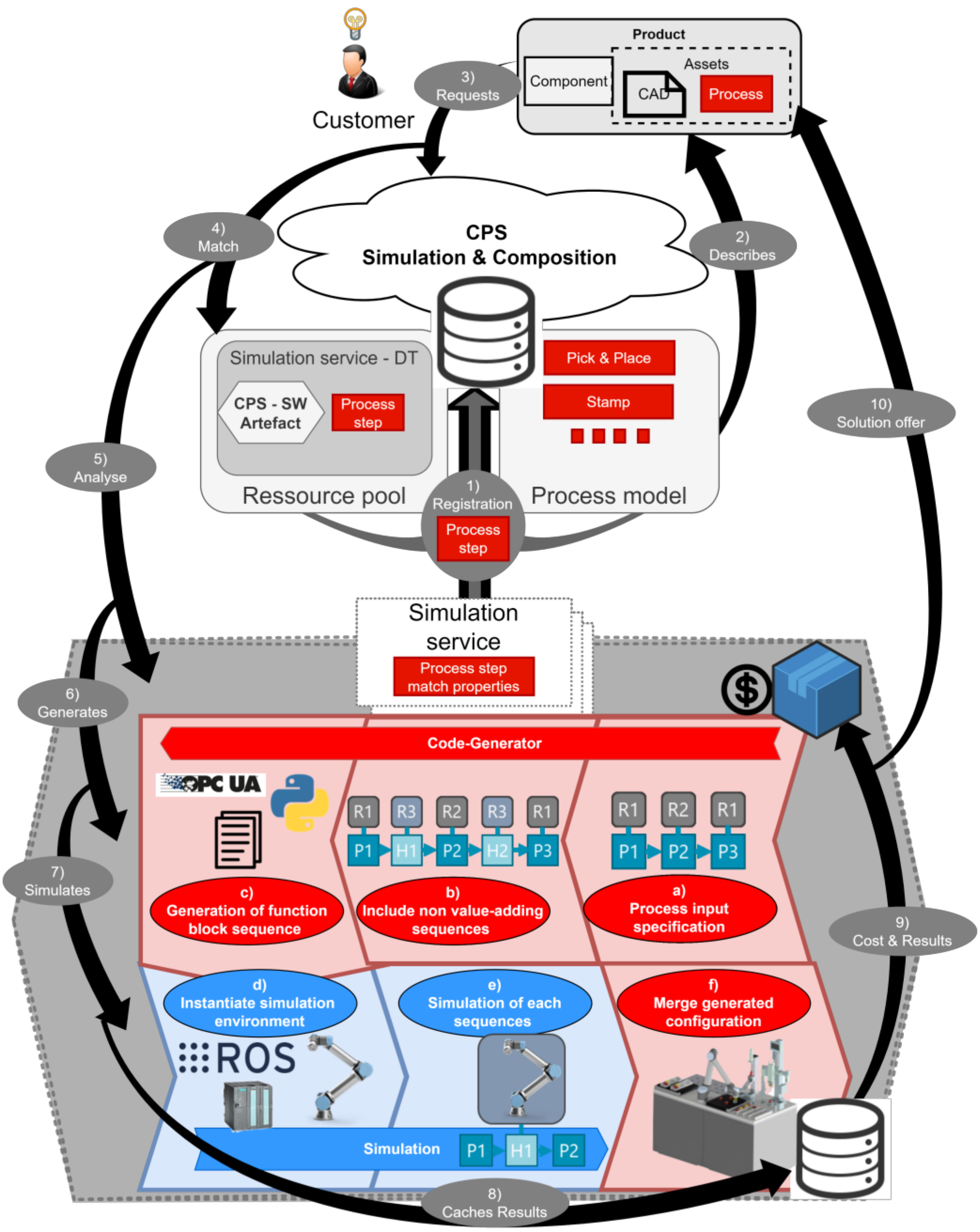


Figure 1 Overview of the architecture for platform-based planning of reconfigurations of production systems with functional sequencing and automated deployment

The CG (step 6) is responsible for translating the process model, which describes the production process sequences in an abstract way, into instructions that are understandable for automated manufacturing equipment. The information that needs to be provided by the CCM platform to the CG is shown in Table 1. This includes resource-related information concerning available production resources and their capabilities and process-related information, i.e. the process sequence to be executed. For a more specific view of the problem of generating and validating control code for RMS, we have subdivided steps 6) and 7) into six more detailed steps a)-f).

With regard to requirement R6 (Integration), the interfaces of the CG used to receive information shall be interoperable and provide self-describing capabilities for efficient integration. The CG should be modular and extensible to accommodate new functionality. To realise this requirement, external data can be passed to the CG (step a) on multiple interfaces, which all get integrated to the internal data model of the CG by data adapters.

Table 1: Overview over input information required to execute the CG classified by the information categories

Information category	Information content	Explanation
Resource-related information	Communication interfaces	Type and address of communication interfaces
Resource-related information	Configuration	Available processes at a resource and meta information (e.g. positions of process modules)
Resource-related information	Capabilities	Capabilities describe in an abstract way the processes that can be executed by the resource.
Process-related information	Process model	Sequence of processes to execute with required resources and capabilities for these processes.

The control code generation begins with an analysis of whether the provided process sequence in the process model is complete, i.e. all transitional conditions between consecutive process steps are logically valid. For instance, an incomplete process sequence could be missing a process step for handling between two process steps. In the case of missing process steps, the CG determines required state transitions to satisfy the transitional conditions and evaluates whether a suiting resource is available. If a resource is available, the process model is adapted by adding a process step (step b). Otherwise, an error is returned to the CCM platform specifying the missing capability for the transition. In code generation (step c), the CG iterates over the process model and generates code for each process step that can be deployed to the associated production resource. Based on the communication interface and the configuration of the resources, it can be determined, how and what information needs to be provided to adjust the control code. Ideally, code for these processes is pre-planned, deployed, and requires only adjustments without further need for planning and generating new control code. Yet, other processes, such as handling tasks, may need to be planned in the CG. This is achieved by providing interfaces to planning solutions, such as ROS path planning.

Quality of planning can be improved by using simulations. Modelling the system in detail without a high degree of abstraction allows to detect errors in the planning process before the physical commissioning. This reduces additional the effort required during ramp-up of the newly configured station is reduced. The information contained in the process model, the generated control code, and machine-specific information serve as the basis for instantiating simulation environments in step d). Each defined process step describes a change of state of the system starting from an initial state before execution and ending in a final state after execution. The definition of these states allows simulation of individual process steps and their simulative validation (step e). If the final state of the process differs from the planned finals state by a defined tolerance, e.g. due to collisions, the process must be re-planned.

After code generation and validation of each process step, the generated code is merged into a configuration file that is returned to the CCM platform (step f). The file contains the newly planned logical configuration of the production resources with information on how to deploy this configuration to the production resources.

Simulatively determined KPIs of the individual machine modules of the configuration are aggregated and combined within step 9) into a normalised cost model according to production duration. The subordinate cost model is initially only required for ordering and evaluating the planned results, but it can map the concrete economic efficiency of offered process sequences in the broader spectrum. Finally, in step 10), the aggregated KPIs are combined with the resulting control code of the CG into an overall planning result. The result can be imported into an execution instance of the selected CG by a user to run the actual production system with the generated control code for the specified process steps of the process model.

4. Case Study

In this paper, the proposed approach including the CG is exemplarily tested on a modular production system for disassembling electric window lifter motors. The system is part of the AgiProbot factory [40] and built based on the Fluid Automation Design Framework [41]. The latter describes a Plug&Produce architecture for production systems for both hardware and software with the underlying vision to enable fine-granular reconfigruations of the system to follow ever-changing requirements on manufacturers in dynamic and volatile environments [40]. The system consists of multiple reconfigurable stations arranged in a matrix layout. Each station comprises of multiple station modules, which can carry up to four elementary units each. Each elementary unit fulfils a certain function.

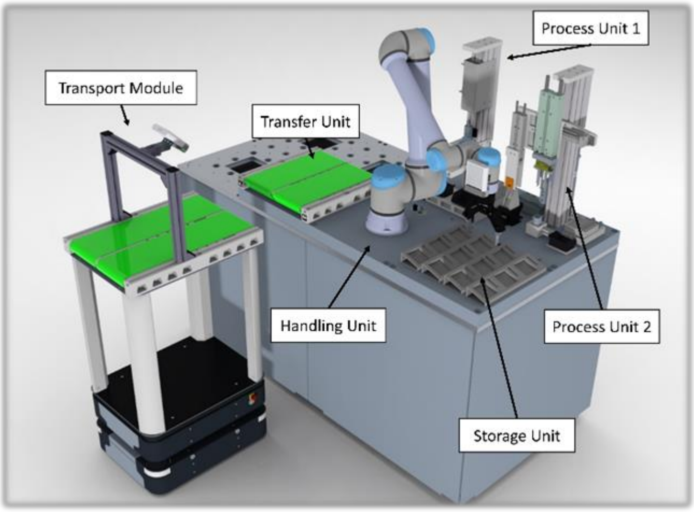


Figure 2 Modular hardware demonstrator based on the fluid automation framework: electric motor disassembly

The disassembly station, as depicted in Figure 2, consists of a handling unit, a storage unit and two process units, which both execute certain tasks of an electric motor's disassembly. A transfer unit moves individual products and components from the station to the transport module, i.e. an autonomous mobile robot. A PLC with an OPC UA interface is responsible to control the processes of individual process units. The handling unit is a universal robot with an interface to the PLC and ROS. Due to its modular design, the station allows to easily reconfigure by changing its process units. To monitor the configuration of process units, i.e. identity, location and rotation of equipped process units, each unit is equipped with RFID tags that specify the process provided by the unit. All resource related information concerning current configuration and meta information such as CAD files can be accessed via the OPC UA server of the station to integrate the station in the CCM platform. The logic of the station is reconfigurable by preplanning and encapsulating control code of each process unit in a function. All functions, each associated with a process step of a process unit, are linked to a specific OPC UA bit. By including a conditional call of every function in the main-loop depending on the associated OPC UA bit, processes can be performed in an arbitrary sequence by triggering their associated OPC UA variable. Moreover, all parameters of the processes can also be adjusted with OPC UA.

The CCM platform provides all information to the CG, comprising of resource and process related information, via REST. The data is parsed into the CG's internal data model (step 6a), and further required process steps are added to the process model based on analysis of location and orientation of the product during the process sequence (step 6b). Code generation (step 6c) for production processes is for the disassembly station trivial, since only the associated OPC UA bits must be specified as control code for every process unit is pre-planned. However, path planning of the handling unit must be done.

Planning and code generation for the handling unit is of particular importance as its kinematic restrictions have a direct influence on the possible configurations of the station. Therefore, the physical 3D simulation environment NVIDIA Isaac in combination with ROS is used as a simulation environment. The process is initiated by transferring all required information from the CG to the planning solution via a ROS action server. This contains the overview of all used assets as well as the initial and final state of this handling step and meta information for simulation and planning. Based on this information, the simulation scenario is instantiated. At first, a fast planning routine is executed, which does not have the goal of finding the best possible path, but to make a statement about the general existence of a valid path. In parallel, optimising algorithms can be used to search for the best possible path. Determined plans are stored in the database and selected plans are additionally tested in the physical simulation. Control code of the planned path is then generated by ROS and returned to the CG.

After code generation and validation, the data required for deploying the new logical configuration to the disassembly station is generated (step 8). This covers a sequence of processes, including process information on how to communicate with the disassembly station for process execution. Subsequently, the data is returned to the CCM platform and can be utilised by an execution client that communicates the information to execute processes to the assembly station via ROS or OPC UA.

5. Discussion and Conclusion

The resulting approach attempts to fully satisfy the requirements R1 - R6, which is done by providing an architecture and a flow diagram for reconfigurable production systems and applying it in a real use case. A container-based system is presented in which the architecture of a CG could be encapsulated for planning and execution of production processes. It is validated in a CM environment to illustrate the interoperability of such an approach. The ability to perform all steps of the flow diagram fully automated in a Docker environment starting from an abstract process description and ending in executable process steps satisfies requirement R1 (Automation) and provides the basis for R4 (End-to-End). By applying the approach to a real-world example, R3 (Generalisation) is also validated. In addition, the interlocking of an abstracted process model with domain-specific CGs shows a high degree of reusability and interchangeability, since domain-specific value-adding process steps can be realised by different underlying hardware, which in turn can be realised by an interchangeable CG. Furthermore, with the integration of interfaces for planning solutions with simulation environments, each process step can be used in a service-oriented manner by a digital twin in its execution for R5 (Virtual validation). The combination of these features, thus, supports R2 (Abstraction). Thanks to the flexible process model and integration of CGs by standardised interfaces of the CCM platform, continuous extensibility to new hardware components is possible through integration via own CGs, process steps or simulation endpoints. Chained planning through multiple CGs allows highly flexible and modular systems to be integrated into more complex projects, thus, achieving an even higher level of abstraction. However, the most crucial limitation of the underlying approach is that it requires a fully digitised production system with open interfaces to control and parametrise processes and evaluate the current configuration of the production system. In addition, CGs with interfaces conforming the interfaces of the CCM platform are required to generate the control code in case of reconfiguration. Since CGs are not widely used yet in practice, this requirement could require a lot of work and adaption of current control infrastructure. Therefore, the presented solution is most efficient in greenfield projects that allow a thorough definition of the software architecture and ideally allow reuse of existing CGs. Yet, the requirements concerning digitisation and availability of open interfaces and CGs prevents application of this approach in most existing production systems. Thus, future research should concentrate on more generally applicable CGs for automated production systems and how these requirements can be reduced to increase the applicability of this approach. Another limitation of the approach becomes present in very complex environments that require execution and orchestration of parallel or concurrent processes. Future research will investigate how this limitation can be overcome and how the approach can be more easily integrated in existing software architectures based on a service-oriented design.

Acknowledgements

The authors thank the Ministry of Science, Research and Arts of the Federal State of Baden-Württemberg for the financial support of the project within the Innovation Campus Future Mobility (ICM).

References

[1] H. A. ElMaraghy, “Flexible and reconfigurable manufacturing systems paradigms,” International Journal of Flexible Manufacturing Systems, vol. 17, no. 4, pp. 261–276, 2006, doi: 10.1007/s10696-006-9028-7.

[2] N. Bennett and G. J. Lemoine, “What a difference a word makes: Understanding threats to performance in a VUCA world,” Business Horizons, vol. 57, no. 3, pp. 311–317, 2014, doi: 10.1016/j.bushor.2014.01.001.

[3] O. Mack, A. Khare, A. Krämer, and T. Burgartz, Eds., Managing in a VUCA world. Cham, Heidelberg, New York, Dordrecht, London: Springer, 2016.

[4] H.-P. Wiendahl et al., “Changeable Manufacturing - Classification, Design and Operation,” CIRP Annals, vol. 56, no. 2, pp. 783–809, 2007.

[5] L. Monostori, “Cyber-physical Production Systems: Roots, Expectations and R&D Challenges,” Procedia CIRP, vol. 17, pp. 9–13, 2014, doi: 10.1016/j.procir.2014.03.115.

[6] R. Baheti and H. Gill, “Cyber-physical systems,” The impact of control technology, vol. 12, no. 1, pp. 161–166, 2011.

[7] X. Xu, Y. Lu, B. Vogel-Heuser, and L. Wang, “Industry 4.0 and Industry 5.0—Inception, conception and perception,” Journal of Manufacturing Systems, vol. 61, pp. 530–535, 2021, doi: 10.1016/j.jmsy.2021.10.006.

[8] A. Lechler and A. Verl, “Software Defined Manufacturing Extends Cloud-Based Control,” in Proceedings of the ASME 12th International Manufacturing Science and Engineering Conference, Los Angeles, California, USA, 2017.

[9] S. Behrendt et al., “Improving Production System Flexibility and Changeability Through Software-Defined Manufacturing,” in Production at the Leading Edge of Technology – Proceedings of the 12th Congress of the German Academic Association for Production Technology (WGP), University of Stuttgart, October 2022. Ed.: M. Liewald, Liewald, Mathiasand Verl, Alexanderand Bauernhansl, Thomasand Möhring, Hans-Christian, Ed.: Springer International Publishing, 2023, pp. 705–716.

[10] B. Wang, F. Tao, X. Fang, C. Liu, Y. Liu, and T. Freiheit, “Smart Manufacturing and Intelligent Manufacturing: A Comparative Review,” Engineering, vol. 7, no. 6, pp. 738–757, 2021, doi: 10.1016/j.eng.2020.07.017.

[11] M. Löppenberg and A. Schwung, “Self Optimisation and Automatic Code Generation by Evolutionary Algorithms in PLC based Controlling Processes,” Apr. 2023. [Online]. Available: https://arxiv.org/pdf/2304.05638.pdf

[12] B. Ashtari Talkhestani et al., “An architecture of an Intelligent Digital Twin in a Cyber-Physical Production System,” at - Automatisierungstechnik, vol. 67, no. 9, pp. 762–782, 2019, doi: 10.1515/auto-2019-0039.

[13] F. Biesinger, D. Meike, B. Kraß, and M. Weyrich, “A digital twin for production planning based on cyber-physical systems: A Case Study for a Cyber-Physical System-Based Creation of a Digital Twin,” Procedia CIRP, vol. 79, pp. 355–360, 2019, doi: 10.1016/j.procir.2019.02.087.

[14] H. ElMaraghy and H.-P. Wiendahl, “Changeable Manufacturing,” in Springer reference, CIRP encyclopedia of production engineering: With 85 tables, L. Laperrière, G. Reinhart, S. Chatti, and T. Tolio, Eds., Berlin: Springer, 2014, pp. 157–163.

[15] A. Tharumarajah, “Comparison of the bionic, fractal and holonic manufacturing system concepts,” International Journal of Computer Integrated Manufacturing, vol. 9, no. 3, pp. 217–226, 1996, doi: 10.1080/095119296131670.

[16] K. Ueda, J. Vaario, and K. Ohkura, “Modelling of Biological Manufacturing Systems for Dynamic Reconfiguration,” CIRP Annals, vol. 46, no. 1, pp. 343–346, 1997, doi: 10.1016/S0007-8506(07)60839-7.

[17] Y. Koren et al., “Reconfigurable Manufacturing Systems,” CIRP Annals, vol. 48, no. 2, pp. 527–540, 1999, doi: 10.1016/S0007-8506(07)63232-6.

[18] Z. M. Bi, S. Y. T. Lang, W. Shen, and L. Wang, “Reconfigurable manufacturing systems: the state of the art,” International Journal of Production Research, vol. 46, no. 4, pp. 967–992, 2008, doi: 10.1080/00207540600905646.

[19] H. ElMaraghy, L. Monostori, G. Schuh, and W. ElMaraghy, “Evolution and future of manufacturing systems,” CIRP Annals, vol. 70, no. 2, pp. 635–658, 2021, doi: 10.1016/j.cirp.2021.05.008.

[20] R. Cioffi, M. Travaglioni, G. Piscitelli, A. Petrillo, and A. Parmentola, “Smart Manufacturing Systems and Applied Industrial Technologies for a Sustainable Industry: A Systematic Literature Review,” Applied Sciences, vol. 10, no. 8, p. 2897, 2020, doi: 10.3390/app10082897.

[21] S. D. Eppinger, “Model-based Approaches to Managing Concurrent Engineering,” Journal of Engineering Design, vol. 2, no. 4, pp. 283–290, 1991, doi: 10.1080/09544829108901686.

[22] Reference architecture model industrie 4.0 (rami4. 0), 2015.

[23] A. Lechler and A. Verl, “Software Defined Manufacturing Extends Cloud-Based Control,” ASME 2017 12th International Manufacturing Science and Engineering Conference collocated with the JSME/ASME 2017 6th International Conference on Materials and Processing, 2017, doi: 10.1115/MSEC2017-2656.

[24] A. W. Wymore, Model-Based Systems Engineering. Boca Raton: Chapman and Hall/CRC, 2018.

[25] A. M. Madni and M. Sievers, “Model-based systems engineering: Motivation, current status, and research opportunities,” Syst Eng, vol. 21, no. 3, pp. 172–190, 2018, doi: 10.1002/sys.21438.

[26] M. Neubauer, C. Ellwein, and F. Frick, “Kontinuität als neues Paradigma,” Computer Automation, vol. 2022, 2022.

[27] D. Brovkina and O. Riedel, “Assembly Process Model for Automated Assembly Line Design,” in 2021 IEEE 3rd Eurasia Conference on IOT, Communication and Engineering (ECICE), 2021.

[28] Strljic, Matthias Milan and Younes, Islam and Riedel, Oliver, Ed., Study on Available Cloud Manufacturing Platforms for Additive Manufacturing Technologies: IEEE, 2022.

[29] M. M. Strljic, I. Younes, and O. Riedel, “Study on Available Cloud Manufacturing Platforms for Additive Manufacturing Technologies,” in 2022 IEEE 4th Eurasia Conference on IOT, Communication and Engineering (ECICE), 2022.

[30] M. M. Strljic, A. Bakovic, and O. Riedel, “Study on Available Cloud Manufacturing Platforms for CNC Milling Processes,” in Study on Available Cloud Manufacturing Platforms for Additive Manufacturing Technologies, 2022.

[31] M. M. Strljic, D. Brovkina, T. Korb, O. Riedel, and A. Lechler, “Platform architecture concept for the composition of collective cloud manufacturing,” in 2018 25th International Conference on Mechatronics and Machine Vision in Practice (M2VIP), 2018.

[32] T. Lechler, E. Fischer, M. Metzner, A. Mayr, and J. Franke, “Virtual Commissioning – Scientific review and exploratory use cases in advanced production systems,” Procedia CIRP, vol. 81, pp. 1125–1130, 2019, doi: 10.1016/j.procir.2019.03.278.

[33] S. Martinez et al., “A Digital Twin Demonstrator to enable flexible manufacturing with robotics: a process supervision case study,” Production & Manufacturing Research, vol. 9, no. 1, pp. 140–156, 2021, doi: 10.1080/21693277.2021.1964405.

[34] J. Pfrommer, D. Stogl, K. Aleksandrov, S. Escaida Navarro, B. Hein, and J. Beyerer, “Plug & produce by modelling skills and service-oriented orchestration of reconfigurable manufacturing systems,” at - Automatisierungstechnik, vol. 63, no. 10, pp. 790–800, 2015, doi: 10.1515/auto-2014-1157.

[35] J. Backhaus and G. Reinhart, “Digital description of products, processes and resources for task-oriented programming of assembly systems,” (in En;en), J Intell Manuf, vol. 28, no. 8, pp. 1787–1800, 2017, doi: 10.1007/s10845-015-1063-3.

[36] L. van de Ginste, A. de Cock, A. van Alboom, S. Huysentruyt, E.-H. Aghezzaf, and J. Cottyn, “A formal skill model to enable reconfigurable assembly systems,” International Journal of Production Research, pp. 1–16, 2022, doi: 10.1080/00207543.2022.2128922.

[37] A. Kocher, A. Hayward, and A. Fay, “Model-Based Engineering of CPPS Functions and Code Generation for Skills,” in 2022 IEEE 5th International Conference on Industrial Cyber-Physical Systems (ICPS), Coventry, United Kingdom, uuuu-uuuu, pp. 1–8.

[38] M. M. Strljic, O. Riedel, and A. Lechler, “Collective Cloud Manufacturing for Maintaining Diversity in Production through Digital Transformation,” in 2019 IEEE 21st Conference on Business Informatics (CBI), 2019.

[39] M. M. Strljic and O. Riedel, “An evolutionary data model for the implementation of collective cloud manufacturing to maintain individual value-added networks,” in 2019 IEEE 39th Central America and Panama Convention (CONCAPAN XXXIX), 2019.

[40] G. Lanza et al., “Agiles Produktionssystem mittels lernender Roboter bei ungewissen Produktzuständen am Beispiel der Anlasser-Demontage,” at - Automatisierungstechnik, vol. 70, no. 6, pp. 504–516, 2022, doi: 10.1515/auto-2021-0158.

[41] M. Wurster, B. Häfner, D. Gauder, N. Stricker, and G. Lanza, “Fluid Automation — A Definition and an Application in Remanufacturing Production Systems,” Procedia CIRP, vol. 97, pp. 508–513, 2021, doi: 10.1016/j.procir.2020.05.267.

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.

Matthias Milan Strljic (*1991) is a research assistant at the Institute for Control Engineering of Machine Tools and Manufacturing Units, University of Stuttgart in Germany. Strljic received his M.Sc. from the University of Stuttgart. His research interests include cloud manufacturing, production process planning, and production automation.

Jan-Felix Klein (*1992) is a research associate at the Institute for Material Handling and Logistics (IFL) and group lead of the Robotic and Interactive Systems group at the Karlsruhe Institute of Technology (KIT). In his research he focuses on autonomous intralogistics and material handling in highly modular production systems, especially for remanufacturing and automated disassembly systems.

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 optimization 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.

CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
CPSL 2023-2

5th Conference on Production Systems and Logistics

Modelling The Digital Twin For Data-Driven Product Development - A Literature Review

Henry Himmelstoss[1], Thomas Bauernhansl[1,2]

[1] *Fraunhofer Institute for Manufacturing Engineering and Automation IPA, Nobelstraße 12, 70569 Stuttgart, Germany*

[2] *Institute of Industrial Manufacturing and Management, University of Stuttgart, Allmandring 35, 70569 Stuttgart, Germany*

Abstract

Due to advanced connectivity and increasing distribution of product-service, more and more data is available from the products used and produced. Scientific publications often describe that this product data can be applied in product development to make it more efficient and that the digital twin can play a central role in data provision and interoperability. However, less attention is paid to how the digital twin should be designed for this purpose and how it should be adequately modelled for these use cases. Therefore, this paper presents a structured literature review to analyse which methods are already described in science to model digital twins in a target-oriented way for use cases of data-driven product development. Not only are the procedures interesting, but also the type of digital twin for which they are intended and whether they describe the procedure at the level of a rough macrostructure or detailed microstructure.

Keywords

Digital Twin; Asset Administration Shell; Product Development; Digital Manufacturing; Industry 4.0; Literature Review

1. Introduction

Fraunhofer ISE's hydrogen roadmap projects a demand between 800 TWh (low scenario) and 2250 TWh (high scenario) in Europe by 2050. [1]. To meet this anticipated demand, a significantly larger electrolysis capacity is required. That is why the H2Giga-FRHY project is concerned with the high-rate production of electrolysers. The competencies of various Fraunhofer institutes are bundled in this project. Fraunhofer IPA is responsible for the IT reference architecture, the digital representation concept, and evaluation services. These services analyse product defects and performance based on various parameters and help in making decisions about product configurations [2]. The Digital Twin (DT), implemented through the Asset Administration Shell (AAS) concept, is the enabler technology that makes the evaluation services possible by providing the necessary data.

The DT is considered a core technology [3], which enables companies to collect, manage and deliver the data of an asset along its lifecycle. For this reason, DT has also received special attention in scientific considerations and practical applications for several years, and the number of scientific publications has increased, especially since 2014 [4]. However, views and definitions of the digital twin are not uniform, and there are many different definitions in both academia and industrial applications. The concept of the DT was mentioned very early by Grieves, who defined it with three central components: the physical product in real space, the virtual product in virtual space, and the connections of information and data between the virtual and real products [5]. Building on Grieves' concept, Tao et al. suggested adding two components: data and services [4,6]. However, there is not yet a unified approach to modelling DTs [4]. For approaches to

DOI: https://doi.org/10.15488/15287
ISSN: 2701-6277

innovation and development, DT is much less often the object of consideration. DT's focus is often on stand-alone applications that meet the needs of a specific use case [7]. ISO 23247 provides a digital twin framework for manufacturing, outlining general principles, reference models, functional, informational, and networking views. However, it lacks detailed guidance for user-specific use case implementation and model development [8–11]. The AAS, in turn, represents a relatively new concept for DT implementation that is currently still part of standardisation activities. In the context of the AAS, the DT is described as a digital representation sufficient to meet the requirements of a set of use cases. A digital representation is, in turn, described as information that represents the characteristics and behaviours of an entity [12]. According to this definition, the use case for the AAS plays a central role. The AAS should be designed for the respective use case, and the necessary submodels should be implemented. This raises the question of a procedure that describes how to design or set up an AAS for a possible application. This paper therefore systematically analyses scientific papers to determine which methods are already described to model a DT – especially for data-driven product development that the evaluation services in the H2Giga-FRHY project will support. Because the AAS can be considered a particular manifestation of a DT, methods for deriving both the AAS and the DT are being researched. Because the concept of DT has been around for some time, it is hoped that more results will be obtained by studying it, too. Although the focus in the project is on the AAS.

2. Method and data

Our goal of systematically searching and analysing literature was to find appropriate methods for deriving the digital twin for data-driven product development to follow or build upon. For this purpose, an overview of already existing approaches will be given here. The applied procedure is oriented towards the framework for literature reviewing described by Brocke et al. and the steps in conducting research literature reviews described by Fink [13,14]. Thus, from the previous section, the question arises about the approaches described in the literature for deriving a DT for data-driven product creation. Therefore, the first research question is:

RQ1: Which approaches to derive a digital twin for data-driven product development are described in the literature?

Lindemann presents a differentiation of concepts within product development. He describes a continuum ranging from micro to macro logic. Within this spectrum, he identifies four different concept types, depending on the level of detail and resolution of the process. These are ordered from micro to macro logic: ‘Elementary thought processes and action processes’, ‘operational tasks’, ‘phases and grouping of tasks’, and a ‘full project or concept’ [15]. 'Elementary thought processes and action processes' are cycles of analysis, synthesis, and evaluation that occur in seconds in the user’s mind. Processes can be described and analysed on an operational level ('operational tasks') or more abstractly on the level of work stages or phases ('phases and grouping of tasks'). However, suppose the goal is to obtain a complete project overview. In that case, it makes sense to map processes with low resolution ('full project or concept') to reduce complexity and maintain an overview. It should also be noted that using systems thinking, it might be necessary to switch between these levels of process granularity and that process models can also be assigned to several levels because these are not always clearly separable. Figure 1 gives an overview of the described differentiation between the approaches in product creation along the spectrum between micro- and macro-logic.

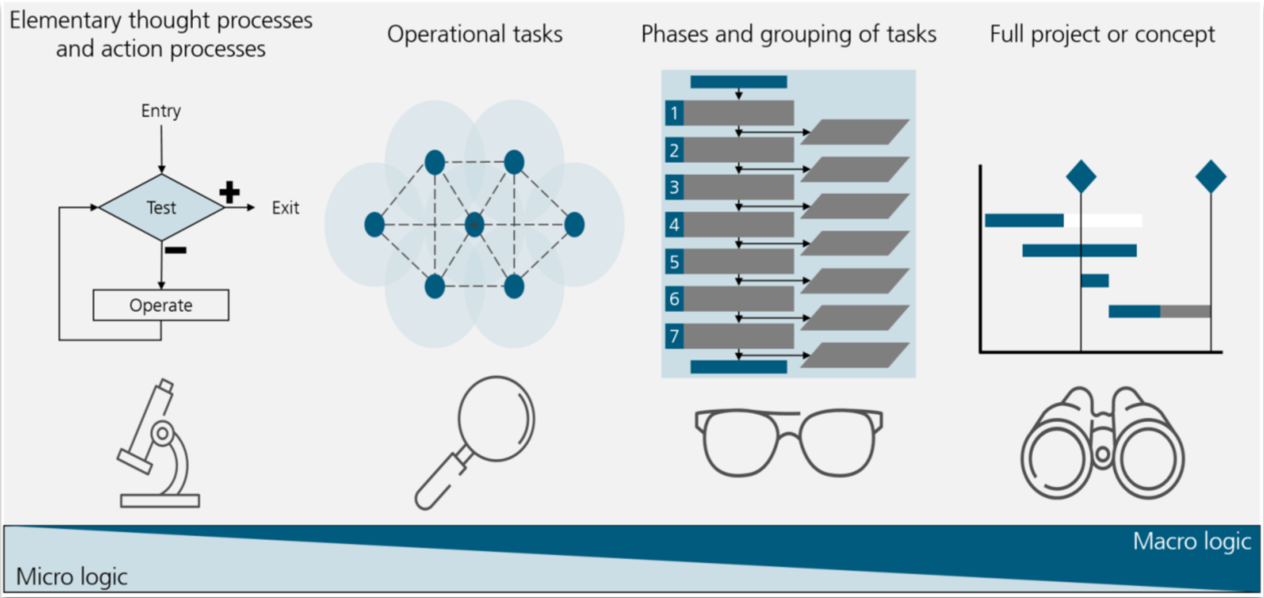


Figure 1: Different degree of resolution of procedures in the product creation in connection with different perspectives according to [16,15]

This leads to the second research question:

RQ2: How do the concepts fit into the differentiation of concepts in product development?

Because AAS will be applied in the H2Giga-FRHY project, the extent to which concepts can be transferred to AAS will be examined. This leads to the third research question:

RQ3: How can approaches from the concepts be transferred to the application of the AAS?

2.1 Search process and selection of literature

In the first step, a search matrix was set up with the aspects relevant to the search. Table 1 shows an overview of the aspects and the associated search terms. The aspects were combined with the AND operator and the search terms with the OR operator to form a search string. Before using the final search string, different ways to combine the aspects were tried. All of them were applied to searches in the same databases. The databases are ACM, IEEE, Scopus, and Web of Science. The search was conducted in August 2023.

Table 1: Relevant aspects and search terms to form the search string.

	Aspect 1	Aspect 2	Aspect 3	Aspect 4	Aspect 5
Operaters	AND	AND	AND	AND	AND
Term 1	framework	"digital twin"	"product creation"	"data driven"	production
Term 2	procedure	"digital shadow"	"product development"	"production data analysis"	manufacturing
Term 3	approach	"asset administration shell"	"product innovation"	"user data analysis"	"industrie 4.0"
Term 4	technique	"virtual twin"	"product design"	"data collection"	"industry 4.0"
Term 5	"process model"		"product planning"	"data mining"	
Term 6			"product improvement"		
Term 7			"generation planning"		

For example, the aspect of product development was removed, and approaches to derive DT in a production context were searched for. This represents the first search string. Here, 994 results were found - no further examination took place. This search string delivered too many results for the available resources, labelled as search string no. 1 in Table 2 Another search string was formed by searching only for the DT in the expression of the AAS and without the production context. After filtering duplicates, this search string yielded 22 results, but they were not considered relevant after screening the title, abstract, or text, labelled as search string no. 3 in Table 2. Using the entire search string, 70 publications were found – labelled as search string no. 2 in Table 2.

Figure 2 shows how the original results were filtered. Filtering in English and by the publication period 2018 to 2023 made no difference. Some publications were found twice, and some only in the form of proceedings, without the information of whether a paper alone meets the requirements of the search string. Most of it was filtered out by screening the abstracts and texts. The selected papers are limited to papers covering the DT in a form that considers it a digital asset or a representation of an asset. Papers were also not included if an analytical or statistical method or a simulation model was referred to as a DT. Thus, there are six remaining papers in total: Barth et al. [17], Che et al. [18], Jeong et al. [19], Josifovska et al. [20], Niu et al. [21] and Riedelsheimer et al. [22].

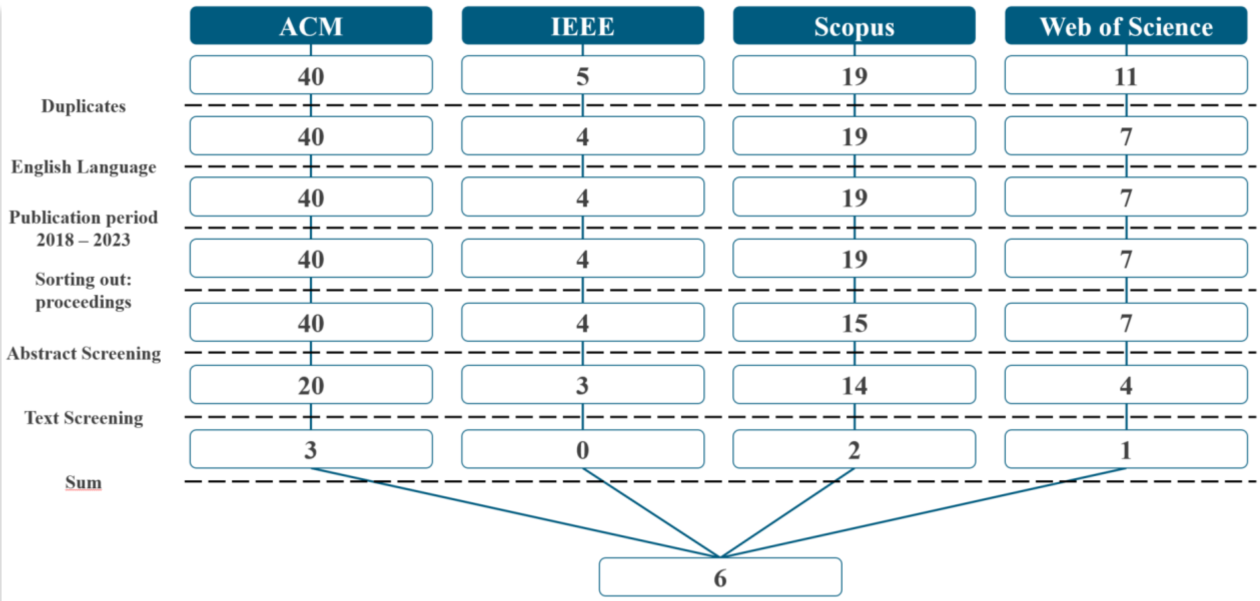


Figure 2: Filtering of the papers and the used databases (August 2023)

Table 2: Overview of the applied search strings.

No.	Search string	Number of results	Remaining results
1	(framework OR procedure OR approach OR technique OR "process model") AND ("digital twin" OR "digital shadow" OR "asset administration shell" OR "virtual twin") AND (production OR manufacturing OR "industrie 4.0" OR "industry 4.0") AND ("data driven" OR "production data analysis" OR "user data analysis" OR "data collection" OR "data mining")	994	/
2	(framework OR procedure OR approach OR technique OR "process model") AND ("digital twin" OR "digital shadow" OR "asset administration shell" OR "virtual twin") AND ("product creation" OR "product development" OR "product innovation" OR "product design" OR "product planning" OR "product improvement" OR "generation planning") AND ("data driven" OR "production data analysis" OR "user data analysis" OR "data collection" OR "data mining") AND (production OR manufacturing OR "industrie 4.0" OR "industry 4.0")	70	6
3	(framework OR procedure OR approach OR technique OR "process model") AND ("asset administration shell") AND (production OR manufacturing OR "industrie 4.0" OR "industry 4.0") AND ("data driven" OR "production data analysis" OR "user data analysis" OR "data collection" OR "data mining")	22	0

3. Analysis and findings

This section addresses the research questions, with RQ1 and RQ2 being answered together in a common course, while RQ3 will be addressed separately.

Barth et al. point out that a lack of a shared conceptual framework for DTs complicates cross-functional discussions. In their work, a systematic literature was conducted, and they proposed the main dimensions of DTs in the form of an ontology and conducted a conceptual framework from it [17]. Josifovska et al. are point out that in the application of cyber-physical systems; there are still many challenges in designing and realizing one. One of the challenges is described as the need for DTs as high-fidelity mirroring images. Nevertheless, no blueprint offers the main building blocks to construct a DT, which hinders best practices. They performed a systematic literature review and proposed a framework that specifies the main building blocks of a DT in terms of structure and interrelations. They identified the main building blocks as Physical Entity Platform, Virtual Entity Platform, Data Management Platform, and Service Platform and described their structural properties [20]. Niu et al. state that it is crucial to effectively capture, share, and manage design-related information in complex design environments due to changing market and customer needs and, therefore, evolving product design and development. They deem a comprehensive product design lifecycle information model (PDLIM) essential. Despite the DT's significant potential for gathering and managing product lifecycle data, they have identified a gap in this area. In their work, they propose, in part, a structure for the PDLIM and have explored the key design information items against product lifecycle stages [21]. Barth et al. [17], Josifovska et al. [20], and Niu et al. [21] do not address process models but rather frameworks that have individual structures, elements, or aspects that can make up a DT. Some of these are so general that they can be applied to a wide range of use cases. According to Niu et al., identifying and reviewing the necessary components that can form a DT is essential. These components may include relationships between elements of the DT, which are highlighted in their study. In some cases, they specifically address hierarchical relationships or links to product development phases. However, the three concepts described in the papers have in common that they do not describe a procedure in terms of processes at a different level of abstraction. Therefore, it is impossible to classify them according to the von Lindemann's classification of product development concepts.

Che et al. [18] explain the use of the Digital Twin-Based Definition (DTBD) and outline a highly abstract process that links product development, manufacturing, and the customer. In doing so, they illuminate that divergent objectives between design and manufacturing can lead to suboptimal design or manufacturing outcomes. In this context, a thorough examination of operational data, fault data and processes a provides an effective method for problem solving and optimisation of the DTBD model. Again, the background is that a lack of methods for defining a digital model has been identified that can be used from design, manufacturing, and up through the product management process. This sequence should, therefore, be understood more as an abstract basic concept because it merely explains the steps of application and the associated development, respectively, optimization steps at the particular stakeholder. The detailing of the procedure describes further modules and functions. The functions of the data analysis model are kept general so that, for example, only PCA, clustering analysis, and data classification are mentioned. The product model is also described with components such as digital twin tech, measuring tools, and the associated dataset. Since the development steps of the DTBD can be described as a sequence of phases, it can be categorized into Lindemann's concept of 'phases and grouping of tasks' as described in section 2 [15]. Jeong et al. [19] present a process built on generic phases for production logistics. It consists of five dimensions the physical environment, virtual environment, data, data exchange connections, and services utilized by production logistics staff. Activities were specifically named and are assigned to the dimensions in the respective phases so that users have a sequence and concrete steps for orientation when designing DTs. Since activities are named and assigned to dimensions but not described in detail, this process is attributed to the grouping of tasks. Riedelsheimer et al. [22] have tested established approaches to product development against their criteria. The approaches tested are V-model for mechatronic systems, V-Modell XT, Waterfall model, Spiralmodell, R(UP) and SCRUM. Whereas the criteria tested against are interdisciplinarity, system complexity and diversity, level of detail, flexibility, relevance, sustainability, variant management and simplicity. The result of their evaluation is that the identified methods pay too little attention to the criteria of sustainability or do not sufficiently fulfil the integration of one or more domains, since there is often a focus on mechatronics or software development and less on the development of services or data engineering. To fill the identified research gap, the paper builds on the V-Model to specifically address the criteria of interdisciplinarity, system complexity and diversity, sustainability and variant consideration for the development of a DT. The resulting and presented approach is called Digital Twin-V-model (DT-V-model), builds on the already-known V-model and also contains several domains and development cycles with different versions of the product, services and DT [22]. While according to Dombrowski, the V-Modell could be classified in both categories 'operational tasks' or 'phases and grouping of tasks', Lindemann assigns it to the category 'phases and grouping of tasks' - which is why the extended DT-V-Model is also classified in this category in this work [15]. The central aspects of the described papers are summarised in Table 3.

Table 3: Summary of central concepts for deriving the DT from the literature analysed.

No.	Paper	Central concept for deriving the DT	Concepts in product development
1	Barth et al.	▪ Literature-derived ontology and framework based on it structure DT into three qualitative dimensions: Data Resources, External Value Creation, and Internal Value Creation. ▪ Conceptual models and ontologies are pivotal in requirements engineering, aiming to clearly represent a system's principles and functionalities. These models should achieve four key goals: enhancing understanding, facilitating communication among stakeholders, providing a design reference, and documenting the system for future collaboration.	Not applicable
2	Che et al.	▪ Digital Twin-Based Definition (DTBD) framework, a tool for product design that supports creation, optimization, and management of physical product models and their Digital Twins, is described and proposed. It includes the following aspects: Design model, process model, product model, virtual model, data analysis model and file model. ▪ The paper illustrates the DTBD model's application and development, detailing an abstract optimization cycle based on process capability and design requirements, facilitating collaboration between design and manufacturing entities.	'phases and grouping of tasks'
3	Jeong et al.	▪ The design process for Digital Twins in production logistics hinges on five dimensions: the physical environment, virtual environment, data, data exchange connections, and services utilized by production logistics staff. ▪ A process for the design of DTs is shown that consists of involves pre-study, conceptual, and detailed design phases. This process encompasses activities that align with the dimensions and stages inherent to the design of Digital Twins in production logistics.	'phases and grouping of tasks'
4	Josifovska et al.	▪ Reference Framework for DTs within Cyber-Physical Systems that specifies the main building blocks of a DT in terms of structure and interrelations. ▪ The identified main building blocks of the DT as a framework are: Physical Entity Platform (PEP), Virtual Entity Platform (VEP), Data Management Platform (DMP) and Service Platform (SP).	Not applicable
5	Niu et al.	▪ The Product Design Lifecycle Information Model (PDLIM) provides a structure referred to as a 'wardrobe,' with designated 'drawers' for organizing and storing key information classified by a product's lifecycle. ▪ The drawers are thereby designated as optional and it explained how the key information items at each design phase associated with both in-house and crowdsourcing design environments.	Not applicable
6	Riedelsheimer et al.	▪ A methodology to develop DTs of physical IoT-based products, the so called DT V-Model, is proposed. It aims to optimize the systems sustainability, specifically environmental aspects. ▪ This approach is an enriched V-model for smart product development, supplemented with additional roles and strategies for the development of DTs.	'phases and grouping of tasks'

4. Transfer to the modelling of the AAS.

This section addresses RQ3: How can approaches from the concepts be transferred to the application of the AAS? This is intended to show the extent to which the findings from the work could also be used for the design and implementation of the AAS.

On the one hand, approaches can be identified that provide the user with reusable elements and elements that are already predefined to a certain degree, which are intended to cover partial aspects of a DT. These are not procedures and can, therefore, not be classified according to the categories established by Lindemann. This is the case for the work of Barth et al., Jorifovska et al., and Niu et al. The ontology shown by Barth et al. and the dimensions based on it that can help to structure a DT can also be of use in structuring the AAS by trying to map the different dimensions and thus systematically holistically map the DT. Jorifovska et al. present the main building blocks mentioned in Table 3 and their associated properties. Application scenarios such as "optimization of production process in an industrial production line" are also mentioned in the framework. These structural properties of the presented DT framework can also be used to design the DT based on the AAS to obtain a holistic representation of an asset. Niu et al. have proposed PDLIM structure that is composed of key information perspectives based on the product life cycle, which in turn are also assigned key design information items. This structure was then, in turn, mapped to a generic perspective model that includes, for example, the perspective of the customer and the perspective of the product. In the conception of the AAS, rough guidelines can be obtained regarding which key design information items from various phases of the product lifecycle are relevant when creating a DT for an asset. It is important to note that these are only rough guidelines, as key information encompasses highly heterogeneous aspects.

Che et al. rather describe how their DTBD is applied with the involvement of different stakeholders and less how to derive a DT for a specific use case with the approach. The focus is also strongly on geometric properties such as tolerance, size, or structure. It is, therefore, not generally applicable to other use cases in the domain of data-driven product development [18]. Therefore, no aspects of the approach shown can be inferred for the design or derivation of the AAS. The framework described by Jeong et al. can be used to orient the structure of the AAS through the dimensions mentioned. In addition, at least some properties of the DT can be derived from the activities that are assigned to the respective phases in the work - e.g., when it comes to the requirements or application purpose of the DT. The framework described by Jeong et al. can be used to orient the structure of the AAS through the dimensions mentioned. In addition, at least some properties of the DT can be derived from the activities that are assigned to the respective phases in the work - e.g., when it comes to the requirements or application purpose of the DT. Several conclusions for the design of AAS can be drawn from the work of Riedelsheimer et al. On the one hand, it shows systematically and sequentially how the steps for creating the DT are integrated – such as the analysis of restrictions and the definition of the capabilities and functions of the DT up to the development of the DT. In this context, the initial tasks can also be applied to the AAS because as described in Section 1, a DT has to fulfil the requirements of a set of use cases in this context, therefore functions and capabilities represent a central aspect. On the other hand, the DT verification in the model's later stages is also covered. The AAS should also be continuously checked to see whether it meets the requirements placed on it and, if necessary, adapted. It also describes how to use (partially) predefined design elements for the DT [22]. However, according to the paper, these represent basic elements of a DT that consider, for example, hardware, software, data, and IT components. However, this differs from the submodels in terms of the AAS, which are all technically separated from each other, and each refers to well-defined subject matters. It should also be noted that the Methodology specifically addresses a use case where a DT is being developed for a product that has already been developed and is in use - so there is no parallel development of the product and the DT. Chet et al., Jeong et al., and Riedelsheimer et al. outline methods for constructing or implementing a DT. Accordingly, they can be categorized under Lindemann's classification, specifically within the 'phases and grouping of tasks' category. When developing new procedures to derive an AAS for specific use cases, it can make sense to map the activities contained therein to or around existing procedure models.

5. Conclusion and outlook

For this paper, a systematic literature review was conducted, searching for scientific publications on the derivation of DTs for data-driven product development in the context of Industry 4.0. The central concepts of the publications were summarised, and the research questions underlying the review were addressed.

First, it can be stated that only a small proportion of the papers found provide the user with approaches to guide him in deriving a DT for data-driven product development. It would be possible to expand or further optimise the literature search. However, examining the actual search string applied suggests that there are only few concepts to guide users for this. Using Lindemann's categories of development processes according to their level of resolution, it can be seen that not all levels of detail of development processes are addressed, which could be another indicator that the topic is not yet very well researched. To be more precise, all the procedures considered belong to the category 'phases and grouping of tasks'. In particular, there is a need for procedures that denote more concrete operational tasks and would fall into the category of the same name because there is also a presumption of a practical level of resolution that could provide guidance to the user.

Considering that the concept of AAS must be applied in the H2Giga-FRHY project, it is particularly noteworthy that no approach in the literature reviewed addresses an approach to derive an AAS. Thus, another research gap can be identified here. In this project, we attempt to develop a general approach for deriving a use-case-specific AAS while working on different AAS. This approach will be tested by developing an AAS to provide the assessment services described at the beginning and the actual transferability of the aspects described in section 4 must be verified.

Acknowledgements

This research is part of the H2Giga-FRHY project funded by the German Federal Ministry of Education and Research (BMBF) since 2021 under grant number 03HY112C.

References

[1] 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. https://www.ise.fraunhofer.de/de/veroeffentlichungen/studien/wasserstoff-roadmap-deutschland.html. Accessed 14 September 2023.

[2] Brandstetter, A., Himmelstoss, H., Risling, M., Schel, D., Oberle, M. Towards A Design Of A Software-Defined Manufacturing System Based On A Systematic Literature Review For Enabling A Decentralised High-Rate Electrolyser Production, in: , Proceedings CPSL 2023 - 1, pp. 479–488.

[3] Bauernhansl, T., 2020. Die Entwicklungsstufen der Digitalen Transformation, in: Hompel, M. ten, Vogel-Heuser, B., Bauernhansl, T. (Eds.), Handbuch Industrie 4.0. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 1–10.

[4] Tao, F., Zhang, H., Liu, A., Nee, A.Y.C., 2019. Digital Twin in Industry: State-of-the-Art. IEEE Trans. Ind. Inf. 15 (4), 2405–2415.

[5] Grieves, M., 2016. Origins of the Digital Twin Concept.

[6] Tao, F., Zhang, M., 2017. Digital Twin Shop-Floor: A New Shop-Floor Paradigm Towards Smart Manufacturing. IEEE Access 5, 20418–20427.

[7] Bertoni, M., 2022. Boosting Value Co-creation in Design Through the Product-Service System Digital Twin: Questions to Be Answered, 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. 592–602.

[8] International Organization for Standardization, 2021. Automation systems and integration — Digital twin framework for manufacturing: Part 3: Digital representation of manufacturing elements. https://www.iso.org/standard/78744.html. Accessed 14 September 2023.

[9] International Organization for Standardization, 2021. Automation systems and integration. Digital twin framework for manufacturing. Information exchange. https://www.iso.org/standard/78745.html. Accessed 26 November 2022.

[10] International Organization for Standardization, 2021. Automation systems and integration. Digital twin framework for manufacturing. Overview and general principles. https://www.iso.org/standard/75066.html. Accessed 26 November 2022.

[11] International Organization for Standardization, 2021. Automation systems and integration. Digital twin framework for manufacturing. Reference architecture. https://www.iso.org/standard/78743.html. Accessed 26 November 2022.

[12] 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.

[13] Fink, A., 2014. Conducting research literature reviews: From the internet to paper, Fourth edition ed. SAGE, Los Angeles, London, New Delhi, Singapore, Washington DC, 257 pp.

[14] vom Brocke, J., Simons, A., Niehaves, B., Riemer, K., Plattfaut, R., Cleven, A. Reconstructing the Giant: On the Importance of Rigour in Documenting the Literature Search Process, in: , European Conference on Information Systems (ECIS) 2009 Proceedings.

[15] Lindemann, U., 2009. Methodische Entwicklung technischer Produkte. Springer Berlin Heidelberg, Berlin, Heidelberg.

[16] Dombrowski, U., Karl, A., 2022. Ganzheitlicher Produktentstehungsprozess für die Zulieferindustrie. Springer Berlin Heidelberg.

[17] Barth, L., Ehrat, M., Fuchs, R., Haarmann, J., 2020. Systematization of Digital Twins, in: Proceedings of the 2020 The 3rd International Conference on Information Science and System. ICISS 2020: 2020 The 3rd International Conference on Information Science and System, Cambridge United Kingdom. 19 03 2020 22 03 2020. ACM, New York, NY, USA, pp. 13–23.

[18] Che, Z., Peng, C., Zhang, Z., 2023. Digital Twin Based Definition (DTBD) Modeling Technology for Product Life Cycle Management and Optimization, in: Kim, K.-Y., Monplaisir, L., Rickli, J. (Eds.), Flexible Automation and Intelligent Manufacturing: The Human-Data-Technology Nexus. Springer International Publishing, Cham, pp. 573–583.

[19] Jeong, Y., Flores-Garcia, E., Wiktorsson, M., 2020. A Design of Digital Twins for Supporting Decision-Making in Production Logistics, in: 2020 Winter Simulation Conference (WSC). 2020 Winter Simulation Conference (WSC), Orlando, FL, USA. 14.12.2020 - 18.12.2020. IEEE, pp. 2683–2694.

[20] Josifovska, K., Yigitbas, E., Engels, G., 2019. Reference Framework for Digital Twins within Cyber-Physical Systems, in: 2019 IEEE/ACM 5th International Workshop on Software Engineering for Smart Cyber-Physical Systems (SEsCPS). 2019 IEEE/ACM 5th International Workshop on Software Engineering for Smart Cyber-Physical Systems (SEsCPS), Montreal, QC, Canada. 28.05.2019 - 28.05.2019. IEEE, pp. 25–31.

[21] Niu, X., Wang, M., Qin, S., 2022. Product design lifecycle information model (PDLIM). Int J Adv Manuf Technol 118 (7-8), 2311–2337.

[22] Riedelsheimer, T., Gogineni, S., Stark, R., 2021. Methodology to develop Digital Twins for energy efficient customizable IoT-Products. Procedia CIRP 98, 258–263.

Biography

Henry Himmelstoß is a research associate and project leader at the Fraunhofer Institute for Manufacturing Engineering and Automation IPA in Stuttgart, Germany. Since 2019, he has been working in the Competence Centre for Digital Tools in the Manufacturing department.

Prof. Dr.-Ing. Thomas Bauernhansl has been head of the Fraunhofer Institute for Manufacturing Engineering and Automation IPA in Stuttgart and the Institute for Industrial Manufacturing and Factory Management IFF at the University of Stuttgart since September 2011. Bauernhansl studied mechanical engineering at the RWTH Aachen and received his doctorate in 2002. He then worked for Freudenberg, most recently as Director of the Technology Centre at Freudenberg Sealing Technologies.

His scientific focus areas include personalised production, the biological transformation and Industrie 4.0.

5th Conference on Production Systems and Logistics

Evaluating Retail Distribution Strategies During Covid-19 Pandemic in South Africa Using Best Worst Method Multicriteria Decision Technique.

Osayuwamen Omoruyi [1], Edward Dakora [2], Albert Antwi [3],
Matthew Quayson[4], Alfred Mwanza [5] , Ramos E. Mabugu[6], Leornard Ndlovu[7]

[1]Department of Management Sciences, Sol Plaatje university , Kimberley, South Africa
[2]Department of Management Sciences, Sol Plaatje university , Kimberley, South Africa
[3]Department of Mathematical Sciences, Sol Plaatje university , Kimberley, South Africa
[4]Department of Logistics and Supply Chain Management, Ho Technical University, Ghana
[5]Department of Computer Science and Information Technology, Sol Plaatje university , Kimberley, South Africa
[6] Department of Accounting and Economics, Sol Plaatje university , Kimberley, South Africa
[7]Department of Accounting and Economics, Sol Plaatje university , Kimberley, South Africa

Abstract

This paper evaluates the distribution strategies adopted by South African retailers during the Covid-19 pandemic and how such strategies have been adjusted for a more resilient post-Covid-19 world. Using the Best Worst method multicriteria decision technique and exploiting data collected from decision makers from the retail industry to rank the distribution strategies according to their level of importance, we show that omnichannel distribution strategy ranked highest, followed by direct shipment distribution capability in contributing to the success of retail distribution during the Covid-19 pandemic. On the other hand, inventory pooling, transhipment, centralised or decentralised strategy, and cross-docking ranked lower while retail distribution strategy was lowest ranked. Finally, particular emphasis must be placed on the critical factors identified in the evaluation in terms of their challenging dimension and impact as they pave way for a more capable retail resilience distribution capability.

Keywords

Distribution strategies; retail organisation; Covid-19; BWM; South Africa.

1. Introduction

The Covid-19 pandemic brought with it different degrees of challenges for South African retailers in respect of their distribution strategies. One of the key challenges presented by the Covid-19 pandemic and subsequent lockdowns was the disruption of the global supply chain network which inherently affected retailers. South Africa’s lockdown was among the strictest in the world, which impacted on the retail sector. Organisations in the retail sector had to adjust and innovate in ways that had not been seen in recent years to cope with the impact of the pandemic. Researcher [69] described retail operations as the ‘ultimate’ component in a supply chain, which was also among the most affected during the pandemic. This is because retailing is the process of promoting products of different manufacturers in a form that is most convenient and accessible to ultimate customers [6]. Retail distribution therefore bridges the gap between a manufacturer's specialized products and its varied consumers, thus enhancing both the value of the product and the service [50]. As the third largest sector in the South African economy, retail operations contribute approximately 15% and 20% to the gross domestic product and employment, respectively [12]. South African retailers were forced to adopt innovative distribution strategies to meet the demands of their

DOI: https://doi.org/10.15488/15291
ISSN: 2701-6277
publish-Ing.

customers ([20], [47]). In this paper, we evaluate the distribution strategies adopted by South Africa retailers during Covid-19 pandemic using Best Worst method (BWM) multicriteria decision technique.

The gradual development of physical distribution and material management from business logistics to an integrated supply chain network is due to realization through a total cost trade-off analysis of the importance of effective physical distribution management and the value of accurate demand forecasting at the retail level [1]. Effective customer service is the main goal of any retail distribution strategy, which significantly influences demand forecasting and management for upstream supply chain efficiency. According to [1], "Supply Chain Management is a set of synchronized decisions and activities used to integrate suppliers, manufacturers, warehouses, all involved transporters, retailers, and final customers more efficiently, all of which help ensure that the right product or service will be available and distributed in the right quantities, at the right prices, in the right locations, in the right conditions, and at the right time, to minimize system-wide costs while trying to satisfy customer requirements for sustained competitive advantage". For this paper, the retail distribution strategy is the planning, implementation and control of the efficient and effective forward/reverse flow and storage of goods, services, finance, and related information from a distribution channel to meet customer requirements for sustained competitive advantage. This definition delineates the study focus on the distribution chain of retailers and does not include members of the upstream supply chain such as procurement, manufacturers/producers, and their suppliers. The rest of the paper is structured as follows: a conceptual framework identifying and explaining the criteria for the evaluation, the methodology, results and discussion, conclusion, and managerial implications.

2. Conceptual Framework

This section identifies the main retail distribution strategies which will be used as the main criteria in the multi criteria decision making analysis.

Trans-shipment

Part of inventory management for both centralised and decentralised system involves its movement between locations and the problem of cost containment. Transshipment may refer to unloading inventory from one vessel and loading to another at a transshipment centre to a destination to ensure timely delivery and reduced cost where there is no direct route. However, inland, it also refers to transfer from one warehouse to another through some logistics depots (urban consolidation centres) [26] or city tolls and delivery time windows [27] in the context of city logistics. Examples include lateral transhipment which refers to the sharing or pooling of inventory within the same echelon [58]. Lateral transshipment achieves cost reduction by ensuring low levels of inventory are maintained and shared horizontally among the members of the same echelon, especially when dealing with perishable or short life inventories such as blood or large items with stochastic demand like machinery parts [58]. In this case, care needs to be taken to ensure availability at short notice while avoiding overstocking. Similarly, during the Covid-19 pandemic, retailers faced intermittent supplies due to lockdown restrictions and had to balance their demand especially with the introduction of online shopping still an unfamiliar channel as well as shifting consumer behaviour [30]. In addition to the shift from traditional to the new digital channels, restrictions during the Covid-19 lockdowns created new demand patterns caused in some cases by panic buying [29] sometimes resulting in stochastic demand which has long been difficult to predict [43]. The unpredictable demand patterns created supply and demand mismatch, and in such situations, inventory transshipment has been proposed as a viable solution to deal with consumer demand- ([14],[25]). Accordingly, during a supply chain disruption, inventory transshipment has emerged as an important enabler to minimise supply and demand mismatch.

Omnichannel

The decision about channel selection have become important in a dynamic market characterised by fast changing consumer behaviours and tastes, distribution channels and product offerings [4]. Among other factors affecting consumer behaviour, continuously advancing digital technologies offer consumers varied choices and these have been accelerated by the effects of disruptions such as the Covid-19 pandemic ([44], [67]). The Covid-19 pandemic has transformed the retail landscape and forced organisations to adopt strategies designed to ensure they adapt to the changing consumer behaviour and to guarantee their survival [17]. Among strategies that have proven useful during a disruption is the omnichannel strategy which offers customers a seamless shopping experience between channels, thus customers can switch between channels in a single shopping journey ([17], [67], [69]). The omnichannel is considered an agile way of responding to supply chain disruptions through which customers can move between fully integrated physical and digital platforms within a single shopping experience [69]. As the foot traffic decreased due to Covid-19 induced lockdowns, some stores temporarily closed or permanently shifted to online shopping, while others blended the physical with online shopping ([4], [17], [45]). Thus, with the advent of Covid-19, twinned with advanced digital technologies, the omnichannel has become critical to cater for various consumer behaviours such as pure offline shopping, showrooming, webrooming, and pure online shopping ([55]. Accordingly, it caters for both in-store brick and mortar and online customer service and order fulfilment [5].

Direct Shipment

One of the core objectives of any producer or supply chain management is to minimize the cost of distribution, thus maximizing profit. However, 30% of the supply chain costs emanates from the distribution process [2]. One of the commonly used distribution channels that is more economical and effective in reducing supply chain distribution without accounting for fixed cost is the direct shipment [33]. This advantage of the direct distribution channel makes it one of the appropriate strategies to adopt in difficult times such as the Covid-19 pandemic, where scaling down on cost is necessary. In direct shipment, customers receive all products from the producers or suppliers directly and the suppliers take control of all distribution channels between the producers and the consumers [33]. In as much as the strategy is cost effective and has other several advantages such as higher revenue from sales and direct feedback from customers, it requires a high set up cost which makes it not feasible for smaller companies to adopt. In addition, when a company use intermediaries such as retail or wholesale outlet, where products are shipped directly to consumers, the length of the supply chain between the producer and the supplier increases which may unnecessarily lengthens the delivery time.

Decentralized Distribution

Managing inventory distribution to the downstream customer remains a critical factor in managing costs and is affected by decisions on average inventory holding levels, minimum lead times, batch sizes, supply and delivery uncertainty and product variety [22]. One of the important strategic decisions is whether to decentralise or centralise the inventory distribution channel as part of the distribution design which is crucial for the performance of a manufacturer [35]. A decentralised distribution channel is where an individual retail store makes its own decisions and inventory warehousing is localised ([22], [37]). In a decentralised distribution channel strategy, where various distribution centres are maintained closer to the end customer, there is a better understanding of the unique regional customer needs and a tailored approach to product offerings is possible. In addition, delivery turnaround times can be shortened to improve customer service at the local level ([22], [40]). On the downside, a decentralised distribution channel strategy has been found to increase costs due to various duplicated costs such as warehousing costs, labour costs, sub-optimum transportation costs and inability to negotiate preferential prices with suppliers on small orders [22] the problems which [22] posits would require local outlets to rely on transshipments to balance their inventory.

Centralised Distribution

The centralized distribution strategy is more appropriate for companies with a wide variety of products which have high volume of sales, thus it is mostly common among large retail chains [23]. The strategy involves a consolidation of all distribution activities from a single location and requires a single decision maker, which is contrary to decentralised distribution. The single decision maker enables the company to solve the problem of double marginalization, which is common among other distribution strategies, thus results the equilibrium outcomes of a supply chain are globally optimized [21]. Other benefits of the centralized strategy include cost-effectiveness [16], better control over the supply chain channels, and an improved Planning. However, in the event of natural disasters such as the Covid-19 pandemic or transportation strikes, there is a higher risk that the supply chain with be disrupted, and this comes with its associated negative impacts on the operations of the business. It will therefore not come as a surprise if this strategy was among the least practice distribution strategies during the height of the Covid-19 pandemic. The centralized distribution strategy has been known to have longer lead-times to stores which subsequently affects production [16]; however, this problem can be solved by the use of crossdocking warehouse strategies by retailer's logistics distribution centres [23].

Cross-docking

Researcher [38] indicates that the distribution process accounts for 30% of the product sale cost thereby increasing overall supply chain processes overheads. Eliminating or reducing storage and other order-picking activities to enhance the flow of the shipping cycle, is therefore desirable. One of the most convenient distribution channels that is tailored for such operation is cross-docking. Cross docking as a logistic procedure is implemented to achieve a competitive advantage reducing time and storage requirements by consolidating and transferring goods directly from an inbound supplier to an outbound customer. The Material Handling Industry of America defines cross-docking as "the process of moving merchandise from the receiving dock to shipping dock for shipping without placing it first into storage locations" [64]. Table 1 below briefly highlights a comparative chart for retail distribution strategies definitions and justification.

Inventory Pooling

Sometimes multiple markets with uncertainty in their demands need to be served from a single stock of inventory [58]. This form of distribution strategy is known as inventory pooling. Inventory pooling could either take the form of location or product pooling. The use of inventory pooling capabilities was rare in the early 2000s, however at the turn of the century cross channel fulfilment programs by inventory pooling were a top strategic priority for retailers. Two aspects that have driven this shift to inventory pooling are maximizing profits and customer expectations. Researcher [57] reports that 62% of retailers invest in such inventory pooling capabilities mainly because of customer expectation. Researcher [56] reports on how firms can achieve maximum profits with the implementation of an inventory pooling mechanism. Inventory-pooling, inventory consolidation, portfolio effect, and consolidation effect are virtual inventory management. Researcher [34] describes Inventory pooling as “a strategic tool in which consolidating inventory at a central location, instead of stocking products at multiple locations, results in reduced variability among orders and, thereby, a reduced inventory cost”. The Covid-19 contingency scenarios show that demand patterns have undergone major changes, some products suffer large increases in the quantities demanded (demand shock), while others suffer an abrupt drop in these quantities requested. This created uncertainty in demands which makes inventory pooling a useful strategy during the pandemic. The strategy is effective in mitigating demand uncertainty [58]. In comparison to other systems, inventory pooling often provides lower costs than when using the independent system of supply [52]. Particularly, when the component of the market demands is negatively correlated, a pooled inventory strategy reduces operational costs and subsequently increases profit [58].

Table 1: Distribution strategies definition and justification

Retail distribution strategies	Definition and justification	References
Direct shipment (DS)	Direct shipment strategies exist to bypass warehouses and distribution centres. Employing direct shipment, the manufacturer or supplier delivers goods directly to retail stores.	[33]; [62].
Centralised strategy (CS)/Decentralized strategy/(DS)	In a centralized system, decisions are made at a central location for the entire supply network. Typically, the objective is to minimize the total cost of the system subject to satisfying some service-level requirements. Centralised control leads to global optimization. In a decentralized system, each facility identifies its most effective strategy without considering the impact on the other facilities in the supply chain. Thus, a decentralized system leads to local optimisation.	[13], [22], [35], [37], [40], [41], [71], [72].
Cross docking (CD)	In this system, warehouses function as inventory coordination points rather than as inventory storage points	[10], [53], [63].
Inventory management pooling (IP)	Pull: By pooling inventory at the central warehouse and pulling from it after customers order a particular vehicle. A push supply chain, in which dealers must order before demand is realized.	[11], [18], [60].
Trans-shipment (TS)	The shipment of items between different facilities at the same level in the supply chain to meet some immediate needs. Trans-shipment capability allows the retailer to meet customer demand from the inventory of other retailers.	[26], [27], [45].
Omnichannel (OC)	Integrated approach across the whole retail operation that delivers a seamless response to the consumer experience through all available shopping channels, be it on mobile internet devices, computers, in stores, on television and in catalogues. For example, drop shipment, click, and collect, store shipment, and click and reserve.	[3], [28], [39], [61], [65].

3. **Methodology**

3.1 Multi-Criteria Decision-Making method

Evaluating retail distribution strategies during Covid-19 in South Africa requires various multi-Criteria Decision Making (MCDM) methods to facilitate this complex and critical decision-making process. As far as we know, few studies applied MCDM method to evaluate retail distribution strategies during Covid-19 in South Africa. This is critical because a robust decision support tool will enable retailers and government prioritize retail distribution strategies and consequently develop resilient strategies that is helpful in crisis and emergency situations. As we can see, there are many MCDM methods to evaluate retail distribution strategies, such as DEMATEL, AHP (Analytic Hierarchy Process), ANP [48]. However, they all have a common disadvantage, which requires a pairwise comparison among all factors. In other words, n factors need to be compared $n * n$ times. If there are many factors, it will bring difficulties to the evaluation.

These complex comparisons and evaluations will affect the accuracy of the final decision. To obtain a consistent and credible evaluation, [50] developed BWM with less inputs for decision-makers. The ability of the BWM to solve inconsistent and complex evaluations makes it suitable for our study. Many researchers (e.g. [7], [24]) have applied BWM in many different contexts. These application studies suggest that BWM can be a valuable tool.

The BWM process is structured by [50] as follows:

1 Decision-makers determine a set of criteria $c=\{c_1,c_2,...c_n\}$.

2 Decision-makers identify the best criterion and the worst criterion.

3 Decision-makers compare the best criterion to others on a 1-9-point scale. A score of 1 represents an equal preference between the best criterion and another criterion. Also, a score of 9 shows an extreme preference for the best criterion over another criterion. The outcome gives the Best-to-Others (BO) vector as: $BO=\{aB_1,aB_2,...,aB_j\}$ where aB_j depicts the preference of the best criterion B over criterion j.

4 Decision-makers compare all other criteria to the worst criterion on a 1-9 -point scale. This result portrays the Others-to-Worst (OW) vector as: $OW=\{a_1W_1,a_1W_2,...,a_jW\}^T$ where a_jW is the preference of the criterion j over the worst criterion W.

5 BO and OW vectors are substituted into a linear programming problem of the form:

a. $min\ \xi L\ subject\ to$

$$\begin{aligned} wB - aBj \times wj &\leq \xi L \\ wj - ajW \times wW &\leq \xi L \sum wj = 1 \\ wj &\geq 0, for\ all\ j \end{aligned} \quad (1)$$

The linear programming problem is solved to get the optimal weights (w_1^*, $w^*{}_2$, ⋯ , w_n^*), and ξL^*. The ξL^* depicts consistency. There is a higher consistency when the value of ξL^* is closer to zero. This means the comparison is more reliable.

3.2 Background Information

To carry out the field analysis, we recruited some decision-makers (retailers) from the South African Retail industry. We had 12 decision-makers for the case study from different stakeholders and multiple levels to participate in the study to understand the retail strategies used during the Covid-19 (see Table 2). Such a wide variety of respondents can give us a general view of the evaluation of the decision criteria.

.Table 2: Demographic information of decision-makers and firms.

Attribute	Number of decision makers	Sample percentage
Age		
20-29	2	17
30-39	9	75
40-49	1	8
Gender		
Male	7	58
Female	3	25
Other	2	17
Education		
High School	4	33
Diploma	5	42
Degree	3	25
Position		
Manager	8	67
Non-Manager	4	33
Turnover		
Less than R500 000	0	0
R500 000-R2million	12	100
Size		
Medium	3	25
Large	9	75
Age of firm before Covid-19		
Less than 5 years	0	0
More than 5 years	12	100
Sector		
Food, beverages and tobacco	8	67
Pharmaceutical, medical, cosmetics and Toiletries	1	8
Textile and clothing	2	17
Other	1	8

3.3 Evaluation and analysis process

Step 1. Identifying retail distribution criteria

We identified seven first-level criteria through a literature review. Three decision-makers in the South African retail industry interviewed, each with more than five years' experience have validated the first level criteria. They were comfortable and understood these factors. They specified which first level enablers retail are relevant to their organizations. Decisions were allowed to suggest related strategies not included in the literature review. Finally, we summarize seven first level retail distribution strategies for the case study.

Step 2. Identifying the most important enabler and the least important enabler

We conducted a questionnaire survey to collect information from 12decision-makers to identify the most important and least important retail distribution strategy during Covid-19. According to ([47]; [59]), the good number of decision-making experts is between 5 and 15. Our 12 experts met those requirements.

Step 3. Determining the Best-to-Others

We asked each decision-maker to use a 1–9 point scale to determine the scores for the preference of the best (most important) criteria over all other enablers.

Step 4. Determining the Others-to-Worst vectors

Then, each decision-maker determined the scores for the preference of other criteria over the worst (least important) enabler using a 1–9 point scale.

Step 5. Calculating the final optimal weights of enablers

We solved the BWM optimization problem for each decision-maker to determine the optimal weights of the first level enablers. Then, we average the evaluation results of 12 decision-makers to the final optimal weights of first level criteria. All consistency ratios are close to zero, making the comparisons highly consistent and reliable.

4. Results and Discussion

4.1 Results

After applying the criteria contemplated in the evaluation and the analysis process section, the results obtained are summarised in Table 3 and Figure 1. Table 3 shows the final optimal weights for the first level criteria while Figure 1 is a graphical representation of the results.

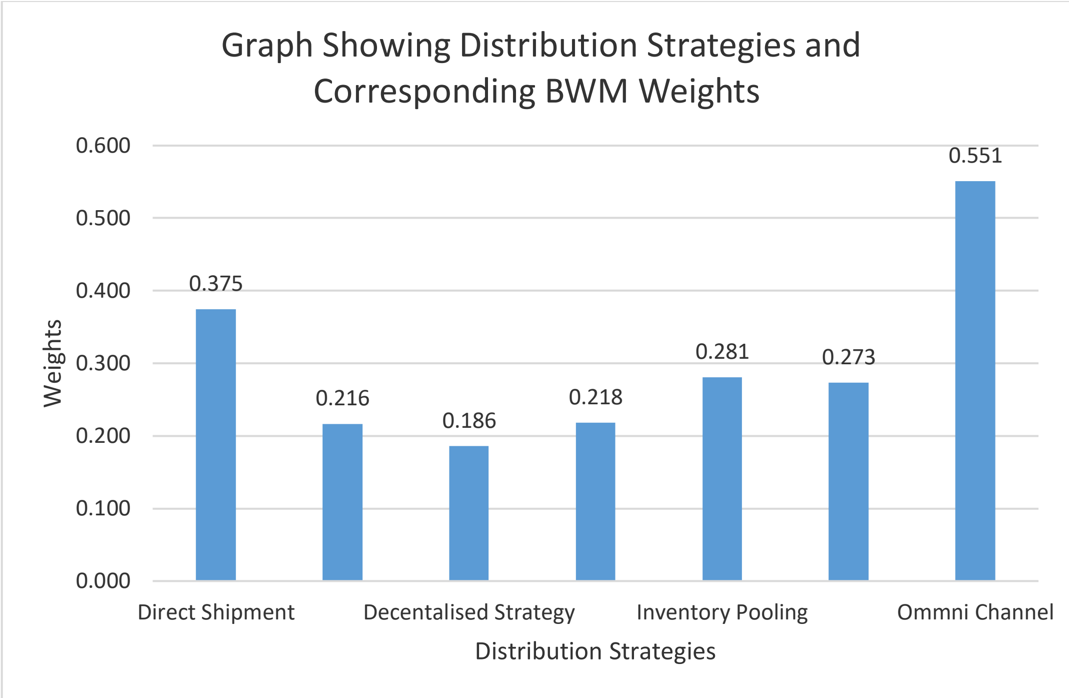


Figure 1 BWM strategies weights and rankings.

Table 3: Evaluation weights and ranking of strategies.

Distribution Strategy	Weight	Rank
Direct Shipment	0.375	2
Centralised Strategy	0.216	5
Decentralised Strategy	0.186	7
Cross Docking	0.218	6
Inventory Pooling	0.281	3
Transhipment	0.273	4
Omni Channel	0.551	1

4.2 Ranking of individual retail strategies

The ranking of the distribution strategies according to their level of importance is detailed in Table 1. From the table, omnichannel was ranked as the highest with a weight of 0.551 implying that it explains 55% of the contribution to the success of retail distribution during the Covid-19 pandemic. Thus, the use of multiple channels (online/mortal stores and online/offline touch platforms) to enhance value delivery of product and service to customers [9] ranks the highest. The omnichannel was introduced into the market environment around 2010 to bridge the gap between mortal stores and digital consumers. In that the objective of omnichannel was to enable seamless shopping accessibility and seamless distribution of orders from any channel the consumers choose to order [15]. This research indicates the importance of omnichannel distribution as the most prominent, fast, and developing demand and order inventory management across the supply chain and physical distribution amongst retailers in South Africa. This also indicates the wide acceptance of electronic commerce.

Direct shipment distribution capability was classified as the second highest with a weight of 0.375 distribution strategy, that is, it explained 38% of the contribution to retail distribution capability. Direct shipment is the bypass of the usual multiple-stop distribution channel within the supply directly from the manufacturer. According to previous research [36], direct shipping reduces cost and delivery time, considering the Covid-19 social distance scenario and the need for flexible delivery of products and services ([51], [8]). However, one of the enabling factors for direct shipment is the growth of technology and internet connectivity. Interestingly, this enabling factor enhances further the earlier result on the role of omnichannel as a more important strategy as omnichannel is enabled by information technology and the Internet of Things. The need for omnichannel distribution results in coordinated and collaborative supply relationships among retailers in South Africa. Omnichannel not only improves customer satisfaction capability, but also improves distribution visibility toward a more sustained and flexible distribution strategy going forward, especially in the event sudden uncertain and disruption. Apart from flexible and visible distribution operations, the effective and efficiency of omnichannel distribution may require higher level trust, commitment, delivery consistency, quick technological adoption/adaption willingness, information systems improvement, and distribution operations expansion to every region in South Africa to achieve effective omnichannel retail distribution plan.

Other distribution strategies such as inventory pooling, transhipment, centralised or decentralised strategy, and cross-docking were ranked lower than omnichannel and direct shipment. The least ranked retail distribution strategy during Covid-19 according to the findings is the decentralised strategy. These results are consistent with [32] who stated that the transitioning to omnichannel distribution requires a high level of centralisation and integration among retailers. However, on the contrary, these authors went further to state that some element of decentralised distribution strategy is still relevant in omnichannel distribution because of the bricks and mortar store acting as fulfilment centre for pick-up-point, return point.

4.3 Managerial implications and conclusion

This paper evaluates retail distribution strategies using multi-criteria decision-making method of Best to Worst. The results clearly indicate the importance of omnichannel and direct shipment retail strategies during Covid-19. It is important for effective decision making and going forward that retail manager continuously adapt to uncertainty within the market environment. To achieve this successfully, the retail manager should be aware of these distribution strategies and their level of importance to enhance the operations. This is particularly so with the emergence of fourth and fifth industrial revolution in addition with Covid-19 pandemic, which necessitates the need for retail managers to be well prepared in their pursuit for customer satisfaction to adapt and carefully implement appropriate distribution strategies such as omnichannel and direct shipment distribution due to their level of importance among other distribution. Beyond the Covid-19, there is a need to build more resilient capability around omnichannel distribution as far as technology advancement and global digitalisation is concerned. The ranking of distribution strategies according to their level of importance in this research can help the retail manager make an appropriate decision around any of the distribution strategies or combination of more than one distribution strategy listed for efficient and effective seamless distribution performance that satisfy the different delivery needs of the customer or clients. Although this research is limited to ranking importance of retail distribution strategies, it will help the retail manager simplify distribution decision-making efforts and help channel distribution investment priorities in the right direction and with the right suppliers. This will further enhance operational cost savings in strategic operational areas such as inventory carrying costs, transportation costs, warehousing costs, and order processing costs.

Acknowledgements

Our sincere gratitude goes to Sol Plaatje university who granted us funding to carry out this study.

References

[1] Anca, V., 2019. Logistics and Supply Chain Management: an overview. Studies in Business and Economics, 14 (2), 201-215.

[2] Apte, U. M., Viswanathan, S., 2016. Effective cross docking for improving distribution efficiencies. International Journal of Logistics Research and Applications: A Leading Journal of Supply Chain Management, 3(3), 291–302.

[3] Aryapadi, M., Dekhne, A., Fleischer, W., Graf, C. & Lange, T. 2020. Supply chain of the future: Key principles in building an omnichannel distribution network. In. Future of retail operations: Winning in a digital era. McKinsey & Company. 22-30.

[4] Asmare, A. & Zewdie, S. 2022. Omnichannel retailing strategy: a systematic review. International Review of Retail, Distribution and Consumer Research. Routledge, 32(1): 59–79. Available at: https://doi.org/10.1080/09593969.2021.2024447.

[5] Avşar, B. Z., 2021. Omni-Channel Trends In Covid-19 Pandemic. Journal of International Trade, Logistics and Law, 7 (1): 97–104.

[6] Ayers, J.B., Odegaard, M.A., 2017. Retail Supply Chain Management. Auerbach Publications, Taylor & Francis Group: New York.

[7] Bai, C., Quayson, M., Sarkis, J., 2022. Analysis of Blockchain's enablers for improving sustainable supply chain transparency in Africa cocoa industry. Journal of Cleaner Production, 358(2020), 131896. https://doi.org/10.1016/j.jclepro.2022.131896.

[8] Barman, A., Das, R., Kanti D.P., 2022. Logistics and supply chain management of food industry during COVID 19: disruptions and a recovery plan. Environment Systems & Decisions, 42, 338-349. https://doi.org/10.1007/s10669-021-09836-w.

[9] Belu, M.G., Marinoiu, A.M., 2014. A new distribution strategy: the omni-channel strategy. The Romanian Economic Journal, 52, 117-134.

[10] Benrqya, Y., Babai, M.Z., Estampe, D., Vallespir, B., 2020. Cross-docking or traditional warehousing: what is the right distribution strategy for your product? International Journal of Physical Distribution & Logistics Management, 50(2), 255-285. DOI 10.1108/IJPDLM-03-2019-0091.

[11] Bimpikis, K., Markakis, M.G, 2016. Inventory Pooling Under Heavy-Tailed Demand. Management Science, 62 (6), 1800-1813. https://www.jstor.org/stable/24740371.

[12] Business Maverick, 2021. South African retail sales rise in May — but looting is set to dent GDP boost. Available at https://www.dailymaverick.co.za/article/2021-07-14-south-african-retail-sales-rise-in-may-but-looting-is-set-to-dent-gdp-boost/. Accessed 15 April 2022.

[13] Cantini, A., Peron, M., De Carlo, F., Sgarbossa, F., 2022. A decision support system for configuring spare parts supply chains considering different manufacturing technologies, International Journal of Production Research, DOI:10.1080/00207543.2022.2041757.

[14] Cheng, L., Guo, X., Li, X., Yu, Y., 2022. Data-driven ordering and transshipment decisions for online retailers and logistics service providers. Transportation Research Part E: Logistics and Transportation Review, 161(2021): 102684. Available at: https://doi.org/10.1016/j.tre.2022.102684.

[15] Chopra, S. 2018. The Evolution of Omni-Channel Retailing and its Impact on Supply Chains. Transportation Research Procedia, 30, 4-15.

[16] Claesson, F., Hilletofth, P., 2011. In-transit distribution as a strategy in a global distribution system. International Journal of Shipping and Transport Logistics, 3(2), 198-209.

[17] Cocco, H., De-Juan-Vigaray, M. D., 2022. A typology of omnichannel retailer activities during the COVID-19 pandemic. International Journal of Retail and Distribution Management, 50(8–9): 1062–1094.

[18] Corbett, C.J., Rajaram, K., 2006. A Generalization of the Inventory Pooling Effect on Nonnormal Dependent Demand, Manufacturing & Service Operations Management, 8 (4), 351-358.

[19] Corniani, M., 2008. Push and Pull Policy in Market-Driven Management. Symphonya Emerging Issues in Management, (1), 45–64. DOI: 10.4468/2008.1.05corniani.

[20] Dakora, E.A.N., Rambe, P., 2022. The digital transformation of food and grocery retailing under the covid-19 pandemic: a case of major South African retailers, The Retail and Marketing Review, 8(1), 59-75.

[21] Das M., Jana, D.K., Alam, S., 2022. Comparative study of centralized and decentralized scenarios of a three-tiered green supply chain in two-period using the game theoretical approach. Cleaner Logistics and Supply Chain, 4 (2022), 100054, DOI: https://doi.org/10.1016/j.clscn.2022.100054.

[22] de Leeuw, S., Holweg, M., Williams, G., 2011. The impact of decentralised control on firm-level inventory: Evidence from the automotive industry. International Journal of Physical Distribution and Logistics Management, 41 (5), 435–456.

[23] Dujak, D., 2019. Causal Analysis of Retail Distribution System Change from Direct Store Delivery to Centralised Distribution. IBIMA Business Review, 2019. DOI: 10.5171/2019.400418.

[24] Effah, D., Bai, C., Asante, W. A., Quayson, M., 2023. The Role of Artificial Intelligence in Coping With Extreme Weather-Induced Cocoa Supply Chain Risks. IEEE Transactions on Engineering Management. https://doi.org/10.1109/TEM.2023.3289258

[25] Feng, P., Chai, J., Hu, Z., Zong, W., Wu, F., Wang, D.J., 2023. Joint inventory and transshipment decisions with consumer behavioral heterogeneity. Journal of Management Science and Engineering, 8(3), 369–385.

[26] Friedrich, C., Elbert, R., 2022a. Adaptive large neighborhood search for vehicle routing problems with transshipment facilities arising in city logistics. Computers and Operations Research, 137(2021), 105491. https://doi.org/10.1016/j.cor.2021.105491.

[27] Friedrich, C., Elbert, R., 2022b. Urban consolidation centers and city toll schemes–Investigating the impact of city tolls on transshipment decisions. Transportation Research Part E: Logistics and Transportation Review, 164 (2021), 102782. https://doi.org/10.1016/j.tre.2022.102782.

[28] Gillpartrick, T., Blunck, E., Boga, S., 2019. Understanding the role of consumer behavior in forecasting the impact of industry 4.0 and the wave of digital disruption driving innovation in retailing. Review, UDK 658.87:004]:336.1.

[29] Hall, W.R., 1992. A Note on Bounds for Direct Shipping Cost. Management Science, 38 (8), 1212-1214. https://www.jstor.org/stable/2632627.

[30] Jensen, K. L., Yenerall, J., Chen, X., Yu, T. E., 2021. US Consumers' Online Shopping Behaviors and Intentions during and after the COVID-19 Pandemic. Journal of Agricultural and Applied Economics, 53(3), 416–434.

[31] Kangi. F., Pasandideh, S.H.R, Mehdizadeh, E., Soleimani, H., 2022. The optimization of a multi-period multi-product closed-loop supply chain network with cross-docking delivery strategy. Journal of Industrial and Management Optimization. 18(5), 3393–3431. doi:10.3934/jimo.2021118.

[32] Kembro, J., Norrman, A., 2019. Exploring trends, implications, and challenges for logistics information systems in omni-channels Swedish retailers' perception. International Journal of Retail & Distribution Management, 47 (4), 384-411.

[33] Kocaoglu, Y., Cakmak, E., Kocaoglu, B., TaskinGumus, A., 2020. A Novel Approach for Optimizing the Supply Chain: A Heuristic-Based Hybrid Algorithm. Mathematical Problems in Engineering, 2020, Article ID 3943798, 24 pages. https://doi.org/10.1155/2020/3943798.

[34] Kurata, H., 2014. How does inventory pooling work when product availability influences customers' purchasing decisions?, International Journal of Production Research, 52(22), 6739-6759. DOI: 10.1080/00207543.2014.916825

[35] Li, B., Zhou, Y., Wang, X., 2013. Equilibrium analysis of distribution channel structures under power imbalance and asymmetric information. International Journal of Production Research, 51(9), 2698–2714.

[36] Li, J., Chen, H., Chu, F., 2010. Performance evaluation of distribution strategies for the inventory routing problem. European Journal of Operational Research, 202, 412-419.

[37] Lin, Z., 2022. The choices of channel structures and information strategies in a supply chain. Journal of Management Science and Engineering, 7(3), 405–422. https://doi.org/10.1016/j.jmse.2022.02.004.

[38] Mavi, K.R.; Goh, M., Mavi, N.K., Jie, F., Brown, K., Biermann, S., Khanfar, A.A, 2012. Cross-Docking: A Systematic Literature Review. Sustainability 2020, 12, 4789. https://doi.org/10.3390/su12114789.

[39] Melacini, M., Perotti, S., Rasini, M., Tappia, E., 2018. E-fulfilment and distribution in omni-channel retailing: a systematic literature review. International Journal of Physical Distribution & Logistics Management, 48(4), 391-414. DOI 10.1108/IJPDLM-02-2017-0101.

[40] Milewski, D. 2020. Total costs of centralized and decentralized inventory strategies—including external costs. Sustainability (Switzerland), 12(22), 1–16.

[41] Moon, I., Sarmah, S.P., Saha, S., 2018. The impact of online sales on centralized and decentralised dual-channel supply chains. European Journal of Industrial Engineering, 12(1), 67-92.

[42] Nakandala, D., Lau, H., Ning, A., 2016. A hybrid approach for cost-optimized lateral transshipment in a supply chain environment. Business Process Management Journal, 22(4), 860–878.

[43] Nanda, A., Xu, Y., Zhang, F., 2021. How would the COVID-19 pandemic reshape retail real estate and high streets through acceleration of E-commerce and digitalization? Journal of Urban Management, 10(2), 110–124. https://doi.org/10.1016/j.jum.2021.04.001.

[44] Ngoh, C.L., Groening, C., 2022. The effect of COVID-19 on consumers' channel shopping behaviors: A segmentation study. Journal of Retailing and Consumer Services, 68, 103065. https://doi.org/10.1016/j.jretconser.2022.103065.

[45] Nwaogbe, O.R., Omoke, V., Ubani, E.C., Ukaegbu, S.I., 2013. Cost minimisation of product transhipment for physical distribution management. Journal of Transport and Supply Chain Management, 7(1), 94-103. http://dx.doi.org/10.4102/jtscm.v7i1.94.

[46] Omoruyi, O., Dakora, E.A.N., Oluwagbemi, O. O., 2022. Insights into the impacts of and responses to COVID-19 pandemic: The South African food retail supply chains perspective, Journal of Transport and Supply Chain Management, 16(0), a739. https://doi.org/10.4102/jtscm.v16i0.739

[47] Quayson, M., Bai, C., Mahmoudi, A., Hu, W., Chen, W., Omoruyi, O., 2023. Designing a decision support tool for integrating ESG into the natural resource extraction industry for sustainable development using the ordinal priority approach. Resources Policy, 85(PA), 103988. https://doi.org/10.1016/j.resourpol.2023.103988

[48] Quayson, M., Bai, C., Sarkis, J., 2023. Building blockchain-driven dynamic capabilities for developing circular supply chain : Rethinking the role of sensing , seizing , and reconfiguring. 2022, 1–20. https://doi.org/10.1002/bse.3395.

[49] Reinartz, W., Wiegand, N., Imschloss, M., 2019. The impact of digital transformation on the retailing value chain. International Journal of Research in Marketing, 36, 350-366.

[50] Rezaei, J., 2016. Best-worst multi-criteria decision-making method: Some properties and a linear model. Omega, 64, 126–130. https://doi.org/10.1016/j.omega.2015.12.001.

[51] Rianthong, N., Dumrongsiri, A. , 2013. Time-partitioning heuristic algorithm for optimal production, inventory, and transportation planning with direct shipmen. Songklanakarin Journal of Science Technology, 35(3), 369-377.

[52] Rojas, F., Wanke, P., Bravo, F., Yong Tan, Y., 2021. Inventory pooling decisions under demand scenarios in times of COVID-19, Computers & Industrial Engineering ,161,pp107591. https://doi.org/10.1016/j.cie.2021.107591

[53] Rostami, P.; Avakh Darestani, S.; Movassaghi, M., 2022. Modelling Cross-Docking in a Three-Level Supply Chain with Stochastic Service and Queuing System. MOWFA Algorithm. Algorithms 2022, 15, 265.

[54] Sayyida, S., Hartini, S., Gunawan, S., Husin, S.N., 2021. The Impact of the Covid-19 Pandemic on Retail Consumer Behavior. Aptisi Transactions on Management (ATM), 5(1), 79–88.

[55] Shetty, G., Nougarahiya, S., Mandloi, D., Sarsodia, T., Dabade, S.J., 2020. COVID-19 and Indian Commerce: An Analysis of Fast-Moving Consumer Goods (FMCG), and Retail Industries of Tomorrow. International Journal of Current Research & Review, 12(17), 23-31.

[56] Silbermayr, L., Gerchak, Y., 2019. Partial pooling by independent firms with allocation according to contribution to pool. International Journal of production Economics, 218(2019), 375-385.

[57] Stanger, S. H. W., Wilding, R., Hartmann, E., Yates, N., Cotton, S., 2013. Lateral transshipments: An institutional theory perspective. International Journal of Physical Distribution and Logistics Management, 43(9), 747–767.

[58] Swinney, R., 2011, Inventory Pooling with Strategic Consumers: Operational and Behavioral Benefits. https://www.hbs.edu/faculty/Shared%20Documents/events/163/Pooling.pdf

[59] Teng, J., 2002. Project Evaluation: Methods and Applications. Project Evaluation: Methods and Applications. https://hk.search.yahoo.com/yhs/search?p=Teng%2C J.Y. (2002)%2C Project Evaluation%3A Methods and Applications%2C National Taiwan Ocean University.

[60] Tetouani, S., Chouar, A., Lmariouh, J., Soulhi, A., Elalami, J., 2019. "Push-Pull" rearrangement while routing for a driverless delivery vehicle. Cogent Engineering, 6, 1-14. https://doi.org/10.1080/23311916.2019.1567662.

[61] Thaichon, P., Phau, I., Weaven, S., 2022. Moving from multi-channel to Omni-channel retailing: Special issue introduction. Journal of Retailing and Consumer Services, 65, 102311. https://doi.org/10.1016/j.jretconser.2020.102311.

[62] Titiyal, R., Bhattacharya, S., Thakkar, J.J., 2019. The distribution strategy selection for an e-tailer using a hybrid DANP VIKOR MCDM model, Benchmarking: An International Journal, 26(2), 395-433. https://doi.org/10.1108/BIJ-01-2018-0018.

[63] Torbali, B., Alpan, G., 2022. A literature review on robust and real-time models for cross-docking, International Journal of Production Research, 0(0), 1-21.DOI: 10.1080/00207543.2022.2062580.

[64] Van Belle, J., Valckenaers, P, Cattrysse,D., 2012. Cross-docking: State of the art. Omega, 40 (6), 827-846. https://doi.org/10.1016/j.omega.2012.01.005.

[65] Vanessa, F., Björn, A., Eric, S., 2018. Digitization in Outbound Logistics – Application of an Industry 4.0 Maturity Model for the Delivery Process. In. Stentoft, Jan (Ed.) (2018): Proceedings of the 30th Annual NOFOMA

Conference: Relevant Logistics and Supply Chain Management Research. Kolding: Syddansk Universitet, S. 113–128.
[66] Verhoef, P. C. ,2021. Omni-channel retailing: some reflections. Journal of Strategic Marketing. Routledge, 29(7), 608–616. https://doi.org/10.1080/0965254X.2021.1892163.
[67] Wang, X., Chen, S.Z., Hu, M., and Ke, J., 2022. Inventory pooling and pricing decisions in multiple markets with strategic customers. RAIRO-Operations Research, 56 (6), 3941-3953.
[68] Weber, A. N., 2021. Responding to supply chain disruptions caused by the covid-19 pandemic: A black swan event for omnichannel retailers. Journal of Transport and Supply Chain Management, 15: 1–16.
[69] Wena, X., Choi, T.M. & Chung, S.H. 2019. Fashion retail supply chain management: A review of operational models. International Journal of Production Economics, 207, 34-55.
[70] Xiong, Y., Okorie, C., Ezeoke, G., 2020. Enhancing distribution network performance: a quantitative approach to developing a distribution strategy model. Journal of Management, Marketing and Logistics, 7(4), 160-182. http://doi.org/10.17261/Pressacademia.2020.1331.
[71] Xu, X., Zhang, M., Dou, G., Yu, Y., 2023. Coordination of a supply chain with an online platform considering green technology in the blockchain era. International Journal of Production Research, 61(11), 3793–3810. https://doi.org/10.1080/00207543.2021.1894367.
[72] Zhang, J., Zhao, S. Cheng, T.C.E., Hua, G., 2019. Optimisation of online retailer pricing and carrier capacity expansion during low-price promotions with coordination of a decentralised supply chain. International Journal of Production Research, 57(9), 2809-2827. DOI: 10.1080/00207543.2018.1516901.

Authors' Biography

Dr Osayuwame Omoruyi is a senior lecturer and researcher in Logistics, Operation, and Supply Chain Management since 2010. She is currently the Research Chair in the School of Economic and Management Sciences, Sol Plaatje University. Professionally affiliated with the Chartered Institute of Logistics and Transport (CILTSA) and has been a chartered member since 2019.

Dr. Edward Dakora is a Senior Lecturer in the Department of Management Sciences at Sol Plaatje University (SPU), where has served in different capacities since 2014, He teaches causes in Entrepreneurship, Marketing and Retail Management at both undergraduate and postgraduate levels. He has facilitated courses on the Professional Doctoral Programme (ProDBA) at the Nelson Mandela University Business School.

Albert Antwi (PhD) is a senior lecturer in Statistics and Operations Research Techniques at Sol Plaatje University. Albert is currently the Post graduate coordinator of the Mathematical sciences Department, Sol Plaatje University and he has been a member of the South African Statistical Association since 2017.

Dr Matthew Quayson received his Ph.D. degree in Management Science and Engineering (supply chain option) from the University of Electronic Science and Technology of China, Chengdu, China. His research focuses on using multi criteria decision techniques to address issues relating to technology applications for sustainable supply chain management in emerging economies.

Dr Alfred Mwanza is a lecturer in the School of Natural and Applied Sciences, Department of Computer Science and Information Technology at Sol Plaatje University. He has worked in industry for 10 years and in academia for 12 years. He holds a BSc in Mathematics and Computer Science, Master of Computer Science and a PhD in ICTs in Education.

Professor Emmanuel Mabugu is a Professor in Economics, School of EMS at Sol Plaatje University since February 2019. He is also currently Research Fellow at the University of Stellenbosch as well as Partnership for Economic Policy. He consults and advises on funded projects, including FF (Canada), IDRC (Canada), Sida (Sweden), World Bank, UNDP and many African governments.

Leonard Ndlovu is a Lecturer in the Department of Accounting and Economics at Sol Plaatje University where he was the founding Head of the Department. He is currently completing a PhD in Business Administration from VUT in South Africa. He is a qualified accountant who has been an Associate member of CIMA (ACMA) since 2015.

CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
CPSL 2023-2

5th Conference on Production Systems and Logistics

The Process Mining Use Case Canvas: A Framework for Developing and Specifying Use Cases

Dino Hardjosuwito[1], Fynn L. Braucks[1], Tobias Schröer[1], Christopher T. Schwanen[2], Wil M.P. van der Aalst[2]

[1]*Institute for Industrial Management (FIR) at RWTH Aachen University, Aachen, Germany*
[2]*Chair of Process and Data Science (PADS), RWTH Aachen University, Aachen, Germany*

Abstract

Process mining has emerged as a crucial technology for digitalization, enabling companies to analyze, visualize, and optimize their processes using system data. Despite significant developments in the field over the years, companies—notably small and medium-sized enterprises—are not yet familiar with the discipline, leaving untapped potential for its practical application in the business domain. They often struggle with understanding the potential use cases, associated benefits, and prerequisites for implementing process mining applications. This lack of clarity and concerns about the effort and costs involved hinder the widespread adoption of process mining. To address this gap between process mining theory and real-world business application, we introduce the "Process Mining Use Case Canvas," a novel framework designed to facilitate the structured development and specification of suitable use cases for process mining applications within manufacturing companies. We also connect to established methodologies and models for developing and specifying use cases for business models from related domains targeting data analytics and artificial intelligence projects. The canvas has already been tested and validated through its application in the ProMiConE research project, collaborating with manufacturing companies.

Keywords

Process Mining; Use Case Canvas; Framework; Manufacturing; Order Processing

1. Introduction and Motivation

Today, companies use various information systems (e.g., ERP, SRM, MES, CRM) to manage their business processes efficiently. These systems store vast amounts of data that contain valuable insights into the processes within a company. While traditional business process management approaches focus on qualitative analyses regarding the process as designed, they typically neglect the available process data. On the other hand, data mining techniques cannot capture the complex temporal relationships present in process data. This gap between traditional approaches and data-driven analysis is where process mining emerges as a promising solution.

Process mining is an evolving discipline at the intersection of process and data science. Its data-driven approaches leverage process data to uncover the actual process dynamics, allowing for qualitative and quantitative analyses. Process mining contains three primary subfields [1]: (1) process discovery, exploring process models from process data; (2) conformance checking, identifying deviations in the execution of a process compared to a given process model; and (3) process enhancement, focusing on methods dealing with business process improvement. Recent developments in areas like object-centric process mining, process digitization and automation, and integrating artificial intelligence for predicting process outcomes are helping to address increasingly complex questions. An overview of process mining and its seminal subfields can be found in [1,2].

DOI: https://doi.org/10.15488/15308
ISSN: 2701-6277

The application of process mining in manufacturing companies offers various benefits. For example, it enables identifying and reducing bottlenecks and repetitive tasks like rework by providing a holistic view of processes down to individual activities. It also facilitates the identification of automation opportunities and fosters process standardization by minimizing the number of process variants, ultimately enhancing process efficiency and reducing throughput times. Moreover, process mining supports root cause analysis, e.g., tracing quality issues back to specific process steps in manufacturing. Despite these advantages, the adoption of process mining in manufacturing companies rarely gains traction due to various challenges. Established project methodologies tailored to process mining [5,3,4] structure such projects into distinct phases and guide their implementation. However, the main challenges confront companies already during project initialization. These challenges include uncertainty about project outcomes, selecting adequate processes, defining success metrics, and data availability and privacy concerns [6]. Small and medium enterprises often require additional guidance and expertise to develop and implement process mining use cases effectively, which can be crucial for the success of a process mining project.

To address these challenges and support manufacturing companies, we introduce the *Process Mining Use Case Canvas*, a semi-formal framework describing process mining use cases, facilitating interdisciplinary communication, and structuring complex subjects [7,8]. By encompassing the key components of a process mining use case and providing a structured approach for its specification, the *Process Mining Use Case Canvas* aims to foster a shared understanding between process mining experts and stakeholders within a manufacturing company [10,9].

The remainder of this paper is structured as follows. Section 2 overviews existing process mining project methodologies, established canvas models, and related work on process mining use cases. We present our Process Mining Use Case Canvas in Section 3 and elaborate on its components. The application of the canvas and its limitations are discussed in Section 4 before Section 5 concludes the paper.

2. State of the Art and Related Work

In this section, we highlight the state of the art when developing and specifying process mining use cases and present related work. To do so, we first go into more detail about process mining project methodologies. Then, we evaluate various use case canvases from related fields before discussing tangible approaches to process mining use cases.

2.1 Process Mining Project Methodologies

Several methodologies have been developed to assist and guide companies in implementing and executing process mining projects. The first project methodology specifically for process mining is the *L* life-cycle model* [1,3]. It includes ten process mining related activities (e.g., discover, compare) divided into cartography, auditing, and navigation categories, guiding users through implementing a process mining project in five stages. While four stages address the project execution from extraction to operational support, an initial *Stage 0* emphasizes the project planning and justification. The *Process Mining Manifesto* [3] also provides guiding principles and states potential challenges specific to process mining projects. The *PM² methodology*, proposed by van Eck et al. [4], introduces an iterative project approach and emphasizes interdisciplinary collaboration between process analysts and business experts. It considers six stages among three phases: an initial phase, the analysis iteration loop, and a final phase regarding improving the process and supporting operations. The first stage *Planning* involves selecting business processes, identifying research questions, and composing a project team. For each of these activities, they highlight its relevance and potential challenges (e.g., data quality or unclear research questions). Aguirre et al. [5] offer a step-by-step methodology with four stages for conducting process mining projects. The initial project definition stage involves defining the main process problems, specifying the scope, modeling the process, and setting the project goals. The second stage handles data localization, extraction, and preparation. The conducted case studies reveal main challenges such as data quality problems, privacy concerns, unclear success measures, or difficulties regarding data extraction.

Although the discussed methodologies guide the execution and structuring of process mining projects, their support to systematically develop and specify appropriate use cases is limited. The use cases have to be developed and specified beforehand or at the beginning and require more comprehensive design aspects beyond the processual description by the methodologies.

2.2 Approaches Regarding Canvas Models

The Business Model Canvas by Osterwalder and Pigneur [9] is probably the best-known canvas model used for structuring and communicating business models. It has inspired numerous canvases and is helpful for practitioners to visualize and analyze business models. Some aspects of the Business Model Canvas can be adapted for developing process mining use cases. However, there are limitations in using this canvas for process mining use cases, as it does not consider the process view and analytical aspects.

Some authors propose data-centric approaches, including canvases for data-driven use cases or data science. For instance, Kronsbein and Mueller suggest a Data Innovation Board [11], offering a solution for generating initial data-centric ideas. Kayser et al. present a data classification scheme for data-driven use case development [12]. Schwarz et al. propose a canvas for data and analytics use cases, with some aspects applicable to process mining, including value creation, data availability, roles, and tools [13]. Neifer et al. introduce the Data Science Canvas [14], which partially applies to process mining use cases. However, further process mining specific components like process-related components or more precise guidance regarding the process mining analyses would be needed. While all these canvases offer valuable input, they are only partially applicable for process mining use cases as they focus solely on data and neither guide further use case development nor focus on processes and process mining specific aspects.

Other approaches specifically focus on technologies like machine learning (ML) and artificial intelligence (AI). Bork et al. [15] highlight integrating ML solutions into the business context and discuss the data-driven and canvas-driven approach. The authors conclude that most of the analyzed canvas-driven approaches focus on data and technology but only a few on business or process dimensions. Thiée's systematic literature research [8] provides a comprehensive overview of existing canvases for machine learning. Kerzel's AI canvas [16] has a more generic focus on AI and comprises a business view and a model & data view. It explores how AI use cases can impact the organization and create business value. Additionally, Steireif et al. [17] propose a participatory approach for identifying, specifying, and evaluating AI use cases in manufacturing, introducing criteria related to technology attractiveness and implementation capability. While some technical and organizational criteria from these four approaches may be transferable, they cannot fully capture process mining use cases. The analyzed canvases often do not consider processes, which makes it necessary to adapt and extend the components.

The previously described approaches show that although they already contain components helpful in designing use case aspects, they cannot provide a comprehensive approach for systematically developing and specifying process mining use cases. Nonetheless, we can adapt and include some existing components in developing such a model.

2.3 Approaches Regarding Process Mining Use Cases

Ailenei et al. [18] focus on defining and validating specific process mining use cases. A literature review, ten interviews, and a survey result in a list of use cases categorized by the used process mining technique. For instance, the discovery category contains a use case to determine the structure of an unknown process. Although the development of the use cases remains unclear, and the small number of interviews suggests a limited representation of possible process mining use cases in companies, the article provides valuable inspiration for potential applications of process mining.

As the number of process mining projects increases, vendors develop and implement a wide variety of use cases. For instance, the market leader Celonis describes over 20 selected use cases covering finance, shop floor, strategic applications, and more areas [19]. While this selection can guide companies, they should consider a potential selection bias, as vendors may prioritize certain use cases based on customer preferences or industries. Therefore, manufacturing companies might prefer a neutral method for developing use cases, bringing out use cases that have received less attention.

Rott and Böhm [20] present criteria that guide organizations in evaluating process mining use cases. These criteria, categorized into six groups, focus on business importance, challenges, employee skills, data state, organizational support, and optimization potential. Their relevance, however, is not limited to evaluating a process mining use case; instead, its development should already account for them. Thus, a canvas to comprehensively develop and specify process mining use cases requires additional components reflecting overall goals, reasons for selecting process mining, a process description, and the type of analysis needed.

3. Process Mining Use Case Canvas

The presented canvases offer a foundation for data-based use cases but require adaptions to address the specific challenges related to process mining. Therefore, we derive a use case canvas specifically targeted to process mining projects. But first, we tackle the challenges that have been raised. Most canvases are not designed for the application to processes, which the study in [15] also confirms. In process mining, the process perspective is essential and should be included in a corresponding canvas. As illustrated and discussed in [6], the main challenges of a process mining project already arise within the initialization. The study participants name the benefits of process mining, selection of appropriate business processes, definition of success metrics, and data availability as their primary concerns. The results from [21] support this point of view and identify a lack of process mining expertise and limited understanding of data usage as additional challenges.

Within the ProMiConE research project, we conducted several interviews and workshops with small and medium-sized manufacturing enterprises, confirming the findings of the studies above. Participants emphasize that estimating the effort and outcome of a process mining project, uncertainties about data availability, and data quality problems are significant challenges. Furthermore, many users feel the need to be more sufficiently informed on the opportunities of process mining and thus have difficulties assessing the potential of this technology.

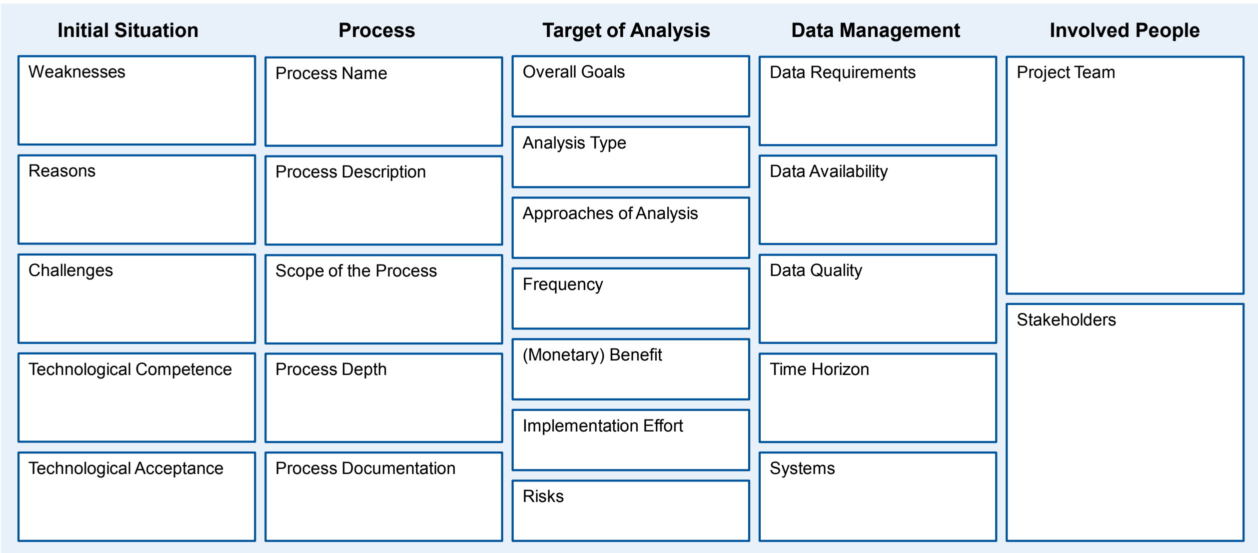


Figure 1: Process Mining Use Case Canvas

The *Process Mining Use Case Canvas* addresses these challenges and enables to identify, develop, and specify process mining use cases in manufacturing companies. It aims to guide and improve the collaboration between process mining experts and company representatives. Each canvas component encourages them to reflect on the specifics of the use case at hand. The associated components are described and defined along the five dimensions: *Initial Situation*, *Process*, *Target of Analysis*, *Data Management*, and *Involved People* (see Figure 1). While existing canvases already address some of the dimensions, their specific application to process mining is novel.

3.1 Initial Situation

In order to assess the company's initial situation, the *Weaknesses* component, in existing canvases [14,20,13] mostly referred to as problems, is intended to describe the current problems and weaknesses that are supposed to be ultimately improved or resolved by the application of process mining. Exemplary weaknesses are a lack of adherence to production schedules or too many process variants. While other approaches aim to choose the right technology [15,14,13,8], we assume process mining to be the methodology of choice. Thus, the *Reasons* component documents the rationale for applying process mining to remedy weaknesses. For example, the ability of process mining to increase process transparency and thus make analysis possible in the first place is a possible reason for its application. Current obstacles preventing optimization measures are described in the *Challenges* component. As mentioned in [20], this includes describing why it has not yet been possible to eliminate the identified weaknesses, for example because of a lack of transparency and various root causes, hence hard to identify without process mining. The *Technological Competence* component considers a company's previous experience and expertise in process mining and other digitalization projects [22,20,17]. For instance, although a company might not yet carry out a process mining project, it can state that it might resort to relevant experience with digitalizing the shop floor. The *Technological Acceptance* component [20,17] assesses the company's workforce acceptance regarding technology and digitalization projects. High acceptance of process mining increases the likelihood that employees will embrace and use the new analytics insights, leading to smoother implementation and greater process optimization success.

3.2 Process

In order to sufficiently capture the process for the use case development, the first step involves documenting the *Process Name* as specified within the company. This identification avoids ambiguity and mitigates the risk of misunderstandings [23]. An example could be the end-to-end manufacturing process. In the *Process Description* component, the process is outlined. A detailed description can additionally indicate which production areas and critical shop floor operations will be included. The component *Scope of the Process* defines the process steps delimiting the process [24]. Exemplary delimiting process steps could be the receipt of a production order as a starting point and the product transport to the packaging area as a final step. The process level at which the respective process takes place and is to be analyzed is defined by the *Process Depth* [25,26], ensuring that the data will have the required granularity. Accordingly, a process can be located, for example, on the level of a main process, a business process, or a work process, whereby the work process can be detailed down to individual activities. The *Process Documentation* component deals with the availability of documentation or description of the process under analysis in the company [5]. Such documentation may be provided in BPMN 2.0 or similar formats and can already give stakeholders an initial understanding of the process.

3.3 Target of Analysis

The *Overall Goals* component, adapted from [5,16], defines the overall goals of the process mining use case to clarify when a process mining project is considered successful. For example, it can be defined that an overall goal is to reduce the process variants in manufacturing. Relevant process mining functionalities are specified in the *Analysis Type* component, as addressed by [5,1,2,4] and consolidated for this canvas. For example, process discovery and bottleneck detection could be mentioned here to identify causes of inefficiencies in manufacturing. Furthermore, the *Approaches of Analysis* component of the analysis records whether the use case is to be classified as descriptive, diagnostic, predictive, or prescriptive. The component is adapted from [22,14,8,2] and consolidated for this canvas. The *Frequency* component defines how often and to which extent the analyses are performed [20,3,27]. The frequency significantly effects the necessary effort and the required data quality. A one-time analysis, periodically repeating application, or a permanent process analysis in real time can be conducted. A repeated analysis, for example, can be necessary to assess and validate improvement measures derived from initial analyses. The *(Monetary) Benefits* component describes the added (monetary) value that can be achieved by the use case [15,12,11,14,9,20,13,17,8]. Such direct and indirect benefits could be eliminated bottlenecks, a measurably reduced throughput time, or an increased service level. Estimating the effort required to implement the process mining use case is focused on in the *Implementation Effort* component adapted from [14,20,13,17,8]. While many sources only address project costs, this component takes a more comprehensive approach, including the necessary staffing, time, and cost efforts. Various risks can accompany process mining projects, e.g., data privacy and compliance risks, insufficient data quality, technical challenges, or resistance to change on the part of employees. If apparent, such project risks are noted in the *Risks* component [11,13].

3.4 Data Management

The *Data Requirements* component, adapted and consolidated from [12,14,20,13], derives the necessary data and its desired target state based on the individual key and driver metrics defined for each goal. Influencing factors are parameters like the type of analysis (pre-facto or post-facto), the desired level of granularity, and the targeted level of significance. In this initial stage, the discussion should solely focus on the desired target state of the analysis and required data. In view of the desired data target state, the component *Data Availability* determines which data is already collected within the company or available from external sources [22,20,13,17,8]. This includes scope, temporal availability of data, existence of raw data for pre-processing, accessibility aspects such as interface availability and compatibility, data security and privacy. In the component *Data Quality*, previously specified available data is now evaluated with regard to their quality [16,14,20,13,8]. In accordance with the defined requirements, the data has to be checked for its completeness, validity, veracity, and consistency. In particular, it has to be verified whether the level of detail in the data suffices the desired level of granularity in the analysis. A characteristic feature of process data is its innate time dimension, which is examined in more detail in the *Time Horizon* component. While the data period or time frame was not explicitly considered in existing canvases so far, we added it as a separate component [28]. The relevant time horizon is estimated based on data volume and frequency. Another distinction concerns whether it is a real-time analysis during operation or a post-facto analysis for long-term investigations to improve the business process. Finally, the *Systems* component describes all information systems involved [22,16,14,20,8]. These include data-providing, data integration and pre-processing systems, as well as data analysis and visualization systems. Here, we distinguish between systems that are already in use and those that have yet to be installed. Also, the primary sources for each data type can be determined and the involved systems' interoperability is evaluated.

3.5 Involved People

The *Project Team* component, adapted and consolidated from [22,11,14,20,13,8], considers roles required in a process mining project, suitable persons to be assigned to these roles and determines whether specific expertise is already available within the company. These roles include the *project manager*, the *process mining expert* and the *data scientist*, all of which can be filled by internal employees or external experts. In addition, the roles of the *process owner*, the *process expert*, and the *system expert* should be filled internally due to the required company-specific in-depth knowledge of the process and information systems involved. People affected by the project should be mentioned in the *Stakeholders* component [15,14,20,13,17,8]. This includes future users of the process mining analyses and those targeted by their measures. In addition, all decision-makers whose areas of responsibility are affected should be considered.

In summary, the *Process Mining Use Case Canvas* structures and supports the development and specification of use cases by assessing the initial situation and deriving the use case based on the identified weaknesses. It characterizes and describes the targeted process in a structured way and enhances understanding of the use case. The actual process mining application is systematically derived from the clearly defined goals through the *Target of Analysis* dimension. In the *Data Management* dimension, the demands on data are brought together with the prevailing situation in the company. Finally, the interdisciplinarity and the implication of a process mining project are considered by addressing the *Involved People*. This way, process mining use cases can be systematically developed and specified based on these five dimensions.

4. Application and Discussion

The *Process Mining Use Case Canvas* has been applied in the ProMiConE research project with two manufacturing companies and validated by an established process mining software vendor. These first two applications suggest that the canvas is suitable for the short-term, initial creation of use cases, starting with idea generation in the company and for the detailed elaboration and specification of use cases. Initial use cases could be formulated by deriving these ideas from the most pressing weaknesses.

We conducted a pilot study using the canvas to develop potential use cases within the ProMiConE project. The two participating companies (see appendix) were selected as the research project focuses on small and medium-sized manufacturing enterprises using ERP systems and are interested in process mining. The companies were informed in advance about the procedure and the canvas so that they had the opportunity to gather the necessary information for the workshops. The workshops took place for each company individually, each with one company representative and a subset of the authors as moderators and experts on process mining, respectively. Initially, the procedure and the canvas, including its components, were explained in detail. Subsequently, the specific components and the respective company's characteristics were discussed. The company representatives provided information on weaknesses, processes, information systems, and other aspects. At the same time, the moderators documented these insights using the canvas and contributed their process mining expertise regarding possible analyses or data requirements. Since the companies had no previous experience with process mining use cases, their goal was first to develop initial use case ideas and describe them. This way, each company developed two or three use cases over the workshops, completing one canvas per use case.

In its first application, the canvas has proven its usefulness. Its current form was well suited to guide and structure the development of use cases in the pilot study and showed no need for adjustments. In addition, we discussed the canvas with a process mining vendor who evaluated its form and content and confirmed its functionality.

These two cases suggest that even when a process mining expert is present, it can be beneficial to educate representatives of manufacturing companies about the possibilities of process mining and different use cases beforehand. Because of the countless ways to apply process mining in manufacturing companies, it takes the internal knowledge of the company representatives involved to identify the most compelling use cases, as the process mining expert does not have sufficient knowledge about the state of the company. The application of the canvas underlines this point, as only the representatives have the knowledge of current weaknesses, which can only be determined with further investigation from the outside. Furthermore, it may be advisable to educate the company representative early on so that there is an opportunity to talk to various stakeholders within the company beforehand to aggregate the information needed to develop the use case. In one case, a company representative followed this approach, and it proved beneficial to the use case development since the person lacked comprehensive information for the use case beforehand.

The application thus far has demonstrated that the canvas should be applied with the assistance of a process mining expert. The expert should guide the user through the canvas, provide important hints and support directly when developing the use cases based on their expertise. It is important to highlight that the canvas only allows a rough estimation of the actual effort required for the process mining project based on the information gathered. As already outlined before, it can be said that at the time of the first use case development there is often uncertainty about the actual data quality [6,21]. For this purpose, after the specification of a use case, a more detailed, use case-specific examination of the data could take place and thus a more precise estimate could be made.

Regarding the challenges discussed at the beginning of this paper in the context of project initialization [6], the pilot study suggests that the canvas supports users in better planning and estimating the expected outcome of the process mining project. Furthermore, the canvas enabled the selection of suitable processes by systematically deriving the process to be analyzed, starting from the company's biggest problems and weaknesses. Even though the canvas does not provide a predefined set of success metrics, it helps users focus on specifying the criteria for project success by providing the corresponding component and facilitating communication with the involved process mining expert. The canvas faces the topic of data availability and privacy by its corresponding component, as well as it considers project risks. Even if the canvas does not describe any use case or process mining project conclusively down to the smallest detail needed for the final implementation, the two applications demonstrated that the structured and structuring character of the canvas fostered exchange, communication, and, above all, reflection about suitable process mining applications in the company. This shows the potential to make process mining applications more accessible and understandable for users. Drawing attention to challenges and possible causes of problems improves awareness, and this early-stage confrontation can mitigate later failures in projects and thus increase the chances of success of process mining in companies.

We intend the *Process Mining Use Case Canvas* as the starting point of any initiative to introduce process mining. Therefore, we designed the canvas to develop or sketch first ideas for potential process mining use cases or to specify them in more depth and detail. In reference to standard process mining project methodologies, the canvas is a suitable complement to be applied at the beginning of a process mining project, or even before, to define the framework and the conditions of a project to be designed and implemented based on the use case.

5. Conclusion and Outlook

The two applications of the *Process Mining Use Case Canvas* suggest that it may bridge the gap for systematically developing process mining use cases and provide a model for potential users to create practice-oriented use cases. With the advancing development of process mining, we intend to adapt and further develop the *Process Mining Use Case Canvas* over time. Since the canvas was only applied with two manufacturing companies and validated with one process mining vendor, it is intended to involve additional partners to broaden the perspective. This is supposed to include small and medium-sized enterprises from other industries and of different sizes. In addition, it has not yet been realized that a use case developed with the canvas is also implemented as a process mining project. It is to be examined to what extent the initially developed use case is modified in the course of a project. Furthermore, since the current focus of the canvas application lies exclusively on manufacturing companies, the canvas is to be transferred and applied to other domains.

Acknowledgments

We developed, applied, and validated the Process Mining Use Case Canvas within the research project ProMiConE. The IGF project 22485 N of the Research Association FIR e. V. at the RWTH Aachen University is funded via the AiF within the framework of the program for the funding of cooperative industrial research (IGF) by the Federal Ministry for Economic Affairs and Climate Action (BMWK) on the basis of a resolution of the German Bundestag. The authors would like to take this opportunity to thank the companies involved in the application and validation of the Process Mining Use Case Canvas.

Appendix

Table 1: Description of the participating companies

	Company 1	**Company 2**
Industry	Plant manufacturing	Metal processing
Manufacturing strategy	Make-to-order	Make-to-order
Size	Medium size company	Small size company
Country	Germany	Germany
Participant	Person with many years of experience in the company in a leading position	Person with many years of experience in the company in a leading position
Number of workshop sessions conducted for use case development	Two	Three
Number of use cases developed	Two	Three
Previous practical experience with process mining	No	No

References

[1] van der Aalst, W.M.P., 2016. Process Mining: Data Science in Action, Second Edition ed. Springer-Verlag Berlin Heidelberg, Berlin, Heidelberg.

[2] van der Aalst, W.M.P., Carmona, J. (Eds.), 2022. Process mining handbook. Springer, Cham, 502 pp.

[3] van der Aalst, W.M.P., Adriansyah, A., Medeiros, A.K.A. de, Arcieri, F., Baier, T., Blickle, T., Bose, J.C., van den Brand, P., Brandtjen, R., Buijs, J., Burattin, A., Carmona, J., Castellanos, M., Claes, J., Cook, J., Costantini, N., Curbera, F., Damiani, E., Leoni, M. de, Delias, P., van Dongen, B.F., Dumas, M., Dustdar, S., Fahland, D., Ferreira, D.R., Gaaloul, W., van Geffen, F., Goel, S., Günther, Christian, Guzzo, A., Harmon, P., Hofstede, A. ter, Hoogland, J., Ingvaldsen, J.E., Kato, K., Kuhn, R., Kumar, A., La Rosa, M., Maggi, F., Malerba, D., Mans, R.S., Manuel, A., McCreesh, M., Mello, P., Mendling, J., Montali, M., Motahari-Nezhad, H.R., zur Muehlen, M., Munoz-Gama, J., Pontieri, L., Ribeiro, J., Rozinat, A., Seguel Pérez, H., Seguel Pérez, R., Sepúlveda, M., Sinur, J., Soffer, P., Song, M., Sperduti, A., Stilo, G., Stoel, C., Swenson, K., Talamo, M., Tan, W., Turner, C., Vanthienen, J., Varvaressos, G., Verbeek, Eric, Verdonk, M., Vigo, R., Wang, J., Weber, B., Weidlich, M., Weijters, T., Wen, L., Westergaard, M., Wynn, M., 2012. Process Mining Manifesto. Business Process Management Workshops. BPM 2011. Lecture Notes in Business Information Processing (99), 169–194.

[4] van Eck, M.L., Lu, X., Leemans, S.J.J., van der Aalst, W.M.P., 2015. PM^2: A Process Mining Project Methodology, in: Johannesson, P., Kirikova, M., Zdravkovic, J. (Eds.), Advanced Information Systems Engineering. 27th International Conference, CAiSE 2015, Stockholm, Sweden, June 8-12, 2015, Proceedings, vol. 9097, 1st ed. 2015 ed. Springer International Publishing; Imprint: Springer, Cham, pp. 297–313.

[5] Aguirre, S., Parra, C., Sepúlveda, M., 2017. Methodological proposal for process mining projects. IJBPIM 8 (2), 102.

[6] Grisold, T., Mendling, J., Otto, M., vom Brocke, J., 2021. Adoption, use and management of process mining in practice. BPMJ 27 (2), 369–387.

[7] Kühn, A., Joppen, R., Reinhart, F., Röltgen, D., Enzberg, S. von, Dumitrescu, R., 2018. Analytics Canvas – A Framework for the Design and Specification of Data Analytics Projects. Procedia CIRP 70 (1), 162–167.

[8] Thiée, L.-W., 2021. A systematic literature review of machine learning canvases. INFORMATIK 2021, 1221–1235.

[9] Osterwalder, A., Pigneur, Y., 2010. Business Model Generation: A handbook for visionaries, game changers, and challengers. Wiley, Hoboken NJ, 278 pp.

[10] Kollwitz, C., Mengual, M.P., Dinter, B., 2018. Cross-Disciplinary Collaboration for Designing Data-Driven Products and Services.

[11] Kronsbein, T., Mueller, R.M., 2019. Data Thinking: A Canvas for Data-Driven Ideation Workshops. Proceedings of the 52nd Hawaii International Conference on System Sciences, 561–570.

[12] Kayser, L., Mueller, R.M., Kronsbein, T., 2019. Data Collection Map: A Canvas for Shared Data Awareness in Data-Driven Innovation Projects. 2019 Pre-ICIS SIGDSA Symposium on Inspiring mindset for Innovation with Business Analytics and Data Science, 1–17.

[13] Schwarz, D., List, M., Mueller, R.M., 2023. A Framework for the Systematic Evaluation of Data and Analytics Use Cases at an Early Stage. Proceedings of the 56th Hawaii International Conference on System Sciences, 5390–5399.

[14] Neifer, T., Lawo, D., Esau, M., 2021. Data Science Canvas: Evaluation of a Tool to Manage Data Science Projects. Proceedings of the 54th Hawaii International Conference on System Sciences, 5399–5408.

[15] Bork, D., Papapetrou, P., Zdravkovic, J., 2023. Enterprise Modeling for Machine Learning: Case-Based Analysis and Initial Framework Proposal, in: Nurcan, S., Opdahl, A.L., Mouratidis, H., Tsohou, A. (Eds.), Research Challenges in Information Science: Information Science and the Connected World, vol. 476. Springer Nature Switzerland, Cham, pp. 1–8.

[16] Kerzel, U., 2021. Enterprise AI Canvas Integrating Artificial Intelligence into Business. Applied Artificial Intelligence 35 (1), 1–12.

[17] Steireif, N., Kranz, M., Langhanki, J., Imorde, J., Maetschke, J., Mütze-Niewöhner, S., 2023. Potenzialanalyse von KI-Anwendungen in der Produktion. Zeitschrift für wirtschaftlichen Fabrikbetrieb 118 (4), 258–264.

[18] Ailenei, I., Rozinat, A., Eckert, A., van der Aalst, W.M.P., 2012. Definition and Validation of Process Mining Use Cases. BPM 2011 Workshops, 75–86.

[19] Celonis. The Big Book of EMS Use Cases: Celonis Execution Management System. https://www.celonis.com/ems/resources/bigbook/. Accessed 1 August 2023.

[20] Rott, J., Böhm, M., 2022. Mine the right process - towards a method for selecting a suitable use case for process mining adoption. ECIS 2022 Research Papers 45.

[21] IDG Research Services, 2019. Studie Process Mining & RPA 2019, München.

[22] Brock, J., Löhr, B., Brennig, K., Seger, T., Bartelheimer, C., Enzberg, S. von, Kühn, A., and Dumitrescu, R., 2023. A process mining maturity model: Enabling organizations to assess and improve their process mining activities. ECIS 2023 Research Papers 256, 1–16.

[23] Bose, J.C., Mans, R., van der Aalst, W.M.P., 2013. Wanna Improve Process Mining Results?: It's High Time We Consider Data Quality Issues Seriously. IEEE, Piscataway, NJ, 321 pp.

[24] Luftensteiner, S., Praher, P., 2022. Log File Anomaly Detection Based on Process Mining Graphs, in: Kotsis, G., Tjoa, A.M., Khalil, I., Moser, B., Taudes, A., Mashkoor, A., Sametinger, J., Martinez-Gil, J., Sobieczky, F., Fischer, L., Ramler, R., Khan, M., Czech, G. (Eds.), Database and Expert Systems Applications - DEXA 2022 Workshops. 33rd International Conference, DEXA 2022, Vienna, Austria, August 22–24, 2022, Proceedings, vol. 1633, 1st ed. 2022 ed. Springer International Publishing; Imprint Springer, Cham, pp. 383–391.

[25] Birk, A., Wilhelm, Y., Dreher, S., Flack, C., Reimann, P., Gröger, C., 2021. A Real-World Application of Process Mining for Data-Driven Analysis of Multi-Level Interlinked Manufacturing Processes. Procedia CIRP 104, 417–422.

[26] Flack, C., Dreher, S., Birk, A., Wilhelm, Y., 2020. Process Mining in der Produktion: Spezifische Herausforderungen bei der Anwendung. Zeitschrift für wirtschaftlichen Fabrikbetrieb 115 (11), 829-833.

[27] van der Aalst, W.M.P., Park, G., 2020. A general framework for action-oriented process mining. Business Process Management Workshops: BPM 2020 International Workshops, Seville, Spain, September 13–18, 2020, 206–2018.

[28] Weerdt, J. de, Schupp, A., an Vanderloock, Baesens, B., 2013. Process Mining for the multi-faceted analysis of business processes—A case study in a financial services organization. Computers in Industry 64 (1), 57–67.

Biographies

Dino Hardjosuwito has been working at the Institute for Industrial Management (FIR) at RWTH Aachen University since 2020, first as a project manager and since 2021 as head of the group Production Planning in Production Management. He works on the ProMiConE research project to make the application of process mining more affordable to small and medium-sized enterprises.

Fynn L. Braucks studied Business Administration and Engineering specializing in Mechanical Engineering at the RWTH Aachen University and KTH Royal Institute of Technology. He is a student assistant in the Production Management department of the Research Institute for Rationalization (FIR) at the RWTH Aachen and works on the ProMiConE research project.

Tobias Schröer 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.

Christopher T. Schwanen is a research associate in the Process and Data Science (PADS) group at RWTH Aachen University. His research interests include business process optimization, operations research, and disruption management. With the research project ProMiConE he contributes to strengthening the application of process mining in small and medium-sized enterprises.

Wil M.P. van der Aalst is a full professor at RWTH Aachen University, leading the Process and Data Science (PADS) group. He is also the Chief Scientist at Celonis, part-time affiliated with the Fraunhofer FIT, and a member of the Board of Governors of Tilburg University. Currently, he is also deputy CEO of the Internet of Production (IoP) Cluster of Excellence and co-director of the RWTH Center for Artificial Intelligence. In 2018, he was awarded an Alexander-von-Humboldt Professorship.

5th Conference on Production Systems and Logistics

Assessment of a Novel Process to Enable Roll-to-roll Production of Catalyst Coated Membranes

Achim Kampker[1], Heiner Heimes[1], Mario Kehrer[1], Sebastian Hagedorn[1], Niels Hinrichs[1*], Philip Heyer[1]

[1]*Chair of Production Engineering of E-Mobility Components (PEM) of RWTH Aachen University, Bohr 12, 52072 Aachen, Germany*
**Corresponding Author*

Abstract

Hydrogen is becoming an increasingly important energy carrier within the next few years for different applications within different industries, such as chemical industry, steel production or mobility. Furthermore, it can be used to store excess energy from renewable energy plants. Within this context, proton exchange membrane-electrolyzer and -fuel cells represent integral parts of this value chain, as they are responsible for hydrogen production and its reconversion to electricity. Both technologies have in common that they need a catalyst coated membrane (CCM) to enable the electrochemical conversion. Since nowadays electrolyzer and fuel cell production is still characterized by small-scale production processes, suitable large-scale production lines will be necessary for the market ramp-up. To address these challenges, a novel coating process to produce CCMs is proposed by using a re-coatable transfer belt at which the catalyst ink is coated and dried first. Afterwards, the catalyst ink is transferred onto the membrane by applying a hot-pressing process. Within the presented research, the hot-pressing process is focussed and assessed for the proposed concept. Therefore, the upstream production processes, such as catalyst ink production, coating and drying are described. A design of experiments is then conducted to investigate the applied process parameters within the hot-pressing process and optimized parameters are analysed. Afterwards, re-coating the transfer belt is tested, and the long-term usability of the employed belt is assessed by focussing structural changes.

Keywords

Electrolyzer Production; Fuel Cell Production; Catalyst Coated Membrane; Decal coating; Roll-to-roll-production; Industrialization

1. Introduction

Industrial production of electrolyzers and fuel cells is still characterised by manufactory production, which is why their production is associated with high costs. To contribute to the market ramp-up of the electrolyzer and the fuel cell, the optimisation of CCM production represents a lever. The CCM is the component where the electrochemical reactions take place. There is cost potential in CCM production due to expensive materials on the one hand, and on the other hand, higher production speeds with consistent quality must be achieved to be able to serve the projected volumes. To address these challenges, an alternative coating process for the membrane of an electrolyzer and a fuel cell is proposed and validated within individual tests, whereby the fuel cell is used as a use case in the context of this paper. The overall objective is to be able to draw conclusions about the development process of the production equipment within the framework of preliminary tests and thus to derive measures for the production equipment development process.

DOI: https://doi.org/10.15488/15242
ISSN: 2701-6277

2. Properties and production of catalyst coated membranes

2.1 Fundamentals of fuel cell catalyst coated membranes

The proton exchange membrane fuel cell (PEMFC) is an electrochemical energy converter in which the chemical energy of the hydrogen fuel is continuously converted into electrical energy. The individual cell consists of multiple functional layers with the components: Two bipolar half-plates, two gas diffusion layers (GDL), two catalyst layers (CL) and one polymer electrolyte membrane. The CLs applied to the membrane form the catalyst coated membrane (CCM), which is the core component of the PEMFC and the location of the electrochemical reaction. The material properties of the components, the interconnection of membrane and CLs as well as the structure of the CLs have a great influence on the performance and lifetime of the cell and therefore make special demands on the manufacturing steps of the CCM.

The CL applied to the membrane is a heterogeneous porous layer and consists of catalyst particles, carbon support particles and ionomer on the anode and cathode side. Usually, platinum particles (Pt) or platinum alloys with cobalt (PtCo) or nickel (PtNi) are used as catalysts on the cathode side [1], [2]. Since the oxygen reduction reaction of the cathode is considerably slower than the hydrogen oxidation reaction of the anode, the platinum loading of the cathode is higher and its CL thicker than that of the anode [3]. Commercial CCMs typically have a total charge of about 0.4 mgPt/cm^2 [4]. The carbon support particles are soot particles with a size of about 50 nm, and Vulcan XC-72 and high-surface-area carbon (HSC), e.g. Ketjenblack [5], are usually used. HSC is less hydrophobic, has a higher internal porosity and a surface area about 4 times larger than Vulcan [6]. Hence, in Vulcan based catalysts most of the Pt particles are on the external surface and in HSC catalysts a large part is in the inner pores [7]. The ionomer is a PFSA polymer and serves as a binder between the particles in the CL and provides electrochemical activity by enabling proton transport to the membrane [8]. The described components catalyst and ionomer together with the reactive gas form the performance-determining triple phase boundary within the CL [9].

2.2 Production of catalyst coated membranes

The performance and the described morphology of the CCM is not only dependent on the material selection and composition of the components, but is also influenced by the manufacturing processes, e.g., mixing, coating and drying. The production strategies are differentiated by the substrate on which the ink is applied and dried. In the CCM-based approach, a distinction can be made between direct and indirect coating of the membrane. With direct coating, the ink is applied directly to the membrane, but swelling of the membrane by the water and solvent in the ink is problematic. In indirect coating, the ink is applied to a carrier film, also called decal film, and dried afterwards. The dry CL on the decal film is transferred to the membrane in a further hot-pressing step. [10] Next to the CCM-based approach, coating the GDL is also applicable. The resulting gas diffusion electrode (GDE) is connected to the membrane by hot-pressing; in this case, no CCM is produced. [11] Due to the industrial relevance, the following explanations refer to indirect decal coating. To enable the application of CLs to the decal substrate, a catalyst ink is first prepared in which the CL components Pt nanoparticles supported on carbons (Pt/C) and ionomer are brought into a liquid form. For this purpose, the CL components are mixed in a water/alcohol solution, whereby the exact formulation of the ink determines the microstructure of the catalyst ink. In addition to the formulation, the dispersion process also has an influence on the microstructure. This further determines the macroscopic properties of the ink, such as the rheology, surface tension and stability.[12] With regard to a roll-to-roll process, which is necessary for the further industrialization of fuel cell production, squeegee coating, slot die coating and gravure printing are particularly suitable as coating processes, as with these only one thick homogeneous wet film is applied to the substrate. In particular, slot die coating and gravure printing are investigated in the literature for the production of CLs in roll-to-roll production. [13], [14], [15], [16] In the following drying process, the solvent evaporates from the wet layer of the CL and the morphology of the dry CL is formed.

The evaporation rate of the solvent in particular influences the drying process, with temperatures between 40 °C and 80 °C often being used. [17], [18] The dry CL is then transferred from the decal film to the membrane by applying increased pressure and temperature. The aim is to achieve the highest possible transfer rate from the decal to the membrane and a good bonding between the CL and the membrane. Most publications consider the discontinuous case of a decal transfer in a hot press in batches with the process parameters pressure, temperature, and time. Only the publications by MEHMOOD ET AL. and FRÖHLICH consider the decal transfer as a continuous process with a roller press or calender, using the process parameters of line pressure, temperature and line speed as characterising variables. [11], [19], [20], [21]

3. Introduction to the novel process and objective

3.1 Description of the novel coating process

The innovative coating process is based on the traditional decal process that is described above. The aim is to save material costs compared to the reference process for the decal material that is used once and then disposed of, and to eliminate the external transfer process, which takes place in an additional process step, and consequently to realise a compact design. The key innovation is a re-coatable, continuous woven and jointless transfer belt. The transfer belt serves as a decal substrate, similar to the decal process, but is directly recoated after the transfer process and runs repeatedly through the entire production process.

The transfer belt passes through the coating, drying, transfer and reuse steps repeatedly. The coating is carried out by a slot die, whereby the substrate is supported by a precision roller and the slot die can be moved to a short distance from the substrate. The catalyst ink is applied to the transfer belt in a homogeneous wet film. After coating, the coated transfer belt passes the drying process. In order to achieve the most compact system design possible and to keep the length of the transfer belt short, infrared drying is used instead of a convection dryer. Compared to convection drying, infrared drying is compared by a much higher heat transfer capacity. Thus, a higher amount of energy can be transferred to the substrate in a shorter time and at lower temperatures. In addition, the infrared radiation diffuses deep into the substrate and the solvents evaporate quickly and effectively.[22] Thus, drying via infrared requires less space compared to convection drying [23]. After drying, the transfer belt passes through the transfer step, in which the transfer belt coated on one side is fed into the calender via a roller. A second roller feeds the membrane. By adjusting the rollers to each other, the necessary line load for the transfer is applied. Additionally, tempering of both rollers ensures the required temperature input for the transfer process. Finally, the transfer belt is guided out of the calender and undergoes the described process again until it is necessary to replace the transfer belt. The one-sided coated membrane is wound up after the transfer, turned and coated on the uncoated side with adapted process parameters, since the anode and cathode of a fuel cell differ from each other, particularly regarding the platinum loading, and optionally also about the used catalyst types.

3.2 Objective

To evaluate the proposed coating process, it is necessary to assess both the technical and economic feasibility of the concept. Hence, a preliminary validation is carried out, whereby the focus in this paper is placed on the technical feasibility. After reviewing the process described above, several questions arise that need to be considered in order to be able to make a statement regarding the technical feasibility:

1)	How is the coatability of the circulating transfer belt and can a sufficient drying process be conducted?
2)	Which process parameters (line pressure, temperature, and line speed) should be applied to realise the highest possible transfer rate within a continuous production?
3)	Which impact does a continuous utilization of the transfer belt has onto the produced CCM and onto the transfer belt itself?

As only the technical feasibility of the process itself is to be investigated, convection drying is used for the drying process, which differs from the described infrared dryer. The investigation of infrared drying will be described in a separate document in the future.

4. Experimental to assess the technical feasibility of the novel coating process

4.1 Assessment of the coatability of the transfer belt

The aim of the investigations is to prove the coatability of the transfer belt with the aim of a defect-free dry dummy CL on the transfer belt. The aim is to achieve the highest possible dry film thickness and carbon loading to simulate cathode layers. For ink production, VULCAN® XC72-R Carbon Black from Carbot is dispersed with ionomer dispersion Aquivion® D83-24B from Solvay S.A., as well as the alcoholic solvent 2-propanol from neoFroxx GmbH or 1-propanol ROTIPURAN® ≥ 99.5% from Carl Roth GmbH together with distilled water. The dispersion is carried out in an ultrasonic bath of the type of Emmi-30HC from Emag AG or by a dissolver of the type DISPERMAT LC75 with a dissolver disc with a diameter of 30 mm from VMA-Getzmann GmbH. A transfer belt made of PTFE-coated glass fibre mesh of the type Fiberflon® 216.13 with a thickness of 125 µm from Fiberflon GmbH is coated by squeegee coating. The coating is applied with an automatic film applicator type ZAA 2600 and squeegee type ZUA 2000 with a width of 220 mm from Zehntner GmbH Testing Instruments. Drying is carried out either at room temperature, on a heating plate of the film applicator or in a heating and drying oven with natural convection of the type of ED 240 from Binder GmbH. The coatability is investigated by iterative layer optimisation with the ink formulations from Table 1. The solids content includes the Vulcan and the dry ionomer.

Table 1: Ink compositions to assess the coatability

Nr.	Ionomer/Carbon (I/C) [wt.%]	Solvent	Solids content [wt.%]	Solvent/H_20 [wt.%]
R1	1.13	2-Propanol	13.17	1.358
R2	1.13	2-Propanol	20	1.358
R3	0.7	1-Propanol	12.75	3
R4	1	2-Propanol	13	3.227

4.2 Assessment of the transfer rate

A GK 300 L laboratory calender from Saueressig is used for the roll-to-roll transfer. In the test set-up, both rolls are heated. The one-sided transfer of a CL onto the membrane is investigated analogous to the described system concept. In the test set-up, roll-to-roll delamination is carried out with a pretension of 1.42 N/cm and a steep peel angle. The used membrane is a fumapem® FS-715-RFS from Fumatech BWT GmbH. It is a PFSA cation exchange membrane in H^+-form with reinforcement with a thickness of 13 – 17 µm. The aim of the investigations is to determine a suitable process window of the transfer, which is why a two-stage, full-factorial experimental design with the three factors temperature, line load and line speed was chosen.

The target variable to be investigated is the transfer rate, i.e., the proportion of CL transferred from the transfer belt to the membrane. Table 2 summarises the selected factor stages.

Table 2: Factor stages of the DoE to investigate the process window of the transfer

Parameter	Lower value	Upper value
Temperature (T) [°C]	150	180
Line load (Q) [N/mm]	22	57
Line speed (V) [m/min]	0.5	2

A defined coating area of the dummy CL of 220 x 70 (W x L) mm is produced on transfer belt sheets with the dimensions 290 x 200 (W x L) mm. In the transfer, a layer of coated transfer belt, membrane, and another transfer belt, to protect the membrane from the calender rollers, is fed through the calender. The transfer rate is then determined using an optical process by applying a photo evaluation and a Matlab script.

4.3 Assessment of the re-coatability of the transfer belt

For the re-coating experiments, one sheet of the transfer belt is cyclically coated, and the layer is transferred to the membrane in the calender transfer. The coated area of the transfer belt is not cleaned in between the cycles to investigate to what extent cleaning is required for the equipment concept. A total of 15 cycles are performed. For each cycle, the transfer rate is determined and used as a criterion for re-coatability. T = 180 °C, V = 0.5 m/min and Q = 57 N/mm are used as transfer parameters, as the best transfer was determined for these in the previous investigations. Formulation R4 with an I/C = 1 is used for the coating. After completion of the repeat tests, the surface of the transfer belt is examined regarding changes. In addition, the mechanical stability and expected service life of the transfer belt are investigated by cyclic calendaring, since the highest thermal and mechanical stress is exerted in the calendering step. For this purpose, a transfer belt sheet is calendered 50 times. Therefore, two different parameter sets (Q = 57 N/mm, T = 180 °C, V = 0.5 m/min and Q = 22 N/mm, T = 180 °C, V = 0.5 m/min) are examined with one sheet each. The basis weight and thickness distribution of the transfer belt are used as criteria for evaluating potential material changes due to the mechanical impact in the transfer belt. To quantify these changes, the assessment of the basis weight and thickness distribution was examined before and after calendering.

5. Results

5.1 Coatability of the transfer belt

First, the dispersing process is carried out and the viscosity of the catalyst inks produced is examined with a rheometer. Basically, it is recognised that the ionomer in the catalyst ink swells and consequently leads to an increase in viscosity. The swelling behaviour and the associated increase in viscosity is generally dependent on the equivalent weight (EW) of the ionomer, the temperature and time. Stronger swelling behaviour is observed for lower EWs, higher temperatures and longer durations. In addition depending on the dispersion method, agglomerates of different sizes are formed, which influence the subsequent ink application on the substrate. Furthermore, solvent evaporation leads to the fact that the processability of the ink is no longer given if the dispersion time is too long. After the catalyst ink has been applied to the substrate and subsequently dried, a correlation between crack formation and squeegee height or wet film thickness can be identified. For example, while significant cracking can be observed for formulation R1 with a squeegee height of 200 µm, only small surface cracks occur with a squeegee height of 100 µm. In contrast, crack-free layers can be produced with formulation R3 up to 150 µm, which can be attributed to the use of 1-propanol as a solvent. The carbon loading produced here is 0.75 mg/cm^2. With formulation R4, layer thicknesses of up to 100 µm can be produced without defects and with carbon loadings of 0.52 mg/cm^2. In addition to the wet film thickness, the solids content is identified as a further influencing factor on the film quality and thus in particular on crack formation. Solids contents that are too high cannot be processed with the squeegee coating. Thus, for recipe R2 with a solids content of 20 wt.%, a crack-free layer cannot be produced even with squeegee heights of 100 µm, whereas this is possible for the other recipes. Furthermore, the subsequent drying also influences the layer quality. After drying at room temperature of approximately 23 °C, the dry CL of an ink of formulation R4 exhibits a stubborn crack structure with crack widths of 40 µm and clod formation. In contrast, an identical comparison sample dried in a heating cabinet at 90 °C shows no cracks. This effect is also observed in the comparison of drying at room temperature and drying on the hot plate at 85 °C, as well as for formulations R1 and R2. Higher drying temperatures therefore seem to reduce cracking for this system, as controlled evaporation of solvent and water is made possible. Taking the described effects into account, a defect-free layer can be produced on the transfer belt, which is used for the transfer rate investigation.

5.2 Transfer rate

The corresponding process windows that characterize the transfer process are shown in Figure 1. From the left diagram, the effective relationship of the factors temperature and line load on the transfer rate can be derived, while the speed is maintained. Thus, the transfer rate can be significantly increased to higher temperatures and line loads. For low values (T = 155 °C and Q = 30 N/mm), only a low transfer rate < 40 % is achieved. When increasing these values (T >175 °C and Q > 47 N/mm), transfer rates > 90 % can be realized. This also shows the somewhat stronger effect of temperature on the transfer rate compared to the line load. The dependence of speed and line load is shown in the middle of Figure 1, where the holding value is assumed to be T = 165 °C. The positive influence of the line load on the transfer rate can also be seen, while at the same time the transfer rate decreases with increasing speed. Due to the steeper course of the effective surfaces, it can also be seen that the line load has a higher influence on the transfer rate than the speed. For a given Q = 57 N/mm, this results in a wide speed range of 0.5 – 2 m/min at which a transfer rate > 80 % can be achieved, which is very positive for the economic efficiency of the process.

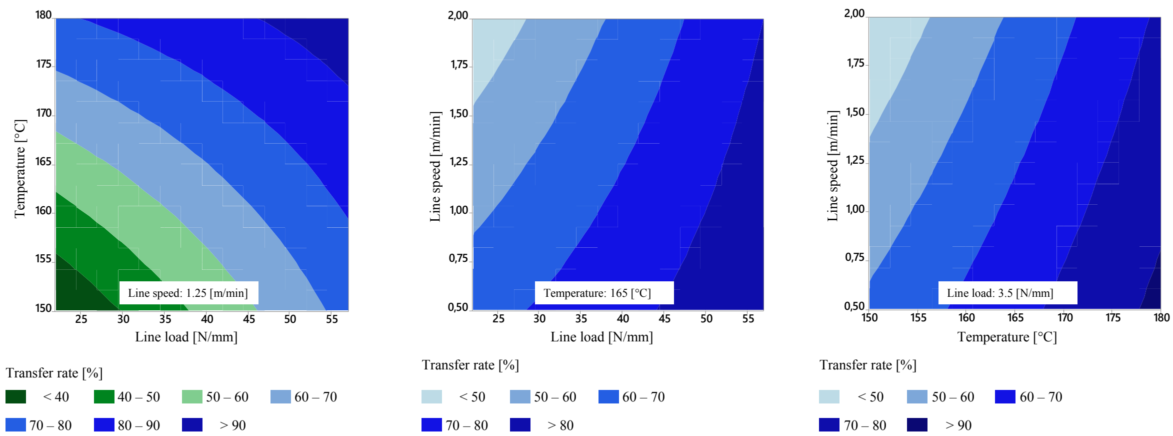


Figure 1: Evaluation of the transfer rates through process windows

The process window as a function of speed and temperature at constant line load (Figure 1, right) is analogous to the one in the middle, but the effective surfaces are even steeper, which on the one hand underlines the stronger influence of the temperature on the transfer rate compared to the line load and on the other hand shows the significantly stronger influence of the temperature compared to the speed. For a selected temperature, this therefore results in a larger speed range with the same transfer rate. Thus, at high temperatures, high transfer rates can also be achieved at high speeds. If T = 180 °C is chosen, a transfer rate > 90 % can be achieved up to a speed of 0.75 m/min. Accordingly, it can be concluded against the background of the examined transfer rate that the described concept can be operated with economic parameters. By having a more profound look onto the steepness and formation of the shown diagrams in Figure 1, the impact of the three parameters can be ranked. The temperature has the greatest influence on the transfer rate, line load the second greatest and speed the third greatest.

5.3 Re-coatability of the transfer belt

The regression line in Figure 2 (left) clearly shows the decreasing trend of the transfer rate. In addition to the decreasing transfer rate, a greater spread of the transfer rate of directly sequential runs can also be observed for the increasing reuse. Accordingly, the process stability of the transfer also decreases with increasing reuse. In addition, punctual residues of the CL remain on the surface of the substrate, which are transferred cyclically to the membrane. This leads to a heterogeneous layer pattern on the membrane. In addition, with the number of repetitions, an increasing adhesion can be seen during delamination, which eventually leads to a less controlled and more abrupt process. This can be explained by residues of ionomer on the transfer belt, from which veils can be seen on the substrate. The described veils ultimately cause the surface energy of the substrate to increase to > 40 mN/m in some cases, drastically limiting adhesion with the catalyst ink. However, cleaning the transfer belt with isopropanol leads to the surface being cleaned in such a way that the original state is restored.

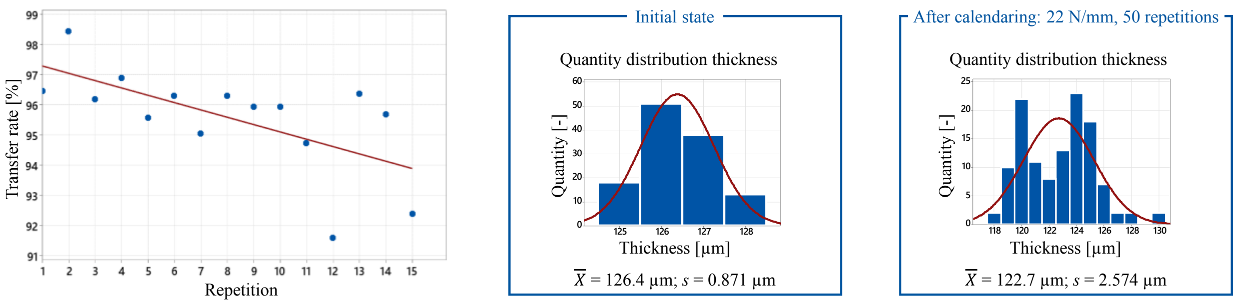


Figure 2: Performance of the re-coating experiment and assessment of the mechanical stability of the transfer belt

In addition to the residues remaining on the transfer belt, an increasing deformation of the transfer belt can be observed with the runs. The mean value of the thickness in the initial state is 126.4 µm. With a standard deviation of 0.871 µm, the spread is low, the measured values scatter between 125 and 128 µm. The frequency distribution follows that of a normal distribution, manufacturing-related systematic inhomogeneities can therefore not be detected and not observed in the surface diagram (Figure 2, centre). Subsequently, the repeat tests in the calender follow, whereby a deformation of the transfer belt can already be seen after 25 repetitions. Thus, starting from the centre towards the outer edges, wave formation occurs. After 50 repetitions, the wave formation is already so pronounced that coating would no longer make sense. The fact that the deformation starts from the centre is most likely due to the inhomogeneous pressure distribution across the width of the calender. Thus, the centre is compressed more than the edge zone, which causes the deformation. Furthermore, an increasing deformation can be seen in the image plane, this is the side with which the transfer belt is inserted into the calender. The larger deformation can be explained by start-up effects. Frequent start-up of the belt should therefore be avoided for the equipment concept. The thickness distribution after the 50 repetitions is shown in Figure 2, right. The mean value of the thickness is reduced to 122.7 µm and the standard deviation is increased to 2.574 µm resulting in a more heterogeneous belt structure.

6. Conclusion

In this paper, an alternative coating concept is evaluated regarding its technical feasibility. For this purpose, three questions were raised concerning the coatability, the process parameters of coating transfer and the reusability of a transfer belt. The criterion used for the coatability of the transfer belt is to be able to produce a defect-free, homogeneous, and dry CL on the transfer belt. In this context, not only the wettability in the coating, but also in particular the wettability and adhesion between ink and transfer belt in the drying process turns out to be particularly relevant. The main influencing factors here are the wet film thickness, the water-to-alcohol ratio of the ink, solids content, ink production and the drying temperature. However, overall, crack-free layers with dummy material and sufficient basis weight corresponding to that of a cathode layer on the transfer belt could be produced with a suitable ink formulation and drying parameters. In general, high transfer rates could be achieved in a one-sided roll-to-roll transfer analogous to the planned system concept. A higher line load and temperature as well as a lower speed increase the transfer rate. During the tests, an inhomogeneous pressure distribution of the calender was determined, with a strong pressure drop towards the roll edges, which is why no more transfer could take place in the edge zone. With an edge zone correction to eliminate these inhomogeneities, a transfer rate of > 99.99 % can be achieved with the parameters $Q = 57$ N/mm and $T = 180$ °C at $V = 2$ m/min. Hence, it was possible to prove line speeds that are a factor of 20 faster than what is known in the literature. The technical feasibility of the roll-to-roll transfer with the transfer belt is thus assessed as fulfilled. According to the results on the reuse of the transfer belt, a decreasing transfer rate can be observed with an increasing number of reuses. This is accompanied by an increasing dispersion of the transfer rate, which means a decreasing process stability. The reason for this can be identified as ionomer that is remaining on the transfer belt. These residues lead to increasing adhesion between CL and transfer belt and thus to a more difficult delamination. Furthermore, a partial transfer of the ionomer veil, which accumulates on the transfer belt surface, to the CCM takes place. This then covers the surface of the CCM, which will negatively influence the mass transfer of the reactants into the CL during cell operation. In addition, the mechanical impact of the calender leads to deformations after frequent reuse of the substrate. Accordingly, the results of reusing the transfer belt show further potentials that contribute to the optimization of the proposed process. Thus, on the one hand, the delamination behaviour of the CL must be optimized, which must be homogeneous even after several cycles. In addition, the equipment design should be rethought to the extent that cleaning of the transfer belt is necessary. To further answer these questions, the presented findings can be used, as the correlation between ink composition and layer production was studied. Furthermore, the transfer properties were extensively investigated and quantified.

Acknowledgement

This research was funded by Federal Ministry for Economic Affairs and Climate Action, Germany grant number 03EN5013A-FCPP.

References

[1] Borup, R.L., Kusoglu, A., Neyerlin, K.C., Mukundan, R., Ahluwalia, R.K., Cullen, D.A., More, K.L., Weber, A.Z., Myers, D.J., 2020. Recent developments in catalyst-related PEM fuel cell durability. Current Opinion in Electrochemistry 21, 192–200.

[2] Xing, W., 2008. Catalyst Layer Composition Optimization, in: Zhang, J. (Ed.), PEM fuel cell electrocatalysts and catalyst layers. Fundamentals and applications. Springer, London, Heidelberg, pp. 1003–1040.

[3] Dicks, A., Rand, D.A.J., 2018. Fuel cell systems explained, Third edition ed. John Wiley & Sons Inc, Hoboken, New Jersey, 460 pp.

[4] Xie, M., Chu, T., Wang, T., Wan, K., Yang, D., Li, B., Ming, P., Zhang, C., 2021. Preparation, Performance and Challenges of Catalyst Layer for Proton Exchange Membrane Fuel Cell. Membranes 11 (11).

[5] Chowdhury, A., Darling, R.M., Radke, C.J., Weber, A.Z., 2019. Modeling Water Uptake and Pt Utilization in High Surface Area Carbon. ECS Trans. 92 (8), 247–259.

[6] Padgett, E., Andrejevic, N., Liu, Z., Kongkanand, A., Gu, W., Moriyama, K., Jiang, Y., Kumaraguru, S., Moylan, T.E., Kukreja, R., Muller, D.A., 2018. Editors' Choice—Connecting Fuel Cell Catalyst Nanostructure and Accessibility Using Quantitative Cryo-STEM Tomography. J. Electrochem. Soc. 165 (3), F173-F180.

[7] Berlinger, S.A., Garg, S., Weber, A.Z., 2021. Multicomponent, multiphase interactions in fuel-cell inks. Current Opinion in Electrochemistry 29, 100744.

[8] Holdcroft, S., 2014. Fuel Cell Catalyst Layers: A Polymer Science Perspective. Chem. Mater. 26 (1), 381–393.

[9] Khandavalli, S., Park, J.H., Kariuki, N.N., Myers, D.J., Stickel, J.J., Hurst, K., Neyerlin, K.C., Ulsh, M., Mauger, S.A., 2018. Rheological Investigation on the Microstructure of Fuel Cell Catalyst Inks. ACS applied materials & interfaces 10 (50), 43610–43622.

[10] Wilson, M.S., Gottesfeld, S., 1992. High Performance Catalyzed Membranes of Ultra-low Pt Loadings for Polymer Electrolyte Fuel Cells. J. Electrochem. Soc. 139 (2), L28-L30.

[11] Frölich, K., 2015. Der Decal-Prozess zur Herstellung katalysatorbeschichteter Membranen für PEM-Brennstoffzellen. Dissertation, Karlsruher Institut für Technologie (KIT).

[12] 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), 3776.

[13] Siegel, F., 2015. Tiefdruckverfahren zur Herstellung von Katalysatorschichten für (PEM) Brennstoffzellen, Chemnitz.

[14] Mauger, S.A., Wang, M., Medina, S., Pylypenko, S., Ulsh, M., 2019. Influence of Coating Method on Performance of Roll-to-Roll Coated PEM Fuel Cell Catalyst Layers. https://www.nrel.gov/docs/fy20osti/77815.pdf. Accessed 15 February 2023.

[15] 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. J Coat Technol Res 15 (6), 1423–1432.

[16] Liu, P., Li, B., Yang, D., Zhang, C., Ming, P., 2023. New insights on the agglomeration and sedimentation behaviours of catalyst ink of proton exchange membrane fuel cells affected by ionomers concentration. Journal of Power Sources 556, 232427.

[17] Suzuki, T., Tanaka, H., Hayase, M., Tsushima, S., Hirai, S., 2016. Investigation of porous structure formation of catalyst layers for proton exchange membrane fuel cells and their effect on cell performance. International Journal of Hydrogen Energy 41 (44), 20326–20335.

[18] 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, 230039.

[19] Mehmood, A., Ha, H.Y., 2013. Parametric investigation of a high-yield decal technique to fabricate membrane electrode assemblies for direct methanol fuel cells. International Journal of Hydrogen Energy 38 (28), 12427–12437.

[20] Mehmood, A., Ha, H.Y., 2012. An efficient decal transfer method using a roll-press to fabricate membrane electrode assemblies for direct methanol fuel cells. International Journal of Hydrogen Energy 37 (23), 18463–18470.

[21] Gatto, I., Saccà, A., Baglio, V., Aricò, A.S., Oldani, C., Merlo, L., Carbone, A., 2019. Evaluation of hot pressing parameters on the electrochemical performance of MEAs based on Aquivion® PFSA membranes. Journal of Energy Chemistry 35, 168–173.

[22] Lambda Technology. Technologie. https://lambdatechnology.com/wellenlaenge-physik/. Accessed 23 April 2023.

[23] Wöll, J., 2018. Platz, Zeit und Energie sparen. J Oberfl Techn 58 (1), 14–17.

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. From March 2019 to 2023, he was PEM's Executive Chief Engineer before being appointed Professor.*

***Mario Kehrer** (*1990) studied electrical engineering and information technology at Karlsruhe Institute of Technology (KIT). He joined the chair "Production Engineering of E-Mobility Components" (PEM) of RWTH Aachen University in 2017, where he became chief engineer of the Fuel Cell and Electrification Engineering division in 2021.*

***Sebastian Hagedorn** (*1992) 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.*

***Niels Hinrichs** (*1996) is research assistant at the Chair of Production Engineering of E-Mobility Components (PEM) at RWTH Aachen University. He studied mechanical engineering with a focus on energy and process engineering at Ruhr-University Bochum.*

***Philip Heyer** (*1994) studied industrial engineering with a focus on production engineering at RWTH Aachen University. Heyer worked as a research assistant and completed master's degree with a master thesis at the Chair of Production Engineering of E-Mobility Components (PEM) at RWTH Aachen University.*

CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
CPSL 2023-2

5th Conference on Production Systems and Logistics

Contamination Control for Sensitive Products in the Era of Electrified Vehicles

Patrick Brag[1] , Bálint Balogh[2] , and Péter Gordon[3]
[1]Fraunhofer IPA, Nobelstrasse 12, 70569 Stuttgart, Germany
[2]Continental Automotive Hungary Kft., Napmátka u. 6, 1106 Budapest, Hungary
[3]Particle Control Ltd., Egry József u. 18, 1111 Budapest, Hungary

Abstract

With the growing trend toward electric vehicles, technical cleanliness is also taking on a more prominent role. Insufficient component cleanliness can lead to more frequent or more serious defects, and although contamination control tools and techniques are well known, they are not widely used in production. This article describes how contamination control can be systematically planned and integrated into existing production processes. Contamination control is not a stationary state, but rather a dynamic search for Points of Interest (POI). Only when all POIs have been identified does contamination control become continuous monitoring, which ultimately allows the cleanliness requirements specified in the customer-supplier relationship to be verified.

Keywords

Contamination control; particle; electronic; vehicle; safety

1. Introduction

As electrification in the automotive industry progresses, a new era of mobility seems to be emerging, which is already becoming evident in the fields of autonomous driving, connected driving and electric drives [1].

When it comes to new technologies, people tend to be averse to taking risks and consequently have a greater need for safety [2]. Drive batteries or high-voltage components can pose an added risk to the occupants of electric vehicles. Short circuits can cause fires or explosions due to the high voltages involved [3,4]. Among others, these can be triggered by collisions [5] or particulate contamination [6].

The fact that particulate contamination can cause malfunctions or failures is not new [7–9]. As early as 2010, the automotive industry developed a guideline for reducing or monitoring particulate contamination in assembly processes [10]. Component cleanliness inspections are indispensable in this regard [11,12].

The cleanliness inspections are carried out in the laboratory by a specialist and are extremely time-consuming [13]. As a result, in practice only approx. 0.002% - 2% of manufactured parts are tested for cleanliness, meaning that at least 98% of components leave the factory without being tested. This estimate applies to many companies in the automobile industry which manufacture safety-critical components.

DOI: https://doi.org/10.15488/15251
ISSN: 2701-6277

Contamination control becomes inevitable in order to avoid vehicle recalls associated with the risk of shorting due to particles. The ever-increasing miniaturization of electronic circuits and product complexity is constantly increasing the pressure to act.

At present, the automotive industry is faced with the challenge of making contamination control an integral part of quality planning and assurance. Attempts to do so have so far been unsuccessful because the necessary know-how is not equally distributed along the supply chain. This article helps to establish a common understanding and approach by explaining basic aspects of contamination control from an operational perspective.

2. State of knowledge and practice

The number of automotive components which are produced in cleanrooms is constantly rising (e.g. cameras, displays, battery cells, microelectronics, etc.). It therefore seems logical to implement procedures for monitoring airborne contamination [14] or methods for evaluating surface cleanliness [15]. However, there are two reasons why this may not be appropriate. Firstly, there is a discrepancy as regards the relevant particle sizes: a) 0.1 µm to 5 µm in ISO 14644 [16] and b) 5 µm to > 3000 µm in VDA 19.1/ ISO 16232 [11,12]. Secondly, the cleanliness of products manufactured in cleanrooms is not taken into account in the ISO 14644 series of standards [17].

However, contamination control in the automotive and electronics industries is aimed at product-specific cleanliness, which is based on a product's functions or sensitivity [18] and thus differs from other industries and standards. For example, in IEST-STD-CC1246E (formerly: MIL-STD-1246C), product cleanliness levels are defined in a more general way, which can be conducive to the implementation of contamination control [19,17] which can be beneficial when implementing contamination control.

The goal of contamination control is to limit the contamination that occurs during production to a level that is acceptable for the product [20,21].

The first step is to define cleanliness targets for the product [22] as well as for the assembly processes and areas [23]. At the beginning of the product life cycle, this can be achieved with the help of failure mode and effects analysis (FMEA), [22,24] something which is rarely done in practice.

Once the production line is completed, the analyses can be performed to monitor compliance with the defined targets. The early detection of out-of-control events helps to reduce reject rates [25]. In ASTM E1548, some procedures (in connection with aerospace) are mentioned for

- sampling surfaces using the tape lift method, which is comparable to the particle stamp technique from VDA 19.2 [10] (see Figure 5),
- sampling products with the spray flush method, which is comparable to the extraction method of pressure rinsing from VDA 19.1/ ISO 16232 [11,12] or
- analyzing the particle load obtained by one of the two previously-mentioned sampling methods using the light microscope. However, this is technically outdated compared to the automated process described in VDA 19.1/ ISO 16232 [11,12]. [26]

Although some techniques are similar, the aerospace industry differs significantly from the automotive industry, which is cost-sensitive and manufactures in large series. The automotive industry's dilemma is, on the one hand, to produce dependable or safe modules - which is associated with high cleanliness requirements - while on the other hand, to minimize production times and costs. The economic optimum corresponds exactly to the cleanliness requirement which ensures that a component will just still function correctly. So-called fault injection tests are suitable for this purpose [27]. According to the understanding of [22] and [23], robust product design is already an integral part of contamination control.

This holistic understanding of contamination control is far removed from actual practice in the automotive industry. For this reason, the following article is limited to the point in time when the product design has been fixed and the production line is about to go into series production. With the production part approval process (PPAP), there is a need to establish conformity to something that usually has not yet been defined.

3. Initial situation

The following section describes Phases I and II based on the example of the electronic control unit (ECU) for the current generation of hydraulic/ electronic brake control units (HECU), see Figure 1. The procedure can also be applied without restriction to other mechatronic or electronic components.

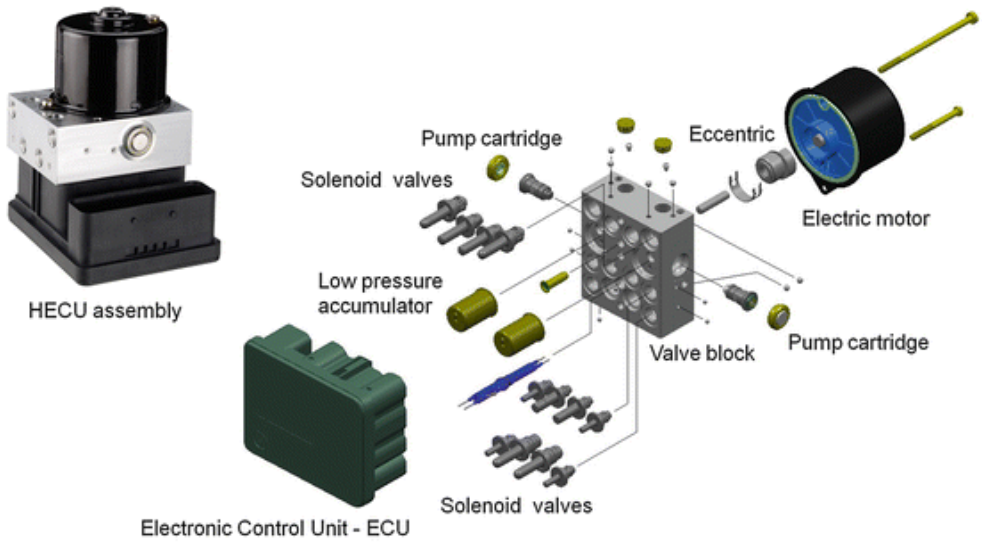


Figure 1: Exploded view of the brake control unit [28]

The HECU controls the anti-lock braking system, electronic vehicle stabilization, and autonomous emergency braking. If the unit has to intervene for any reason, the brake pressure is individually adjusted by the hydraulic valves on each wheel. Particles in the electronics or hydraulic valves could cause a malfunction or failure and cause an accident.

Figure 2 shows the assembly processes for the ECU. This article does not go into further detail about the surface mounted technology line (SMT line) or test line. The risks of particles being generated or transferred on these lines is lower compared to the back-end line.

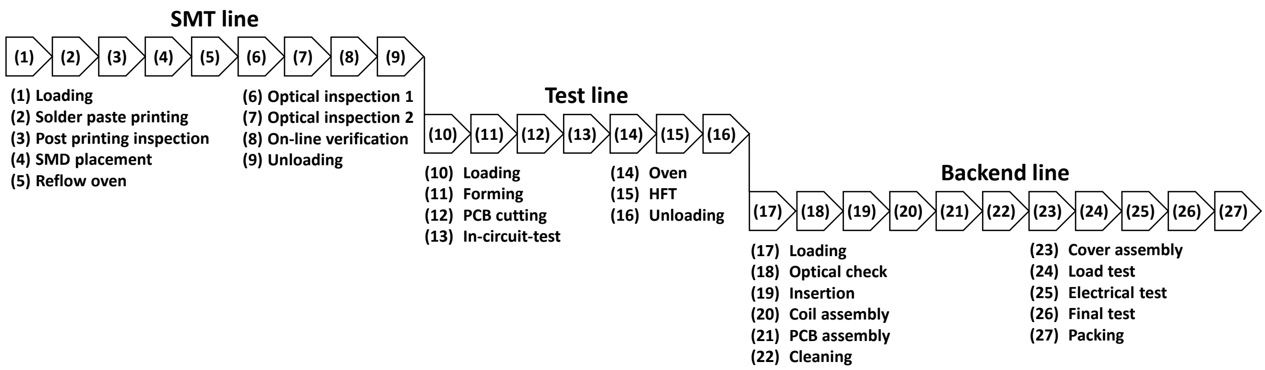


Figure 2: Process chain for assembling the ECU

For the purpose of this article, only Size Class F (100 - 149 µm) is discussed, with a maximum permissible amount of 64 particles. The approach presented here can be transferred to the other size classes. Further criteria are indispensable to complete the cleanliness specification:

a) After which process step does the cleanliness specification apply?
b) To which control areas does the particle size distribution refer?
c) How often must cleanliness be checked?

Unfortunately, in practice these criteria are specified far too rarely, resulting in a potential conflict between the manufacturer and the customer. For example, without specifying a), it is often assumed that cleanliness applies to the End of Line (EOL) - i.e. after Process (27). This assumption is incorrect and a sign of insufficient knowledge about technical cleanliness. The ECU is already closed after Process (23), meaning that only the exterior would be accessible for a cleanliness inspection. If b) is also not specified, this could already cause the conflict to escalate.

The ECU cleanliness specification applies after Process (22), see Fig. 4. Once the cover has been mounted, the relevant inside area is no longer accessible. A cleanliness inspection would then require a mechanical opening of the ECU housing, which is associated with additional residues from the breakage. It is impossible to distinguish between residual assembly particles and residues from the breakage. Therefore, the cleanliness of a component has to be specified at a point where it can be inspected. The particle increase from Process (23) is typically hidden from view**.**

However, additional cleaning processes can also improve cleanliness elsewhere, for example if an EOL cleaning step is not feasible. Since cleaning is a key process, it should always be monitored, cf. Annex A.B.1 in [10]. Consequently, the cleaning processes in Phase I do not need to be taken into account.

In Phase I, expectations and results are constantly compared through new analyses, which gives this phase an iterative character. Conclusions can be drawn from the comparison, which in turn can lead to further tests. Phase I is complete when only little or no further knowledge can be gained.

4. Phase I

The aim of Phase I is to identify critical particle sources or processes. A process is considered as critical if it significantly contributes to the accumulated contamination of the product or if the cleanliness specification is not met.

Depending on the amount of value added and the complexity of the product, Phase I can rapidly become extremely time-consuming or cost-intensive. Therefore, the iterative refinement of the search grid (from coarse to fine) is a compromise to economic constraints, see Figure 3. If a company has little or no experience in this field, expert advice should be sought from production line operators, logistics specialists, etc.

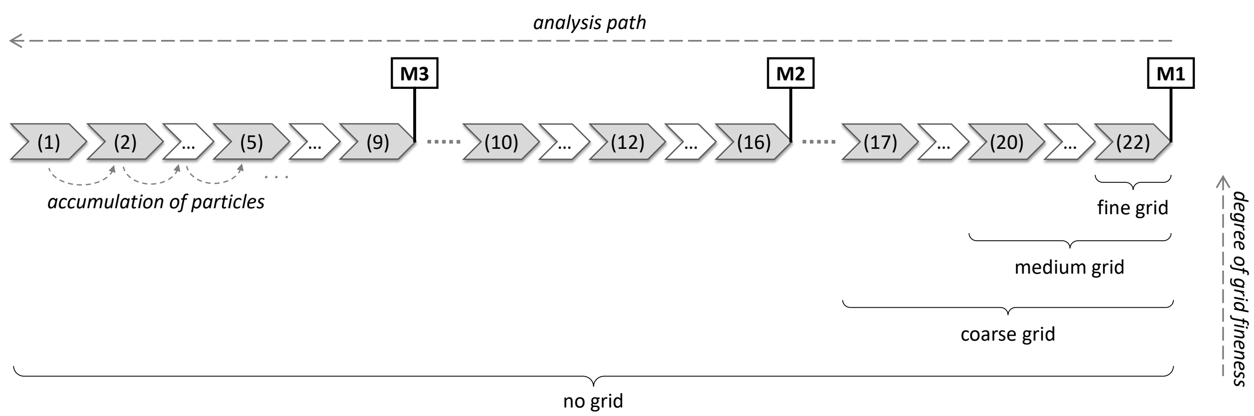


Figure 3: Approach for analyzing the process chain

How much the search grid needs to be refined or which processes should still be examined can only be seen from the previous analysis cycle. The initial analysis cycle could consist of the measurements M1, M2 and M3. In a second cycle, processes (21), (20) and (19) could then be analyzed etc. However, a complete (fine grid) process chain analysis as shown in Figure 4 is rarely found in practice.

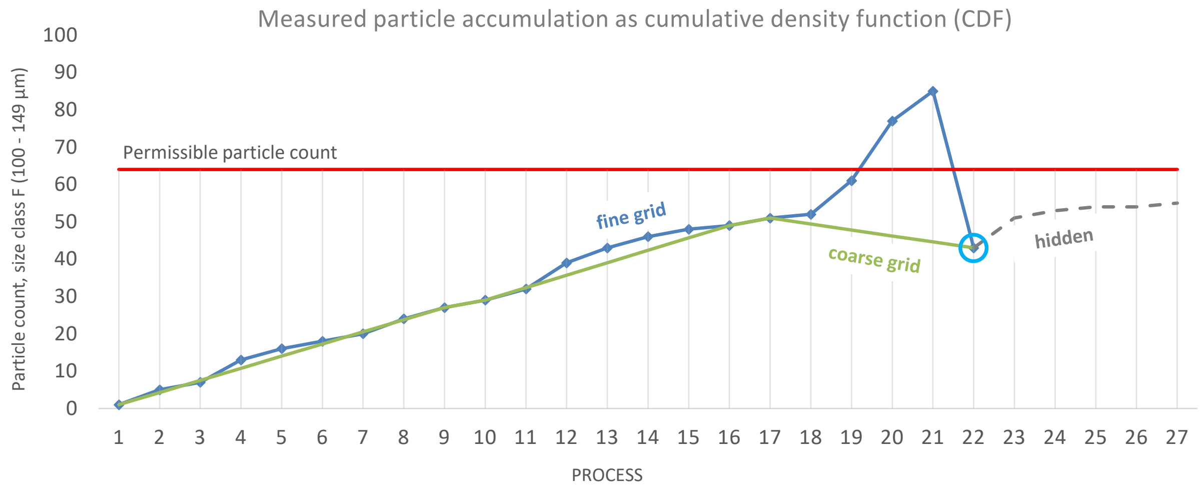


Figure 4: Information density in relation to the search grid

The methods and tools used in Phase I and Phase II are largely identical. Nevertheless, the results from Phase I are not suitable for ratings in the customer-supplier relationship. The analyses carried out in Phase I have an exploratory character, enabling the maximum amount of information to be gained about the process chain as quickly as possible. The following tools can be used in Phases I and II:

Particle traps are an inexpensive and simple tool for measuring the cleanliness of the environment or processes. Particles settling on the adhesive surface are fixed by the adhesive tape and can be analyzed automatically with a light microscope after the trap has been deployed for a certain period of time, such as 5 working days, see Figure 5. [10] Instead of particle traps, particle deposition counters can also be used, which provide measurement data in real time [29].

Particle stamps are a further inexpensive and simple tool for determining the cleanliness of surfaces. The tape is used to remove contamination from the surface, which in turn can be analyzed automatically with a light microscope, see Figure 5. [10]

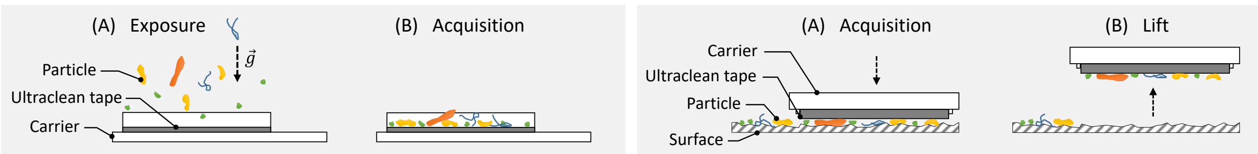


Figure 5: Left: particle trap, Right: particle stamp [30]

Component cleanliness inspections are used to verify the level of cleanliness specified in the customer-supplier relationship and provide the best results as a direct evaluation method. In Phase I, a simplified procedure can be implemented. In Phase II, the component cleanliness inspections must be performed exactly according to VDA 19.1 or ISO 16232. [11,12]

Tracer components tend to be used at the end of Phase I, when the previous results are verified by measuring the contamination generated by the process step. This is done by cleaning the assembly or its individual components in the laboratory until no further residues can be extracted. The assembly then has a defined state of cleanliness, which can be verified in a cleanliness inspection. The assembly is then ready for processing. After the assembly step, another cleanliness inspection is performed, see Figure 6. [10]

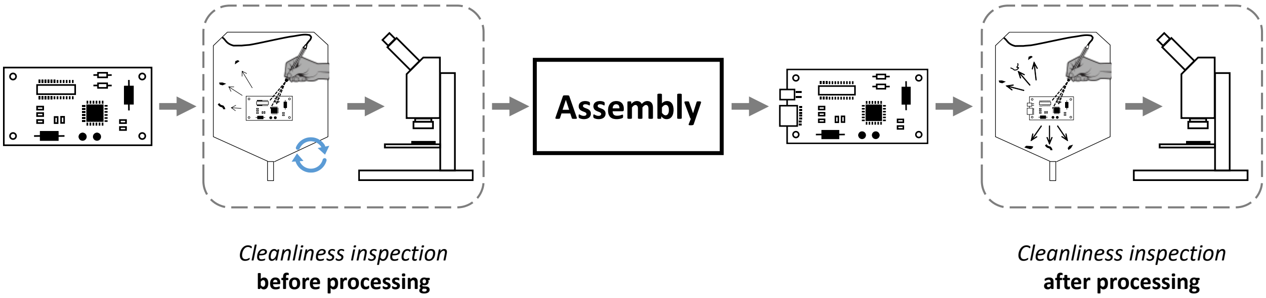


Figure 6: Application of tracer components

Tracer particles have specific properties that make them distinguishable from ordinary contamination in the manufacturing environment. Tracer particles are suitable, for example, for evaluating cleaning results or for visualizing the transfer of contamination due to logistics processes. Figure 7 gives examples of tracer particles.

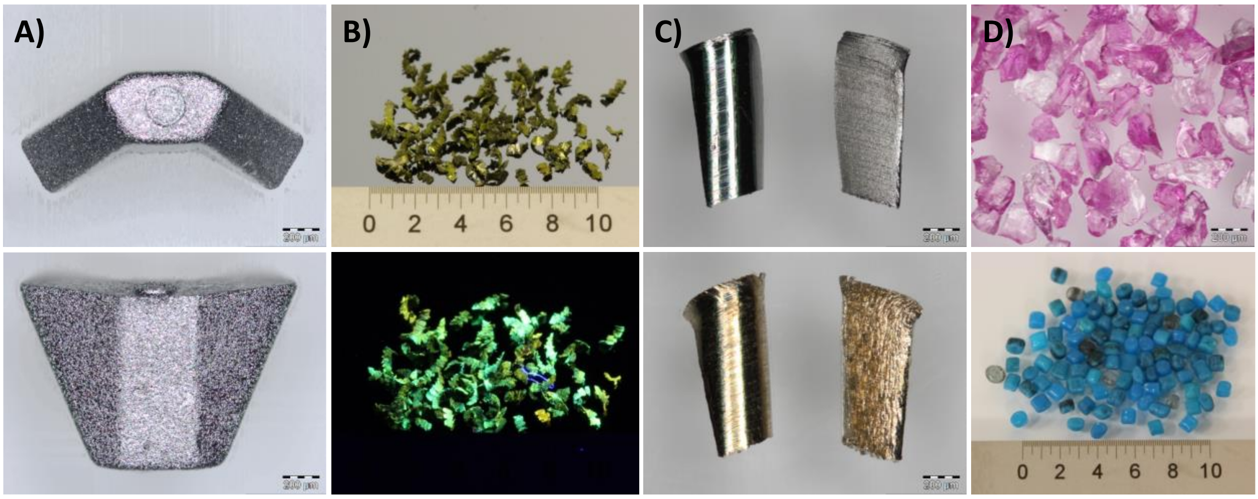


Figure 7: Tracer particles. A) Regular shapes [31]. B) Fluorescent [32]. C) Milled chips [33]. D) Blasting material.

Besides the correct use of the tools, the type of information required from the respective analysis is another important factor. For example, a particle trap mounted underneath the conveyor belt can supply information about the quantity of particles emitted in this area. However, this information is of little help in assessing the cleanliness of the ECU. Such approaches may be useful in Phase I but should be verified by component cleanliness inspections in a further iteration.

Difficulties arise when examining the data from a statistical point of view. As opposed to other features that can be specifically produced, values tend to fluctuate much more when it comes to technical cleanliness, see Figure 8. This is because technical cleanliness is strongly influenced by random events. Therefore, a once-only assessment of component cleanliness is not sufficient.

Verifying inspection results also has another advantage. Should contradictory results arise, information deficits can be better identified, thus stimulating the development of new or further process analysis techniques. Only when additional analyses fail to deliver any further information can the process chain analysis in Phase I be concluded.

The minimalistic approach is a consequence of the high cost pressure prevailing in the automotive industry. However, this does not mean that analyses should be dispensed with. In the case of supplied parts, it is not only their state of cleanliness when they are ready for dispatch at the supplier's and at the point of use that must be monitored. The cleanliness of these parts should also be monitored on arrival at the customer's.

For instance, the coils actuating the hydraulic valves are monitored not only before shipment at the supplier's but also on receipt at Continental and again at Process Station (20). This makes it possible to find out whether the particles originate from internal logistics processes, from external logistics processes or from the supplier's production process.

5. Phase II

Phase II is aimed at long-term process monitoring and at reducing particle sources / emissions. As a rule, Phase II commences once series production is up and running. The respective tools and analysis sites are already known from Phase I. The frequency of analyses should be determined primarily by the cleanliness specification. If no information is given, the frequency of inspection should be in the range of 0.002% - 2% of the products manufactured. The long-term reduction of particle sources or emissions is achieved through three fields of action:

Intervention limits enable steps to be taken at an early stage if cleanliness levels show signs of worsening. An intervention limit can be set after about 30 analyses have been conducted. Several procedures can be used. Figure 8 shows three possible intervention limits. IL #1 corresponds to Quantile 3 and represents a clear intervention threshold that would trigger an alarm at 25% of all values. IL #2 corresponds to the 1σ level known from quality control. IL #3 is an intervention limit that is well suited for technical cleanliness and mostly applied by vehicle manufacturers and first-tier suppliers in practice. This is obtained from the point where x intercepts with F(x) of the empirical CDF.

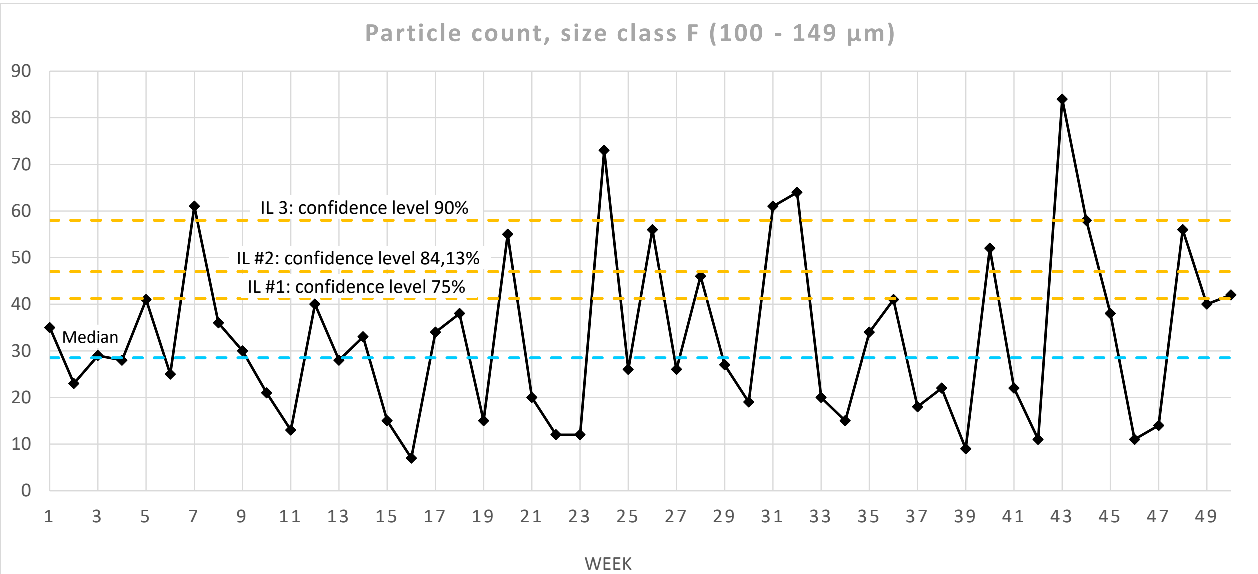


Figure 8: Selection of recommended intervention limits

The intervention limit chosen depends on company preferences. At present, there is no standardized regulation or convention on this. However, choosing a high sigma level, as pursued by quality control, is not recommended. As the sigma level increases, the warning threshold decreases.

Staggered analyses can increase sensitivity and allow faster intervention. This results from the causal relationships observed between the processes due to particle accumulation. Instead of always measuring Processes (22), (21) and (20) on a Monday, it would be better to measure Process (22) on a Monday, Process (21) on a Wednesday and Process (20) on a Friday.

Particle galleries make it easier to identify particle sources. In addition to light microscopic analyses, spectroscopic analysis methods are also used. The origin of particles can be derived from material data. Scanning electron microscopes with energy dispersive x-ray (SEM/EDX) or laser-induced breakdown spectroscopy microscopes (LIBS) are suitable for identifying inorganic particles. Fourier-transform infrared microscopes (FTIR), on the other hand, can be used to identify organic particles.

6. Summary and Outlook

Contamination control might be established since decades in aerospace or semiconductor industry. But the automobile industry needs a divergent approach in this field to be successful in a price sensitive milieu. For that purpose, this article describes the method to establish contamination control in the automobile industry.

Phase I reflects an explorative survey to understand the severity of impacts that is the basis for a lean monitoring in phase II. The method can be applied to any automobile component. In this work, the phases were explained on the example of the hydraulic brake control unit (HECU). It was found that multiple iterations were needed with varying measurement techniques to conclude if a process is relevant (critical) in terms of its added proportion to the cumulative contamination, typically found in the product, end of line. The information density illustrated in Figure 4 is not common so that a very economic approach (coarse grid) could end up in wrong conclusions. But the example of the HECU showed, that the limit violations of process 20 and 21 are finally not critical, when followed by an efficient cleaning process. In return, process 22 is relevant for the monitoring instead of process 20 and 21.

However, the comparability of different measurement techniques was not discussed in this work, but is still an issue, when Phase I is carried out. It is questionable, if the same amount and size of contaminants that were found in particle traps would have been found in the product as well, to name only one. Some of the measurement techniques can be only used for trend analyses, when compared to a component cleanliness specification. Nevertheless, particle traps or stamps are cheap tools for single or multiple process monitoring and usually the preferred choice in the automobile industry. There are particle deposition monitoring systems available that could measure the sediment in or near real time [34,35]. But they are sometimes too big to fit in a machine, too expensive for the aspired measurement frequency or do not present the desired information [36].

A further development of contamination control in the automobile industry requires more handy solutions as described in [37] for example and a higher degree of automation as presented in [38] to gain more information in less time. Nevertheless, new technical solutions should be able to provide the same information as a microscope, i.e. actual shape and dimension of a contaminant.

As long as there are not such technical solutions available, this paper provides a method for an economic oriented contamination control that might be of interest for all manufacturers of safety relevant automobile components.

References

[1] Trovao, J.P., 2019. Trends in Automotive Electronics. IEEE Vehicular Technology Magazine 14 (4), 100–109.

[2] van Themsche, S., 2016. The Advent of Unmanned Electric Vehicles. Springer International Publishing, Cham.

[3] Sun, P., Bisschop, R., Niu, H., Huang, X., 2020. A Review of Battery Fires in Electric Vehicles. Fire Technology 56 (4), 1361–1410.

[4] Wang, B., Dehghanian, P., Wang, S., Mitolo, M., 2019. Electrical Safety Considerations in Large-Scale Electric Vehicle Charging Stations. IEEE Transactions on Industry Applications 55 (6), 6603–6612.

[5] Lian, Y., Zeng, D., Ye, S., Zhao, B., Wei, H., 2018. High-Voltage Safety Improvement Design for Electric Vehicle in Rear Impact. Automotive Innovation 1 (3), 211–225.

[6] Gibbs, N., 2020. BMW plug-in hybrids recalled due to fire risk. Automotive News, October 16.

[7] Bao, P.Q., Ko, S.L., 2013. Characterization and recognition of particles for improving cleanability in automotive production. Int. J. Precis. Eng. Manuf. 14 (6), 977–984.

[8] Koevi, M., Ji, J., 2020. Technical Cleanliness in Electronics Manufacturing, in: PCIM Asia 2020; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management. PCIM Asia 2020; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management, pp. 1–4.

[9] Rochowicz, M., 2015. Design of functional automotive components with requirements for cleanliness, in: Bargende, M., Reuss, H.-C., Wiedemann, J. (Eds.), 15. Internationales Stuttgarter Symposium. Springer Fachmedien Wiesbaden, Wiesbaden, pp. 641–652.

[10] VDA 19 Part 2. Technical Cleanliness in Assembly, 2011.

[11] VDA 19 Part 1. Inspection of Technical Cleanliness, 2015.

[12] ISO 16232. Road vehicles - Cleanliness of components and systems, 2018.

[13] Faber, J., Brodzik, K., Nycz, M., 2021. Understanding technical cleanliness: importance, assessment, maintenance. Combustion Engines 186 (3), 41–50.

[14] ISO 14644-2. Cleanrooms and associated controlled environments - Part 2: Monitoring to provide evidence of cleanroom performance related to air cleanliness by particle concentration, 2016.

[15] ISO 14644-9. Cleanrooms and associated controlled environments - Part 9: Assessment of surface cleanliness for particle concentration, 2022.

[16] ISO 14644-1. Cleanrooms and associated controlled environments - Part 1: Classification of Air Cleanliness by Particle Conecentration, 2016.

[17] Kanegsberg, B., Kanegsberg, E., 2017. Chapter 4 - The Role of Standards in Cleaning and Contamination Control, in: Kohli, R., Mittal, K.L. (Eds.), Developments in Surface Contamination and Cleaning: Types of Contamination and Contamination Resources. William Andrew Publishing, pp. 125–150.

[18] Tautscher, C.J., 1991. Contamination effects on electronic products: A basic discussion of common contaminants, their origin, effects, removal, and control, and product protection against contaminants from the use environment, 1. ed. ed. Dekker, New York, NY, 600 pp.

[19] IEST-STD-CC1246E. Product Cleanliness Levels - Applications, Requirements, And Determination, 2013.

[20] Tribble, A.C., 2000. Fundamentals of Contamination Control. SPIE.

[21] Welker, R.W., Nagarajan, R., Newberg, C.E., 2006. Contamination and ESD control in high-technology manufacturing. IEEE Press, Hoboken, NJ, 498 pp.

[22] Gresham, R.M., Totten, G.E., 2008. Lubrication and Maintenance of Industrial Machinery : Best Practices and Reliability. Taylor & Francis Group, Baton Rouge, UNITED STATES.

[23] Department of Defense USA, 1972. MIL-HDBK-407. Contamination Control Technology.

[24] van der Donck, J.C., 2010. Chapter 2 - Contamination Control: A Systems Approach, in: Kohli, R., Mittal, K.L. (Eds.), Developments in Surface Contamination and Cleaning. William Andrew Publishing, Oxford, pp. 57–80.

[25] Jensen, D., 2001. Sources of Contamination and Their Control, in: Donovan, R.P. (Ed.), Contamination-free manufacturing for semiconductors and other precision products. Dekker, New York, NY, pp. 358–441.

[26] ASTM E1548. Standard Practice For Preparation Of Aerospace Contamination Control Plans, 2022.

[27] Brag, P., Rochowicz, M., 2021. Safety in Electromobility – Technical Cleanliness Between the Poles of Design Requirements and Efficient Production, in: Advances in Automotive Production Technology – Theory and Application, Berlin, Heidelberg. 2021. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 319–326.

[28] Remfrey, J., Gruber, S., Ocvirk, N., 2016. Hydraulic Brake Systems for Passenger Vehicles, in: Winner, H., Hakuli, S., Lotz, F., Singer, C. (Eds.), Handbook of Driver Assistance Systems: Basic Information, Components and Systems for Active Safety and Comfort. Springer International Publishing, Cham, pp. 703–730.

[29] Agricola, K., 2020 - 2020. Particle deposition rate application in system contamination control, in: Systems Contamination: Prediction, Control, and Performance 2020. Systems Contamination: Prediction, Control, and Performance 2020, Online Only, United States. 24.08.2020 - 28.08.2020. SPIE, p. 24.

[30] Gommel, U., Holzapfel, Y., Kreck, G. Particulate cleanliness and cleaning validation in fields ranging from automotive industry to medical devices, in: , International Symposium on Contamination Control (ICCCS) 2014.

[31] Brag, P., Piotter, V., Plewa, K., Klein, A., Herzfeldt, M., Umbach, S., 2022. Development and Production of Artificial Test Swarf to Examine Wear Behavior of Running Engine Components—Geometrically Derived Designs. Journal of Manufacturing and Materials Processing 6 (5).

[32] Hansel, M., 2016. Testpartikel gemäß VDA 19 - Ermittlung der Sensibilität von Komponenten gegenüber partikulären Verunreinigungen. https://www.reinraum.de/uploads/files/newsletter_de_09_2016.pdf. Accessed 31 August 2023.

[33] Brag, P., Piotter, V., Plewa, K., Umbach, S., Herzfeldt, M., 2021. Determining the required cleanliness level using synthetic test contamination. IOP Conf. Ser.: Mater. Sci. Eng. 1193 (1), 12072.

[34] Agricola, K., 2015. Practical experiences in practical deposition monitoring. Clean Air and Containment Review (21), 4–8.

[35] Menant, N., Faye, D., Nouet, P., Lafontan, X., Lellouchi, D., 2014. Monitoring of particle deposition in cleanrooms: State-of-the-art, in: 2014 Symposium on Design, Test, Integration and Packaging of MEMS/MOEMS (DTIP). 2014 Symposium on Design, Test, Integration and Packaging of MEMS/MOEMS (DTIP), pp. 1–4.

[36] Pecault, I.T., Gensdarmes, F., Basso, G., Sommer, F., 2012. Performance Assessment of Probes Dedicated to the Monitoring of Surface Particle Contamination. Part. Part. Syst. Charact. 29 (3), 156–166.

[37] Wei, Q., Qi, H., Luo, W., Tseng, D., Ki, S.J., Wan, Z., Göröcs, Z., Bentolila, L.A., Wu, T.-T., Sun, R., Ozcan, A., 2013. Fluorescent imaging of single nanoparticles and viruses on a smart phone. ACS nano 7 (10), 9147–9155.

[38] Fahr, M., 2022. Technische Sauberkeit vollautomatisiert bestimmen. J Oberfl Techn 62 (S3), 62–63.

Biography

Patrick Brag (*1980) has been project manager for technical cleanliness at the Department of Ultraclean Technology and Micromanufacturing at the Fraunhofer Institute for Engineering and Automation (IPA) since 2011. Dipl.-Wirt. Ing. Patrick Brag was a member of the VDA 19 Part I standardization committee (2014-2015) and has been a PhD candidate since 2021. He is also a trainer and consultant for technical cleanliness in the worldwide automotive industry.

Bálint Balogh (1980) has dedicated his career to the Automotive industry. Since 2015 he has been the member of the Executive management at Continental Automotive Hungary Ltd. He demonstrates strong commitment in leading the company to success: first as the Leader of the Laboratory (2010-2015), then as the Head of Quality Management (2015-2021), and currently as the Head of Focus Factory Automotive Plant Budapest. He was graduated in Electrical Engineering MSc at Budapest University of Technology and Economics and continued his academic journey as a PhD student at the Department of Electronics Technology.

Peter Gordon, PhD (*1976) is associate prof. at Dept. of Electronics Technology, Faculty of Electrical Engineering and Informatics, Budapest University of Technology and Economics. He is the co-founder of EFI-labs, specialized in material and failure analysis of electronic products. He is also the co-founder of Center of Particle Control (CPC), which is the competence center for technical cleanliness in Hungary.

CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
CPSL 2023-2

5th Conference on Production Systems and Logistics

FlexEnergy - A Prosumer-based Approach For The Automated Marketing Of Manufacturing Companies' Energy Flexibility

P. Pelger[1,2], C. Kaymakci[1,2], L. Baur[1,2], A. Sauer[1,2]

[1]*Fraunhofer Institute for Manufacturing Engineering and Automation IPA, 70569 Stuttgart, Germany*
[2]*Institute for Energy Efficiency in Production EEP, University of Stuttgart, 70569 Stuttgart, Germany*

Abstract

The transition to renewable energy sources and the need to address climate change has significantly changed the energy landscape. However, the fluctuating nature of renewables and increased electricity price volatility pose challenges to power grids and companies. This study focuses on energy flexibility achieved through industrial demand-side management (DSM) as a solution. Information technology (IT) and standardization are vital for enabling energy flexibility by optimizing energy consumption and facilitating interoperability. Digital energy platforms allow energy-intensive industries to optimize energy usage, thus enabling industrial demand optimization and effective communication within the energy ecosystem. Standardization ensures efficient implementation of energy flexibility measures across diverse energy markets. This study proposes a process model to streamline the integration of energy flexibility measures into manufacturing processes. This model eliminates the labor-intensive manual implementation process, enabling seamless adoption of energy flexibility measures and participation in energy markets. Marketing energy flexibility is addressed through the prosumer-based process that leverages standardized communication facilitated by the energy flexibility data model (EFDM), optimizing the energy consumption of manufacturing companies. The contributions of this paper lie in the proposed process model for marketing energy flexibility, streamlining energy flexibility implementation through automated EFDM modeling. The findings provide insights for researchers and practitioners, guiding the adoption of energy flexibility measures and supporting a sustainable energy future.

Keywords

Industrial Energy Flexibility; Energy Flexibility Measures; Energy Flexibility Data Model; Process Model

1. Introduction

Climate change concerns and global commitments to reduce greenhouse gas emissions have significantly changed the energy landscape [1–3]. Governments worldwide, including Germany, are phasing out fossil energy sources such as coal and oil while promoting renewable energy sources such as wind and sun [4, 5]. However, the intermittent nature of renewable energy sources poses considerable challenges to power grids and results in greater electricity price volatility [6–8]. One potential solution to the challenges at hand is the concept of energy flexibility (EF), which can be achieved through industrial DSM [9–12]. In this context, IT and standardization are crucial in enabling EF. By leveraging digital energy platforms, energy-intensive industries can use EF measures to optimize their energy consumption according to energy price forecasts or network operators' flexibility requirements while maintaining logistical and operational objectives [13–16]. Standardization facilitates interoperability between manufacturing and energy-related domains, enabling the efficient use and marketing of EF measures in various energy markets. Despite the advantages of IT and standardization, a major challenge remains in modeling and marketing EF measures in manufacturing.

DOI: https://doi.org/10.15488/15259
ISSN: 2701-6277
publish-Ing.

Currently, manufacturing companies often do not know how to monetize EF of manufacturing processes. Also, the generic description of EF with the EFDM poses a significant hurdle for companies and often is manually implemented for each manufacturing process and EF, which is a time-consuming and labor-intensive task. To address these issues, our paper proposes a process model for the automated description and marketing of EF in manufacturing processes utilizing the EFDM to streamline the implementation of EF measures and enable seamless participation in different energy markets. The approach takes into account both proactive and reactive EF marketing. Proactive marketing aims to optimize energy consumption based on forecasts, while reactive marketing focuses on responding to real-time changes in energy markets [17–19]. While existing approaches and tools address aspects of EF in manufacturing processes, they do not provide a comprehensive framework for both describing and marketing EF measures in a seamless manner. This leaves manufacturing companies with fragmented solutions that lack end-to-end automation and standardization. Recognizing this gap, the research question of our work is defined as:

How can an information technology process be modeled that enables manufacturing companies to automate the description and marketing of energy flexibility?

Adopting a design science research (DSR) approach, an artifact in the form of a process model informed by literature and qualitative expert interviews is developed, thereby ensuring rigor. DSR, pivotal for developing solutions to real-world problems, supports our endeavor to offer a holistic and applicable model for automating the description and marketing of EF in manufacturing processes. This research directly responds to the need for the communication of EF, thus ensuring relevance. Therefore, our main contribution is a prosumer-based approach leveraging the EFDM for standardized communication with energy markets to monetize EF of manufacturing companies. The proposed process addresses the challenges associated with both proactive and reactive EF marketing and enables seamless participation in different energy markets. The remainder of this paper is structured as follows: The literature review highlights EF, the EFDM's foundations, and its application. The proposed process model details automated description and marketing of manufacturing companies' EF, emphasizing continuous information flow between companies and energy markets. A case study showcases the process models and resulting EFDM's practical application in an industrial setting. The findings, research implications, and future prospects in EF conclude the discussion.

2. State of the Art

EF is defined as the "ability of a manufacturing system to quickly and process-efficiently adapt to changes in the energy market" [17]. An energy-flexible factory allows for potential economic use of energetic flexibility [18]. The temporal deployment of EF is specified in the definition of the Federal Network Agency, which describes flexibility as "the change in feed-in or withdrawal in response to an external signal (price signal or activation), to provide a service in the energy system" [20]. In general, numerous types of energy (electricity, heat, natural gas) can be described by this term. In the energy transition context, the term mainly describes measures necessary to enable the power system to accommodate additional volatile renewable energy sources such as wind and solar power plants. Thus, the term "energy flexibility" represents an extension of the concept of "power grid flexibility", but is often also used synonymously [8]. The VDI guideline 5207 describes industrial EF measures such as adapting shift times, changing manufacturing sequences, interrupting orders but also technical EF measures on the shop floor level, such as storing energy inherently or changing the energy source of a manufacturing process [18]. The EFDM aims to model and describe EF from technical, organizational, and energetic aspects, therefore enabling standardized communication of EF data captured in manufacturing processes to market it to flexibility markets [21]. Consequently, the EFDM is the foundation for all services that automate and standardize the entire EF trading process from the machine to the energy market. Based on this, data models for specific use cases, such as optimization of manufacturing processes or flexibility marketing, can be derived, only containing part of the information of the central data model [22].

The EFDM represents EF using a flexibility range and specific measures. This description uses a minimal set of parameters to convey essential technical and energetic details, while minimizing data complexity and volume. Sensitive manufacturing data exchanges are avoided. The flexibility range describes the possibilities of an energy-flexible system to adjust its performance compared to the reference operation. This technical energy-flexible system is characterized with the classes "flexible load", "dependency", and "energy storage" [21]. In addition to the three classes for describing the "flexibility range" of a system, the EFDM also includes the class "energy flexibility measure”, which describes a specific change in the system's performance within its flexibility range [23]. A flexible load models a technical system or the interaction of different technical systems that have the potential to bring about a change in performance. Whether the technical system is a producer or consumer of power is irrelevant. The ability to market EF measures in manufacturing provides potential economic benefits for companies [11]. By adjusting energy consumption in response to price signals or other external factors, companies can exploit fluctuations in energy prices and potentially reduce their overall energy costs [24]. The process of marketing EF measures typically involves participating in energy markets or demand response programs.

Companies can participate directly in wholesale energy markets, such as day-ahead or intraday, to sell their EF. Through demand response programs, they adjust energy consumption based on grid conditions, receiving financial incentives or reduced rates in return. Small manufacturers or those with limited flexibility resources may engage via an aggregator. Aggregators pool the flexibility resources of multiple companies and market them collectively, enabling smaller companies to access the benefits of participating in energy markets or demand response programs [23, 25]. By marketing their EF measures, companies can reduce energy costs and enhance energy system stability. As renewable energy integration rises, the role of EF in supporting energy transition will grow. This underscores the need for a systematic approach to identify and market EF measures adaptable across various industries. Especially the challenges associated with proactive and reactive EF marketing, enabling seamless participation in different energy markets, and fostering efficient use of energy resources must be overcome. Compared to the extensive literature on energy-oriented production planning and control, the novelty of the presented approach resides in the application of the EFDM to facilitate standardized communication and automate the description and marketing of EF in manufacturing processes. This application streamlines the marketing process and permits a broader range of EF marketing strategies, including proactive and reactive approaches. While various tools and software applications, such as the "Flexfinder" and the "EFDM GUI" developed in the SynErgie project, provide valuable solutions in the domain, our approach offers a comprehensive integration of the EFDM for standardized communication with energy markets and emphasizes the diverse applications of the data model. This distinction underscores the novelty and relevance of our work in the context of EF.

3. Automated description and marketing of manufacturing companies’ energy flexibility

This chapter presents FlexEnergy, a process model implemented in the business process modeling notation (BPMN) that illustrates how manufacturing companies can automate the process of describing and marketing EF to achieve electricity cost savings [26, 27]. The approach is designed to help manufacturing companies benefit from increasingly volatile electricity prices by exploiting unused EF potential with proactive as well as reactive EF marketing. The fundamental prerequisite for minimizing electricity costs is to reduce electricity consumption in phases of high electricity prices. To adjust the electrical load accordingly, it is necessary to optimize the production plan and the underlying plant parameters concerning predicted electricity prices and thus be able to react dynamically to fluctuating prices of the volatile electricity market of the future [25]. Furthermore, adjusting the production schedule based on volatile electricity prices leaves room to identify additional EF potentials. These residual EFs can be characterized as an EFDM and sold on energy markets. To maximize the revenue generated in this way, it is necessary to examine in which energy markets or with which energy market products the highest revenue can be generated.

When making manufacturing processes more flexible, care must be taken to ensure that the EF measures implemented do not harm the overriding objectives of factory operations [28]. To combine the objectives of short processing times, high-quality products, and low costs with an energy-flexible mode of operation, production planning, and control must always be involved. Energy management forms the interface between manufacturing operations and strategic energy procurement and therefore plays an essential role in marketing EF. To benefit from the opportunities of marketing EF, an end-to-end IT connection of the energy-flexible manufacturing systems to the external energy markets is required. The market enables communication between flexibility buyers and sellers and forms the basis for reducing electricity costs and helping to stabilize the power grid. To optimize the power flows in the grid and avoid bottlenecks, flexibility purchasers such as grid operators can use the EF marketed on flexibility markets to stabilize the energy system.

3.1 Adjusting the production plan to fluctuating electricity prices

The first part of the process model FlexEnergy, describes utilizing energy flexibilities as a consumer to benefit from fluctuating electricity prices. Figure 1 presents the step-by-step sequence for production plan adjustment based on forecasted electricity prices.

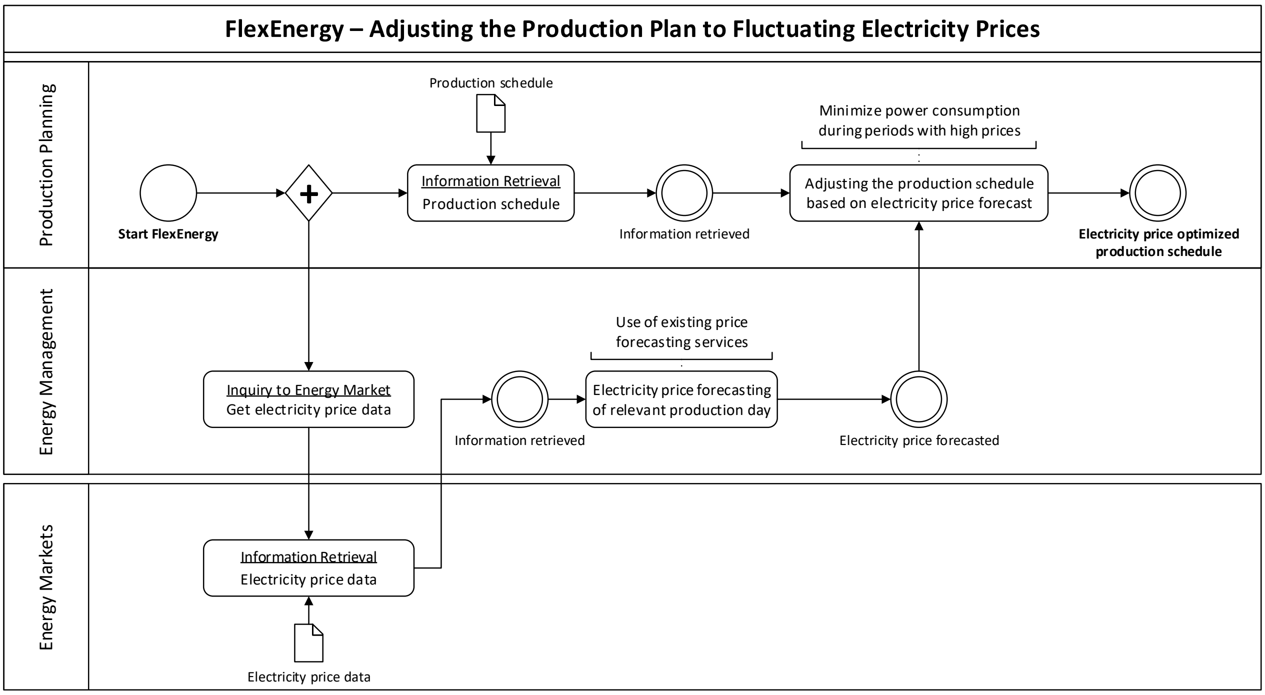


Figure 1: Process model for adjusting the production schedule to electricity price forecasts

The company's production planning and control trigger the start of FlexEnergy. To be able to react to volatile markets and utilize fluctuating electricity prices to reduce electricity costs, market information must be obtained first. To this end, the company's energy management team acquires electricity price data from the relevant electricity market. In parallel, production planning and control must acquire the production schedule of those manufacturing systems capable of energy-flexible operation to enable optimization of the load profile. Based on the electricity price data, energy management can generate electricity price forecasts for the relevant electricity markets and trading days. The focus is getting forecasts of the electricity prices for the day-ahead and intraday electricity markets as early and as accurately as possible so that they can be considered in short-term production planning and adjustments to reduce electricity costs can be planned. By implementing existing solutions for electricity price forecasting, like those developed in the SynErgie project, companies can optimize the load profile of energy-flexible manufacturing systems based on the forecast and reduce electricity costs by minimizing electrical power consumption during periods of high electricity prices. By implementing the described adjustments, the company's operations can be optimized regarding forecasted electricity prices, and electricity procurement costs can be reduced sustainably [29].

3.2 Automated description and marketing of energy flexibility of manufacturing companies

After implementing the first segment of the FlexEnergy process model, which provides an electricity price-optimized production schedule, the second section of FlexEnergy presents a systematic approach to identify, describe, and market additional EFs of manufacturing companies. Identifying additional EFs in the electricity price-optimized production plan is a sub-process detailed in the case study. The second part of the FlexEnergy process model is illustrated in Figure 2 and explained in detail.

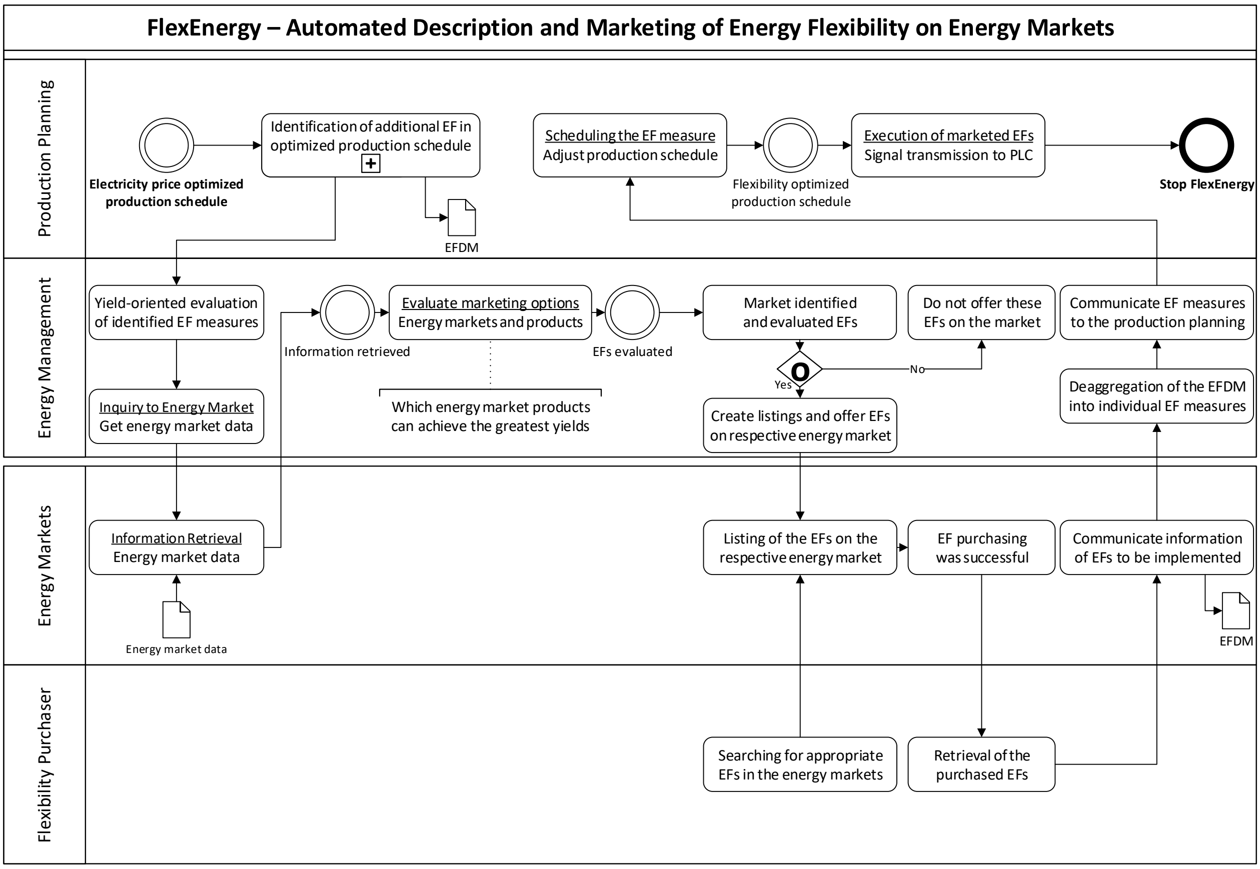


Figure 2: Process model for the automated description and marketing of energy flexibility on energy markets

For marketing manufacturing companies' EF, it is first necessary to identify additional EF measures in the electricity price-optimized production schedule and to describe them with appropriate figures. The additional EFs identified in this process are described with the help of an EFDM and form the basis for all downstream process steps. One of the central goals of FlexEnergy is to maximize revenue when marketing EF. Based on this objective, energy management performs a yield-oriented evaluation of the identified EF measures. It also acquires information on which markets and with which products the most significant revenue can be achieved with the identified EFs. The revenue-based assessment can be automated by utilizing services such as the flexibility deployment planning tool, developed as part of the SynErgie project, and thus help companies decide which EFs should be marketed on which energy market [25]. EFs advertised on markets that enable EF marketing can be viewed and purchased by interested flexibility buyers, such as grid operators. In the case of a successful purchase and call, the information about the EF measure to be provided is transmitted from the market to the company utilizing the EFDM. Subsequently, the EFDMs are disaggregated into EF measures and forwarded to the production planning and control, where the sold EF must be entered into the electricity price-optimized production plan to block the marketed periods for different operational measures. To ultimately provide the marketed EF, a control signal must be provided to the PLC of the respective energy-flexible manufacturing system, enabling an adjustment of the electrical load to provide the EF sold.

4. Automated energy flexibility marketing of a magnesium die casting company

Based on the process model developed for the automated identification, description, and marketing of EF of manufacturing companies, a case study is presented, demonstrating and validating the applicability and benefits of FlexEnergy. The focus here is, in particular, on EFDM modeling. The use case originates from the SynErgie project and involves the energy-flexible operation of a magnesium die-casting process [30]. To contribute to science and practice, it is shown how EFs can be identified, described, and marketed utilizing the EFDM. The furnace, needed to melt the magnesium and keep it at a specific temperature, can be utilized as inherent energy storage to make energy consumption in manufacturing more flexible and, through the marketing of EF, help reduce the company's energy costs. The use of inherent energy storage is an EF measure that can be implemented on the shopfloor level and, according to VDI guideline 5207, is defined as the "use of tolerances of various state variables in processes as energy storage" [17]. Depending on the material, the furnace must be operated within a defined temperature range to ensure consistent product quality. Within this range, the furnace exhibits EF. The power consumption of the furnace can be adjusted by controlling the output of its electric heating elements, provided the process limits are maintained. Description of the furnace static EF space enables deriving concrete EF measures, thus facilitating EF marketing. The energy-flexible furnace is modeled using the EFDM JSON format to represent its operating possibilities.

EFDM 1: Static modeling of the energy flexibility space of the magnesium-melting furnace


```
{
    "flexibility": {
        "id":                        "b7c4d95d-4d3b-4f48-9dcf-3bde75e7c67e",
        "origin":                    "f8c54c80-34a6-4d4f-8da8-62755a44d7e3",
        "flexibleLoads": [{
            "flexibleLoadId":        "d62a3c5b-8c16-40e6-a9e9-0195c1655b68",
            "marketingDeadline":     "2023-05-03T12:00:00+00:00",
            "measurementLocation":   "Shopfloor - Magnesium Melting Furnace 001",
            "deactivationGradient": {"unit": "kW/s", "value": -4.0},
            "activationGradient":   {"unit": "kW/s", "value": 4.0},
            "regenerationDuration": {"unit": "s", "value": 0.0},
            "reactionDuration":     {"unit": "s", "value": 10.0},
            "modulationGradients":  [{
                "min":  {"unit": "kW/s", "value": -4.0},
                "max":  {"unit": "kW/s", "value": 4.0}}],
            "validity":  [{
             "from":     "2023-05-04T05:00:00+00:00",
             "until":    "2023-05-04T08:00:00+00:00",
             "temporalType": "TOTAL"}],
            "powerStates": [{
             "power": {
                "min":  {"unit": "kW", "value": 0.0},
                "max":  {"unit": "kW", "value": 0.0}}},{
             "power": {
                "min":  {"unit": "kW", "value": 40.0},
                "max":  {"unit": "kW", "value": 40.0}}},{
             "power": {
                "min":  {"unit": "kW", "value": 80.0},
                "max":  {"unit": "kW", "value": 80.0}}},{
             "power": {
                "min":  {"unit": "kW", "value": 120.0},
                "max":  {"unit": "kW", "value": 120.0}}}]
    }],
         "storages": [{
            "storageId": "a2c7ca70-f0f4-435c-9f94-ee2228e3c1fc",
            "usabelCapacity": {
                "min":  {"unit": "kWh", "value": 0.0},
                "max":  {"unit": "kWh", "value": 7.8}},
            "suppliers": [{
             "flexibleLoadId": "d62a3c5b-8c16-40e6-a9e9-0195c1655b68",
             "conversionEfficiency": 1.0}],
            "energyLoss":{"unit": "%/s", "value": "E_Loss%"},
            "drain": [{
             "time":     "2023-05-04T05:00:00+00:00",
             "power":    {"unit": "kW", "value": 10.0}},{
             "time":     "2023-05-04T08:00:00+00:00",
             "power":    {"unit": "kW", "value": 10.0}}],
            "initialEnergyContent": {
             "time":     "2023-05-04T05:00:00+00:00",
             "value": {
                "min":  {"unit": "kWh", "value": 0.0},
                "max":  {"unit": "kWh", "value": 7.8}}},
            "targetEnergyContent": {
             "time":     "2023-05-04T08:00:00+00:00",
             "value": {
                "min":  {"unit": "kWh", "value": 0.0},
                "max":  {"unit": "kWh", "value": 7.8}}}
    }]
}}
```

Static modeling of the EF of the furnace is the basis for electricity price-optimized operation and identification of marketable EFs. In addition to mathematical and evolutionary optimization, another possibility for energy-flexible optimization of the furnace is implementing a (deep) reinforcement learning (RL) agent that controls the operation based on a simulation model. RL works through a series of actions that can trigger a reward or a punishment. In this process, an agent interacts with its environment, aiming to find appropriate actions to maximize rewards without the actions being predetermined by a teacher. The characteristic of RL is learning by trial and error and often delayed rewards for the agent's actions [31, 32]. Within the framework of this case study, a simulation model was developed that allows the calculation of the temperature inside the furnace as a function of power and time and serves as the basis for energy-flexible operation optimization. Furthermore, an AI-based control system was implemented utilizing deep RL to enable energy-flexible operation. Using a reward function, the agent learns a strategy to adjust the furnace's load profile based on electricity price forecasts. [31]. According to EFDM 1, the agent can only select from four power states: 0, 40, 80, or 120 kW as actions (cf. lines 20-32). The reward function is based on two constraints: adhering to the temperature limits of 640 °C and 660 °C modeled as the usable capacity (cf. lines 36-38) and reducing electricity costs by adjusting the furnace's load profile. In a simplified description, the choice of a particular action is influenced by the current temperature or energy content in the furnace and the boundary conditions determined by the reward.

The optimization output of the agent is automatically transferred into an EFDM format, which describes the furnace's electricity price-optimized load profile as a flexibility measure. An exemplary flexibility measure in the form of an EFDM can be found in the appendix of this paper. To market additional EFs in the electricity price-optimized production schedule (cf. Figure 2), additional EF measures must be identified and modeled as an EFDM. The EF measures to be marketed are identified utilizing a rule-based approach. This method, implemented utilizing a Python script, automatically detects suitable EF measures based on two conditions and translates them into an EFDM. Specifically, the case study focuses on identifying load increase measures by detecting phases where the electric heating element's power is 0 kW, and the furnace's temperature is below 641 °C, subsequently transforming these findings into the EFDM. An exemplary EFDM based on the agents' optimized load profile and the resulting EF measure attached in the appendix (cf. EFDM 3) is shown below.

EFDM 2: Additional energy flexibility in the melting furnaces optimized production schedule

```
{
        "flexibility": {
            "id":                     "f47ac10b-58cc-4372-a567-0e02b2c3d479",
            "origin":                 "f8c54c80-34a6-4d4f-8da8-62755a44d7e3",
            "flexibleLoads": [{
                "flexibleLoadId":       "d62a3c5b-8c16-40e6-a9e9-0195c1655b68",
                "marketingDeadline":    "2023-05-03T12:00:00+00:00",
                "measurementLocation":  "Shopfloor - Magnesium Melting Furnace 001",
                "deactivationGradient": {"unit": "kW/s", "value": -4.0},
                "activationGradient":   {"unit": "kW/s", "value": 4.0},
                "regenerationDuration": {"unit": "s", "value": 0.0},
                "reactionDuration":     {"unit": "s", "value": 10.0},
                "price":                {"unit": "EUR", "value": 50.0},
                "usageNumber": [{
                    "min":   0,
                    "max":   1}],
                "modulationGradients":   [{
                    "min":   {"unit": "kW/s", "value": -4.0},
                    "max":   {"unit": "kW/s", "value": 4.0}}],
                "validity":  [{
                 "from":     "2023-05-04T07:00:00+00:00",
                 "until":    "2023-05-04T07:05:00+00:00",
                 "temporalType": "TOTAL"}],
                "powerStates": [{
                 "power": {
                    "min":   {"unit": "kW", "value": 40.0},
                    "max":   {"unit": "kW", "value": 40.0}},
                 "holdingDuration": {
                    "min":   {"unit": "s", "value": 60.0},
                    "max":   {"unit": "s", "value": 300.0}}},{
                 "power": {
                    "min":   {"unit": "kW", "value": 80.0},
                    "max":   {"unit": "kW", "value": 80.0}},
                 "holdingDuration": {
                    "min":   {"unit": "s", "value": 60.0},
                    "max":   {"unit": "s", "value": 300.0}}}
        ]}
]}}
```

The furnace's additional EF can now be introduced to energy markets, ideally targeting a specific market for its offering. If a flexibility buyer acquires the EF, the corresponding measure is relayed to the company for execution, increasing the furnace's load. Additional revenue opportunities arise from marketing the existing EFs as control energy via a flexibility marketer, minimizing peak loads and thus reducing costs through lower grid fees, and from atypical grid usage models and thus reduced grid fees. The economic benefits from EF also lead to environmental benefits from increased energy purchases and usage from renewable sources. Through the intelligent usage of inherent energy storages and intelligent control of manufacturing processes, companies can save energy costs and, at the same time, contribute to the stabilization of the power grid.

5. Conclusion and implications

In the course of the energy transition and the associated volatile supply of electricity, the use of flexible loads as a balancing mechanism to stabilize the power grid is being increasingly intensified. Due to the high energy consumption, the demand-side EF of the industrial sector is becoming more important. By making electricity consumption more flexible, manufacturing companies can create an instrument that, on the one hand, helps to ensure grid stability and, on the other, makes it possible to save electricity costs. The basis for benefiting from the monetary advantages of demand flexibility and, at the same time, contributing to the energy transition is the implementation of EF measures in manufacturing. Given this context, a process model was developed that enables manufacturing companies to automate EF identification, description, and marketing. This paper specifically focuses on the comprehensive modeling of EF using the EFDM and the associated marketing of EF in energy markets. The case study has demonstrated the practical use of the process model FlexEnergy, utilizing a concrete EF measure, the use of inherent energy storages, and thereby presented how companies' identification, description, and marketing of EF can be implemented in practice to achieve more cost-efficient and sustainable factory operations.

Naturally, our study is subject to limitations and prospects for further research. Within the validation scope, it was shown that the complete characterization of the melting furnace makes it possible to identify numerous EF measures in the available flexibility range and market them. Numerous EF configurations can be described as EFDM and offered in energy markets by varying the power states and their holding periods. To satisfy market needs and achieve the highest yield, it will be important in the future that the scheduling and marketing of EFs are made in close consultation with the market or the flexibility purchaser. For suppliers and purchasers to benefit maximally from the existing flexibilities, an IT architecture that enables end-to-end communication between the two sides must be created, enabling further automation of the individual steps described in the process model and simplifying the EF identification, description, and marketing. Only in this way can the marketing of EF of manufacturing companies become a valid option in the future, in order to save energy costs on the one hand and stabilize the power system on the other.

Acknowledgments

The authors gratefully acknowledge the financial support of the Kopernikus Project SynErgie (Funding code: 03SFK3Q2-3) by the Federal Ministry of Education and Research (BMBF) and the project's supervision by the project management organization Projektträger Jülich (PtJ).

Appendix

As stated in chapter four, an excerpt of an exemplary flexibility measure in the form of an EFDM can be found hereafter. The measure is a concrete output of the deep RL agent, which is automatically transferred to an EFDM and illustrates an electricity price-optimized load profile of the melting furnace.

EFDM 3: Electricity price optimized production schedule of the magnesium-melting furnace


```
{
        "flexibleLoadMeasure": {
                "flexibleLoadId":       "d62a3c5b-8c16-40e6-a9e9-0195c1655b68",
                "reactionDuration":     {"unit": "s", "value": 10.0},
                "modulationGradients":  [{
                   "min":               {"unit": "kW/s", "value": -4.0},
                   "max":               {"unit": "kW/s", "value": 4.0}}],
               "startTime":             "2023-05-04T07:00:00+00:00",
               "powerStates": [{
                 "power":            {"unit": "kW", "value": 0.0},
                 "holdingDuration":  {"unit": "s", "value": 300}},{
                 "power":            {"unit": "kW", "value": 80.0},
                 "holdingDuration":  {"unit": "s", "value": 300}},{
                 "power":            {"unit": "kW", "value": 0.0},
                 "holdingDuration":  {"unit": "s", "value": 300}},{
                 "power":            {"unit": "kW", "value": 0.0},
                 "holdingDuration":  {"unit": "s", "value": 300}},{
                 "power":            {"unit": "kW", "value": 0.0},
                 "holdingDuration":  {"unit": "s", "value": 300}},{
                 "power":            {"unit": "kW", "value": 120.0},
                 "holdingDuration":  {"unit": "s", "value": 300}},{
                 "power":            {"unit": "kW", "value": 0.0},
                 "holdingDuration":  {"unit": "s", "value": 300}},{
                 "power":            {"unit": "kW", "value": 0.0},
                 "holdingDuration":  {"unit": "s", "value": 300}},{
                 "power":            {"unit": "kW", "value": 0.0},
                 "holdingDuration":  {"unit": "s", "value": 300}},{
                 "power":            {"unit": "kW", "value": 80.0},
                 "holdingDuration":  {"unit": "s", "value": 300}},{
                 "power":            {"unit": "kW", "value": 0.0},
                 "holdingDuration":  {"unit": "s", "value": 300}},{
                 "power":            {"unit": "kW", "value": 40.0},
                 "holdingDuration":  {"unit": "s", "value": 300}},{
                 […]
         }]
}}
```


References

[1] Büttner, S.M., Schneider, C., König, W., Mac Nulty, H., Piccolroaz, C., Sauer, A., 2022. How Do German Manufacturers React to the Increasing Societal Pressure for Decarbonisation? Applied Sciences 12 (2), 543.

[2] IPCC, 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.

[3] United Nations, 2015. Transforming our world: The 2030 Agenda for sustainable development.

[4] European Commission, 2023. A European Green Deal: Striving to be the first climate-neutral continent. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en. Accessed 12 June 2023.

[5] Umweltbundesamt, 2023. Treibhausgasminderungsziele Deutschlands. https://www.umweltbundesamt.de/daten/klima/treibhausgasminderungsziele-deutschlands#undefined. Accessed 12 June 2023.

[6] Graßl, M., 2015. Bewertung der Energieflexibilität in der Produktion. utzverlag, München.

[7] Canzler, W., 2018. Die infrastrukturelle Umsetzung der Energiewende. dms 11 (2-2018), 461–477.

[8] Sauer, A., Bauernhansl, T. (Eds.), 2016. Energieeffizienz in Deutschland - eine Metastudie: Analyse und Empfehlungen, 2. Aufl. 2016 ed. Springer, Berlin.

[9] Bdew, 2021. Stromverbrauch in Deutschland nach Verbrauchergruppen 2020. https://www.bdew.de/service/daten-und-grafiken/stromverbrauch-deutschland-verbrauchergruppen/. Accessed 12 June 2023.

[10] Bauer, D., Hieronymus, A., Kaymakci, C., Köberlein, J., Schimmelpfennig, J., Wenninger, S., Zeiser, R., 2021. Wie IT die Energieflexibilitätsvermarktung von Industrieunternehmen ermöglicht und die Energiewende unterstützt. HMD 58 (1), 102–115.

[11] Langrock, T., Achner, S., Jungbluth, C., Marambio, C., Michels, A., Weinhard, P., 2015. Potentiale regelbarer Lasten in einem Energieversorgungs-system mit wachsendem Anteil erneuerbarer Energien. Climate Change (19/2015).

[12] Buhl, H.U., Fridgen, G., Körner, M.-F., Michaelis, A., Rägo, V., Schöpf, M., Schott, P., Sitzmann, A., Bertsch, J., Sachs, T., Schweter, H., 2019. Ausgangsbedingungen für die Vermarktung von Nachfrageflexibilität: Status-Quo-Analyse und Metastudie. 2. Fassung.

[13] Körner, M.-F., Bauer, D., Keller, R., Rösch, M., Schlereth, A., Simon, P., Bauernhansl, T., Fridgen, G., Reinhart, G., 2019. Extending the Automation Pyramid for Industrial Demand Response. Procedia CIRP 81, 998–1003.

[14] Bauernhansl, T., Bauer, D., Abele, E., Ahrens, R., Bank, L., Brugger, M., Colangelo, E., Eigenbrod, H., Fridgen, G., Gonzalez Vasquez, F., Grigorjan, A., Jarke, M., Keller, R., Lodwig, R., Pullmann, J., Reinhart, G., Rösch, M., Sauer, A., Schel, D., Schlereth, A., Schott, P., Schulz, F., Sedlmeir, J., Seitz, P., Simon, P., Weber, T., 2019. Ergebnisse aus dem Kopernikus-Projekt: Synchronisierte und energieadaptive Produktionstechnik zur flexiblen Ausrichtung von Industrieprozessen auf eine fluktuierende Energieversorgung (SynErgie). Fraunhofer Verlag, Stuttgart.

[15] Pfeilsticker, L., Colangelo, E., Sauer, A., 2019. Energy Flexibility – A new Target Dimension in Manufacturing System Design and Operation. Procedia Manufacturing 33, 51–58.

[16] Goswami, D.Y., Kreith, F. (Eds.), 2017. Energy management and conservation handbook, Second edition ed. CRC Press, Boca Raton.

[17] VDI, 2020. VDI 5207 Blatt 1 - Energieflexible Fabrik - Grundlagen. https://www.vdi.de/richtlinien/details/vdi-5207-blatt-1-energieflexible-fabrik-grundlagen. Accessed 12 June 2023.

[18] Goldkamp, P., Schallenberg, J., 2020. Probleme lösen bevor sie entstehen: Lokale Flexibilitätsmärkte, in: Doleski, O.D. (Ed.), Praxis der digitalen Energiewirtschaft von den Grundlagen bis zur Verteilung im Smart Grid. Springer Vieweg, Wiesbaden, 627–637.

[19] Häfner, L., 2018. Demand Side Management. HMD 55 (3), 627–645.

[20] Bundesnetzagentur, 2017. Flexibilität im Stromversorgungssystem: Bestandsaufnahme, Hemmnisse und Ansätze zur verbesserten Erschließung von Flexibilität. https://www.bundesnetzagentur.de/SharedDocs/Downloads/DE/Sachgebiete/Energie/Unternehmen_Institutionen/NetzentwicklungUndSmartGrid/BNetzA_Flexibilitaetspapier.pdf?__blob=publicationFile&v=1. Accessed 12 June 2023.

[21] Schott, P., Sedlmeir, J., Strobel, N., Weber, T., Fridgen, G., Abele, E., 2019. A Generic Data Model for Describing Flexibility in Power Markets. Energies 12 (10), 1893.

[22] Schilp, J., Bank, L., Köberlein, J., Bauernhansl, T., Sauer, A., Kaymakci, C., Eigenbrod, H., Fridgen, G., Bahmani, R., Potenciano Manci, S., Schöpf, M., van Stiphoudt, C., Weigold, M., Lindner, M., 2021. Optimierung auf der Energiesynchronisationsplattform.

[23] Lindner, M., Wenninger, S., Fridgen, G., Weigold, M., 2022. Aggregating Energy Flexibility for Demand-Side Management in Manufacturing Companies – A Two-Step Method, Proceedings of the 11th Congress of the German Academic Association for Production Technology (WGP), 631–638.

[24] Strobel, N., 2021. Einsatz inhärenter Energiespeicher in Produktionssystemen zum elektrischen Lastmanagement, Darmstadt, Technische Universität Darmstadt, URN: urn:nbn:de:tuda-tuprints-175810.

[25] Reinhart, G., Bank, L., Brugger, M., Hieronymus, A., Köberlein, J., Roth, S., Bauernhansl, T., Sauer, A., Bauer, D., Kaymakci, C., Schel, D., Schlereth, A., Fridgen, G., Buhl, H.U., Bojung, C., Schott, P., Weibelzahl, M., Wenninger, S., Weigold, M., Lindner, M., Ronge, K., Oeder, A., Schimmelpfennig, J., Winter, C., Jarke, M., Ahrens, R., 2020. Konzept der Energiesynchronisationsplattform : Diskussionspapier V3, Augsburg.

[26] Stephen White, 2004. Business Process Modeling Notation (BPMN), Version 1.0.

[27] Chinosi, M., Trombetta, A., 2012. BPMN: An introduction to the standard. Computer Standards & Interfaces 34 (1), 124–134.

[28] Bender, B., 2020. Dubbel Taschenbuch Für Den Maschinenbau 2, 26th ed. Springer, Berlin.

[29] Bank, L., Wenninger, S., Köberlein, J., Lindner, M., Kaymakci, C., Weigold, M., Sauer, A., Schilp, J., 2021. Integrating Energy Flexibility in Production Planning and Control: An Energy Flexibility Data Model-Based Approach, Vancouver, Canada.

[30] Sauer, A., Buhl, H.U., Mitsos, A., Weigold, M. (Eds.), 2022. Markt- und Stromsystem, Managementsysteme und Technologien energieflexibler Fabriken: Kopernikus Projekte SynErgie - Die Zukunft unserer Energie. Fraunhofer Verlag, Stuttgart.

[31] Russell, S.J., Norvig, P., 2021. Artificial intelligence: A modern approach, Fourth Edition ed. Pearson, Hoboken, NJ.

[32] Graesser, L., Keng, W.L., 2020. Foundations of deep reinforcement learning: Theory and practice in Python. Addison-Wesley Data & Analytics.

Biography

Philipp Pelger (*1995) studied Technology Management at the University of Stuttgart. Since 2022, he has been a research associate at the Fraunhofer Institute for Manufacturing Engineering and Automation IPA and the Institute for Energy Efficiency in Production of the University of Stuttgart. His research focus comprises data-driven optimization of industrial energy systems.

Can Kaymakci (*1993) has been working as a research associate in the Industrial Energy Systems Department at the Fraunhofer Institute for Manufacturing Engineering and Automation 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.

Lukas Baur (*1995) is a research associate at the Institute for Energy Efficiency in Production at the University of Stuttgart and at the Fraunhofer Institute for Manufacturing Engineering and Automation IPA since 2022 with a background in computer science. His research focuses on electrical load forecasting, machine learning, and data analysis in the context of energy flexibility.

Prof. Dr.-Ing. Alexander Sauer (*1976) received his PhD at the RWTH Aachen University, where he studied mechanical engineering and business administration. He is the Executive Director 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.

5th Conference on Production Systems and Logistics

Development Of Scalable Production Concepts For The Cost-Efficient Assembly Of PEM Fuel Cell Systems For Mobile Applications

Achim Kampker[1], Heiner Heimes[1], Mario Kehrer[1], Sebastian Hagedorn[1], Julius Hausmann[1], Johann von Harling[1]

[1]*Chair of Production Engineering for E-Mobility Components, RWTH Aachen University, Aachen, Germany*

Abstract

Polymer-Electrolyte-Membrane (PEM) fuel cell systems will contribute to enable climate-neutral mobility through the chemical reaction of hydrogen and oxygen. PEM fuel cells address applications which are hardly decarbonized by HV batteries. But apart from its advantages, such as short refuelling times and higher energy densities related to batteries or locally emission-free operation compared to conventional drivetrains, the fuel cell technology still faces challenges that inhibit its wide market penetration. Especially the low production volumes result in costly manufacturing processes. The assembly of the fuel cell stack and balance-of-plant components to a system is predominantly of manufactory character. There is a consensus in the literature that scaling up the production is associated with cost reduction effects. But in order to increase the demand that justifies a growth in unit numbers, the costs per system have to be reduced. With regard to this so-called "hen-and-egg problem", a reduction of production costs for small output numbers is necessary, while already considering the future necessity to scale the production.

This paper discusses the development of scalable production concepts for PEM fuel cell system assemblies. In addition to a modular production concept, the associated production scenarios are also considered. For a generic fuel cell system, a possible assembly sequence and assembly tasks are derived from the bill of materials. The assembly durations for the individual steps are then determined according to the Methods-Time-Measurement (MTM) methodology. This methodological approach is intended to provide an estimate for each process step in the assembly and can be transferred to other fuel cell systems. The paper shows how a bill of materials can be used to estimate the cycle time for a system, but also the cycle time for defined stations. In addition, by considering different scaling mechanisms, further improvements in the assembly process are shown, based on the results from the MTM analysis.

Keywords

Fuel Cell System Assembly; PEM Fuel Cell System; Scalable Production Concept; Methods-Time-Measurement; Assembly; Production

1. Introduction

The fuel cell system assembly and End-of-Line-Testing (EoL) is the final step in the value chain of the fuel cell system production [1]. Since it is by now mainly conducted in small scale and manual labor, it is still a cost intensive part within the manufacturing process, taking a share of about 7 % in the cost breakdown of the fuel cell system manufacturing costs [2]. A reduction of the fuel cell system costs is crucial in order to

DOI: https://doi.org/10.15488/15269
ISSN: 2701-6277

allow market penetration and therefore a decrease of assembly costs would contribute to this goal. This cost reduction can be achieved with scalable concepts allowing the production to follow the fuel cell system demand at low-cost investment decisions and at the same time result in a higher level of flexibility for the production system to adapt to system design changes. In this work, an approach will be discussed, which is based on the number of parts of a generic fuel cell system. Different to the approach from JAMES ET AL. [3], it will be combined with the MTM (Methods-Time-Measurement) approach. Three mechanism, that allow scaling of the production output will be explained and based on two of those mechanisms, a scalable concept for the assembly of fuel cell systems introduced.

2. Objectives & state of the art

2.1 Fuel cell system set-up

The main component of the PEM fuel cell system is its stack, where the reaction of oxygen and hydrogen takes place. Apart from the stack, the fuel cell system needs subsystems to supply the stack with the necessary reactants. Those subsystems can be summarized under the term Balance-of-Plant (BoP). The BoP can be differentiated into the anode system, cathode system, cooling system and power and control unit. **Figure 1** yields an overview of a possible system set-up. Whereas the cathode system includes components like air filter, compressor, turbine and humidifier to lead the filtered and compressed air to the stack, the anode system contains components like the hydrogen storage, solenoid valves, pressure reducer, purge and drain valves and ejector or recirculation blower units for circulation of hydrogen through the system. The cooling system mainly includes thermal management components such as the radiator, heat and ion exchanger and cooling pump. The power and control unit includes a power distribution unit as well as the control unit with all the interfaces for cables transmitting electrical power or data. These cables are connected to all sensors allocated within the other subsystems like pressure, temperature or hydrogen sensors. [4]

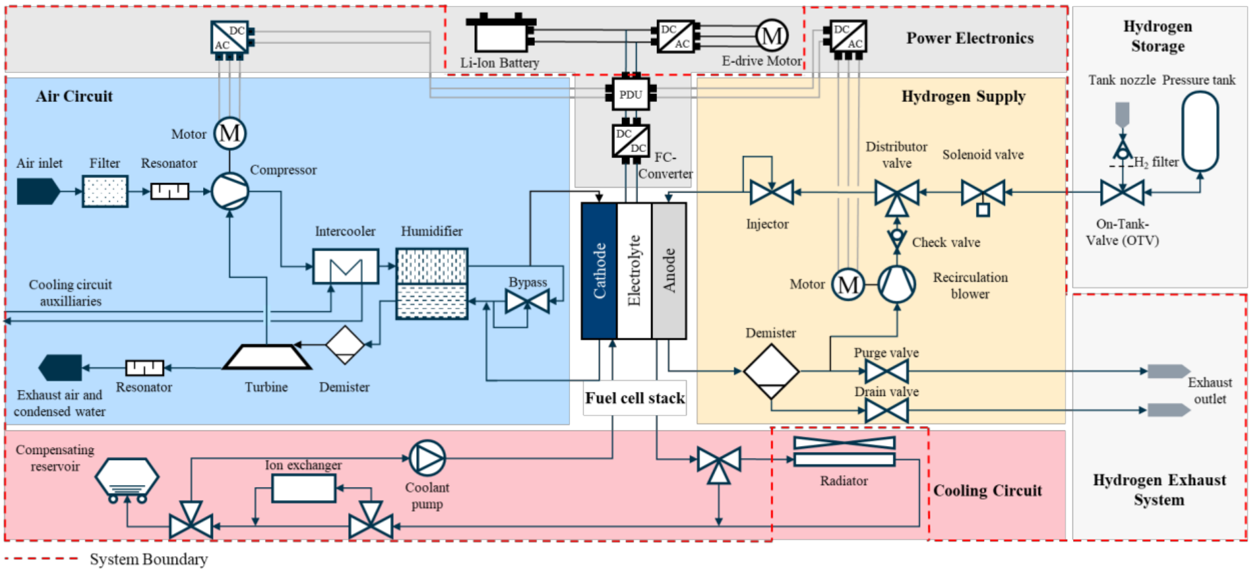


Figure 1: Generic and simplified fuel cell system for the definition of assembly contents adapted from PEM RWTH Aachen [4]

2.2 Fuel cell system assembly

The assembly of the fuel cell stack with BoP components is a currently not scientifically discussed part of the fuel cell system value chain. One early approach for estimating the assembly and cycle time of the assembly of fuel cell systems is undertaken by JAMES ET AL. [3], [5] in the context of an overall estimation of the production cost of fuel cell systems. This approach was conducted within an analysis of an automotive fuel cell system with a net power output of 80 kW in the year 2018. In this former approach a heuristic estimation based on the approximate number of parts was conducted. The various parts of the system were differentiated into major components such as the stack, pumps, motors and compressors and minor components such as measuring instruments and devices. For additional activities such as welding, piping, wiring etc., static assembly times were determined, based on the sole differentiation between major and minor components. These durations for piping, welding and a functionality test were added and led to a total system assembly time of 177.1 minutes at a single work station [3], [5]. This approach does not take the real number of components into account and therefore does not allow a detailed analysis of the assembly contents and associated cycle times. A static value for the time needed to assemble was assigned to each kind of component of the previously described groups, so that the components in one group all have the same assembly duration. In a second approach for the scale-up of production output, a system with ten workstations was introduced, that should reduce the cycle time to 14.2 minutes per station. In a further estimation for different scaled up production systems, JAMES ET AL. [3] estimated, that for an annual production volume of 1,000 systems, the cycle time drops to 9.9 minutes and the line utilization amounts to 2.2 %. This configuration is based on a single assembly line with 18 workers and ten workstations. From a production volume starting with 10,000 systems up to 500,000 systems per year a different configuration is needed, and the cycle time decreases to 7.9 minutes per system. [3]

In order to put these results into perspective, the values were compared to data known from industrially used fuel cell assembly systems. Within the production of the Mercedes-Benz GLC F-Cell fuel cell system in the year 2018 the assembly time is yielded 300 minutes [6] and a subsequent time for End-of-Line-Testing is added with 90 minutes [7]. The system contains around 250 parts [6]. The assembly takes place in an assembly system equipped with an electric monorail conveyor system, where the fuel cell system is hung in and can be rotated to get better angles for the assembly processes. Leakage tests for subsystems are included within the assembly procedure and conducted at the assembly line through a sniffer sample. [8]

2.3 Fundamentals of production technology

In the following, specific terms within production technology will be further explained. The terms of flexibility investigated in this work focus on the flexibility of variants and flexibility of production volume.

Flexibility in the context of production technology describes the time as well as the effort necessary to change over a production according to altered basic conditions. In order to measure the required effort, changeover times are introduced [9]. Flexibility of variants on the other hand can be understood as the ease with which new parts can be added or substituted within the production [10]. Therefore, the flexibility of variants of products can be defined as well as the ability of a production system to adapt changes in the part matrix currently produced rapidly and inexpensively. This means, that the change in parts still goes along with a change in the production system set up and therefore distinguishes the flexibility of variants from the flexibility of process [10].

Within the ongoing production, the assembly system can be adapted for new products as identical assembly activities can take place on different assembly cells. Individual assembly cells on the other hand need to be deactivated or reconfigured. For the integration of a new product within a mixed-model assembly, the assembly line requires a complete redesign and synchronization and also isolated additional assembly activities can cause a modified balancing of the assembly line. [11]

Scalability can be described as the ability to extend or restrain a system by either adding or reducing its resources. This can be a matter of technical, organisational or spatial resources. [12] Scaling mechanisms can be differentiated in three groups, which consist in intrastationary and interstationary scaling mechanisms as well as organisational scaling mechanisms. Whilst organisational scaling mechanism can be applied through changes in the number of workers or different shift models, for the two other types of scaling mechanisms a different architecture of the production system is needed. Hence the intrastationary scaling mechanisms foresee an adjustable level of automation, the rearrangement of assembly tasks and the reconfiguration of a production system section. A production system section can be understood as a part of the production system. The interstationary scaling methods on the other hand are provided by the duplication of system sections or the duplication of the whole assembly system. [13]

2.4 Methodological approaches existing

The methodological approach relevant for this study, the Methods-Time-Measurement (MTM) will be further explained in the following.

The MTM is a commonly used method in manual assembly processes to investigate and determine times within manual assembly. Through MTM it is possible to track the specific time that is needed for different types of motions in assembly and production. As MTM aims to optimize existing processes in assembly, it can also be used in the phase of planning assembly processes. Therefore, all the motions within the manual assembly process are divided into smaller motion sequences, that are categorized and structured. Afterwards these TMU (Time Measurement Units) can be allocated to the motion sequences. One TMU equals 10^{-5} hours, which is the equivalent of 0.036 seconds [14]. [15]

For this purpose, the correct MTM data map must be used, as there exists a variety of maps published by REFA AG. Therefore, REFA proposes a method including six steps to determine the times in assembly processes. In a first step the correct MTM scenario is chosen in accordance with the process type within the production system, the methodological level and the targeted production output [16]. Subsequently, the conditions and circumstances at the workstation are further examined. Therefore, especially the supply with working material and the working conditions at the workstation are relevant. In the third step, assembly contents and assembly sequences are either analyzed for existing assembly processes or planned for new assembly processes. An assembly content consists in the task of joining and assembling components. Afterwards, these assembly sequences are differentiated into the basic motion sequences of the respective MTM process. During the fifth step, these basic motion sequences are coded, taking the relevant influencing variables and the correct MTM data map into consideration. Finally, the times for manual assembly from the MTM data map are assigned to the coded basic movements and the activity times of the workflow are determined by adding the individual TMU values. The described procedure for determining times in manual assembly with MTM is shown below in Figure 2. [17]

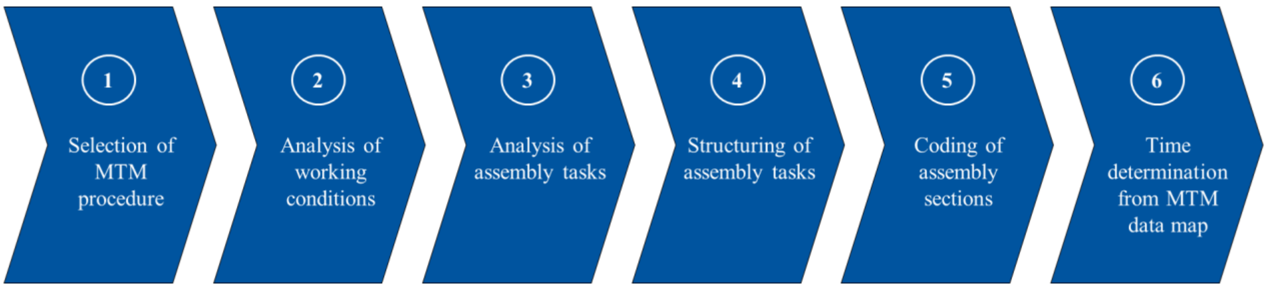


Figure 2: Methodology for determining the duration of assembly tasks in a manual production through MTM adapted from REFA [17]

3. Methodological concept

3.1 System definition

A generic and simplified PEM fuel cell system consists of a basic configuration of a PEM fuel cell stack and its periphery components. The system boundaries of this generic fuel cell system exclude the radiator unit from the cooling circuit and the hydrogen storage system. As well not included is the cooling circuit supplying the auxiliary units, which consists of the intercooler, the compressor and power distribution unit. Drawing these boundaries, the generic and simplified fuel cell system contains the fuel cell stack, the high temperature cooling circuit (without the radiator), the anode system for supplying the stack with hydrogen and the cathode system for providing oxygen from ambient air to the stack. Such a generic fuel cell system can still differ in many ways in its interconnections and therefore in its assembly process. **Figure 1** gives the exact picture of the generic fuel cell system, which was used for the development of scalable production concepts within this work.

3.2 Definition of assembly contents and deriving the assembly time

In the first two steps of the methodological approach of deriving determined assembly times with MTM, the MTM data card UAS (Universales Analysier-System, English: Universal Analysis-System) was chosen, and the working conditions for this mainly manual assembly were defined [16]. The choice for the MTM data card UAS was reasoned by the aim to analyse and plan assembly contents for series production, whereas the MTM standard includes data cards for mass manufacturing processes as well. Within the third and fourth step of the MTM methodology, the assembly contents were determined and structured into repetitive assembly sections. The assembly contents therefore were derived from a Bill-of-Materials (BoM) (Table 1) and the fuel cell system layout, yielded above. The BoM contains all components of the defined fuel cell system including connection elements such as pipes and hoses. As well included are brackets and screws to mount to components around the stack and frame. For wiring the power electronics and the control unit with motors and sensors, the BoM contains also cables for transmitting power and data. Due to the analysis of the fuel cell system an assembly sequence for each module of the complete fuel cell system was elaborated. It was assumed that the subsystems will be assembled continuously around the stack. At first the overall assembly task is determined. Afterwards the assembly of each module can be further divided into sections. An exemplary section is shown in Figure 3 and visualizes the assembly content beginning at the air inlet of the cathode system and ending at the humidifier. In a subsequent step, those sections are examined further to determine on a next dimension the necessary motions for joining two components such as the air inlet pipe and the air filter.

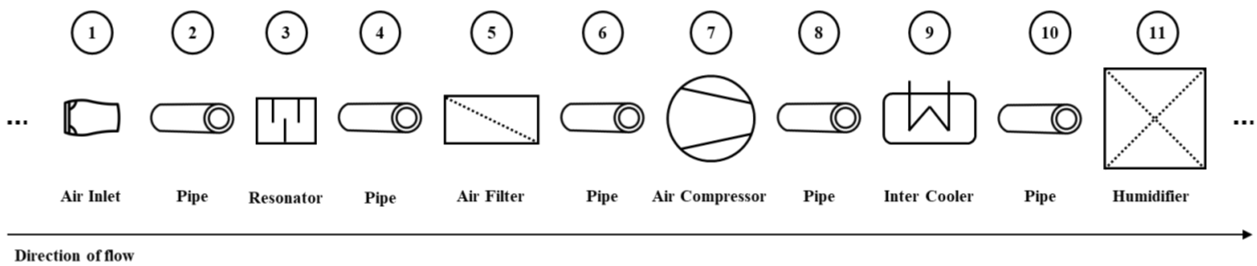


Figure 3: Example of an assembly section in the cathode system

3.3 Development of a scalable production concept

For the development of scalable production concepts in the fuel cell system assembly, a scenario where the production volume was scaled up from 1,000 systems to 10,000 systems was examined. These scales are in line with current market information that announce similar production volumes [18], [19]. Scalable production concepts were derived by comparing the production of fuel cell systems to that of battery systems, electrolysers, electric motors and combustion engines. As an evolution from the current status of manual assembly, a scalable production with features from a series production was targeted. The screening concluded that despite of their similarity in system structure and technology, electrolysers have larger dimensions and therefore favour manual assembly conditions with high manufacturing character and low production volume. Hence, those systems were excluded from the further procedure. From the other technologies, which differ a lot in their technological structure from the fuel cell system but have similar scale-up scenarios and targeted production volumes, assembly concepts were derived. Those concepts comprise for example an increasing degree of automation [20], [21], [22] hybrid assembly structures [21], [23] modular assembly structures [23], [24], human-robot-collaborations [21], [25], approaches including augmented reality for variant flexibility [21], approaches of machine learning in automation [25], digital twins for testing [25], a separation of assembly tasks into pre- and end assembly [26], [27], [28] and the implementation of automated guided vehicles (AGV) [24], [25] or conveyor systems [24] for high and stable production volumes. For this study it was decided to apply the separation of assembly tasks into pre- and end assembly and to develop modular assembly structures. This can be justified by the fact that the fuel cell system assembly contains numerous assembly sequences like wiring, or joining hoses and pipes, that are currently hard to automate as robots are limited in their assembly adaptability in complex assembly environments [21], [29] .

The existing and accessible assembly systems of fuel cell systems were investigated. The fuel cell system production of Mercedes Benz AG for the GLC F-Cell and the production system of HYVIA, a joint venture between PlugPower and Renault for a 30 kW range extender system, were further analysed [30]. The assembly system of Mercedes Benz was chosen as reference system as it was set up for series production, which is also targeted within this work**.** In this production system, the fuel cell system was mounted onto an electric monorail system that carried the fuel cell system through the assembly line. This line contained several workstations, where the electric monorail system with its mounting aid could be stopped at the positions, where racks with the supplying material for assembly or testing infrastructure were located. [8], [28]

Based on this assembly system, a reference system was developed and unknown parts were adapted from literature or other productions [5], [27], [28]. The assembly line of this reference configuration was assumed with six workstations using the electric monorail system and structured comparably to the production of the GLC F-Cell system. The configuration of this reference assembly line, is shown on the left in **Figure 4**. It was assumed, that the system would be assembled continuously without integration of pre-assembled modules. On the other hand, the scalable concept with a modular configuration in its production system design is visualized on the right in **Figure 4.** It as well contains six workstations for the manual end assembly, but in addition there are three workstations for the pre-assembly of sections of subsystems. The stations are connected via an AGV and can be scaled-up separately if required.

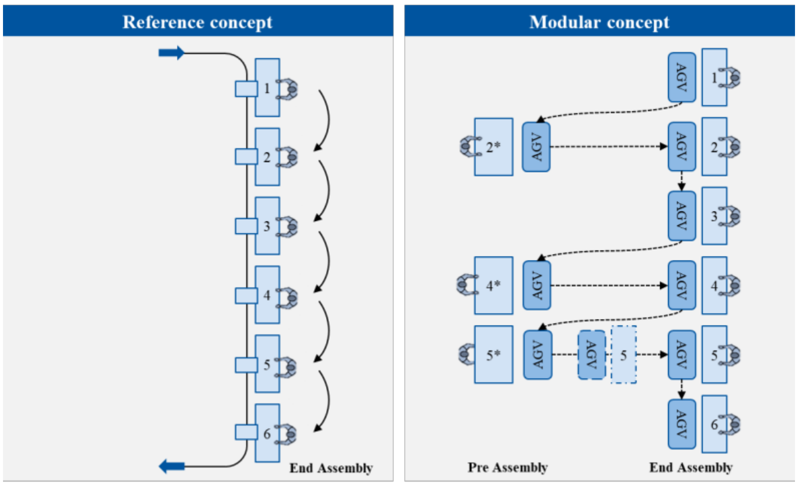


Figure 4: Assembly line configurations examined in this work

The scalable concept developed for the fuel cell system assembly shall be introduced in the following as the modular concept. The concept includes the separation of assembly tasks into a pre- and end assembly and a modular assembly line structure. Regarding the scaling mechanism explained above, the separation of assembly tasks can be allocated to intrastationary scaling, whereas the modular assembly line structure has to be allocated to interstationary scaling. This modular assembly line structure consists of the workstations for the pre- and end assembly. The AGVs connect the workstations among each other in a flexible way and hereby allow elementary changes within the structure of the assembly system. This allows flexibility in variants as well as in volume since single workstations can be duplicated and therefore bottlenecks in an unbalanced system can be reduced swiftly. The assembly line layout therefore is structured in three pre-assembly stations and six end assembly stations. The assembly within the reference and as well the modular concept was planned with the same distribution of assembly contents on the planned stations. At station 1, the fuel cell stack will be lifted by crane into the fuel cell housing and afterwards locked by screwing the media distribution plate with most of the media interfaces. At station 2, the complete anode circuit will be assembled around the housing by screwing and fixating the hydrogen lines with brackets. It was assumed that on a third station, larger components like the compressor, power distribution unit and fuel cell control unit have to be mounted around the housing due to the geometrical restrictions and further accessibility for following assembly operations. On station 4, the entire cathode system is mounted and subsequently on station 5 the whole cooling system finalized. Subsequently to mounting the fluid containing systems around the housing of the stack, an interim leakage testing will be conducted on station 5. This is due to the possibility of rework in case of a failed test. Finally, on station 6 the electronic assembly and wiring is concluded and the system can be removed from the monorail mounting aid.

3.4 Transition from a qualitative concept to a quantitative model

In this chapter, the concept introduced in chapter 3.3 will be evaluated. Therefore, the theoretical and qualitative concept will be transferred into a quantitative model through applying MTM.

For the motion sequences that are assumed to repeat in specific patterns in the overall assembly for several times, codes are defined regarding the MTM methodology and the MTM data map [16]. These codes can be translated within a next step into TMU values, which afterwards can be converted into seconds or minutes. **Table 2** yields an impression of the determination of the TMU values for the assembly of a generic pipe section.

A recombination and reallocation of the assembly contents is conducted aiming to determine suitable assembly sections, that can be outsourced in the pre-assembly. Those pre-assembly contents require to be mountable from chronological later positions within the assembly process and therefore also must meet topological restrictions within the assembly sequence.

In order to determine possible output scenarios for a fuel cell system assembly based on the developed assembly sequence, the durations generated by the MTM-method were transferred into an output model. Therefore, an organizational model of one shift per day with 8 working hours, and 220 working days per year were assumed. Through the cycle time, which is specific for the configuration of the production system, the total possible amount of assembled fuel cell systems per year could be determined. The different production systems will be compared in their demand for assembly personnel and the demand of simultaneous assembly lines.

4. Results and discussion

The application of the MTM methodology under the premise of the derived assembly contents from the BoM resulted in an overall assembly time of around 100.7 minutes for the generic and simplified fuel cell system. By duplication of the workstation with the largest station time, the cycle time of the whole production system decreases to the level of the station with the second largest station time. The station time of this workstation then becomes the new cycle time. The assumed cycle time of the reference concept was determined to 43.97 minutes, including an additional 25 % of estimated set-up time [3]. The cycle time of the modular concept resulted to 30.85 minutes, and could be further decreased to 16.79 minutes by duplication of workstation 5 or to 15.01 minutes by duplication of both, workstation 5 and 6. Transferring these cycle times into possible production volumes as described above, leads to capacity demands in simultaneous assembly lines and personnel for the compared production concepts. The diagrams in **Figure 5** show the development of the demands within the scaling from 1,000 systems to 10,000 systems per year. Whereas the reference concept initially starts with a lower demand for personnel, the modular and therefore scalable concept shows a higher, but for a larger output corridor more stable, demand for personnel. This can be explained by the effect from separation of assembly contents. It is assumed that the pre-assembly and the end assembly can be conducted at the same time and therefore the end assembly at different stations can be reduced. This results in a lower cycle time for the modular concept. The demand for personnel is connected to the number of necessary simultaneous production lines. Within the production volume corridor of 1,000 up to 6,000 fuel cell systems per year for the modular concept, the demand in simultaneous production lines is stable. In the reference concept, which was assumed less flexible in its configuration, a change in production volume of the system results also in a necessary scale-up of this system. Hence, the demand for assembly lines and assembly personnel increases almost linearly. The modular concept therefore has due to its structure the ability to scale-up the production output with less capacity in assembly lines and personnel over the observed production volume corridor. The higher flexibility of the modular concept can be explained with the structure of this concept. The absence of a fix conveyor system allows the duplication of single workstations, which therefore lowers the demand of assembly lines and personnel. This modularity in the production system has therefore also an effect of the cycle time.

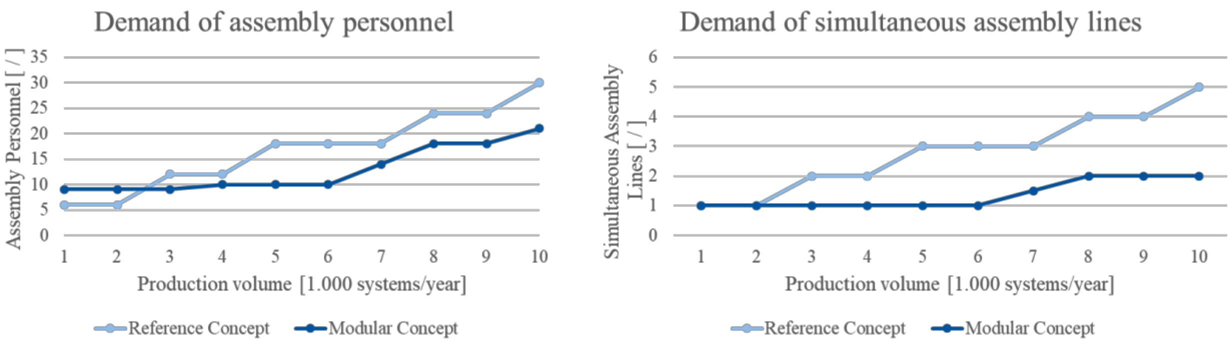


Figure 5: Demand of assembly personnel and simultaneous assembly lines in dependence of the annual production volume

Comparing the values calculated through MTM for a generic and simplified fuel cell system it must be stated that these time values are still far below the durations mentioned in the literature above. This can be justified by the fact that the system was simplified with a limited count for parts in the BoM. In addition, assumptions for the assembly tasks had to be made while applying MTM that can differ from practical handling in assembly. As well, the EoL-Testing is not included within this approach, which reduces the efforts of the considered processes. As mentioned in chapter 3.3, a short leakage test for the fluid conducting subsystems via sniffing probe is included at workstation 5, however it is not covering the whole spectrum of tests to be finally conducted for EoL.

5. Summary and Outlook

In this work, a scalable production concept, that was derived and further elaborated as a modular structured production system, where the assembly content is separated into a pre- and an end assembly. With the help of the methodology of MTM, the derived scalable production concept was at first transferred into a quantitative model that was afterwards compared to a reference model. The comparison showed the scalable concept therefore performed better regarding the examined parameters. It required less simultaneous assembly lines and less assembly personnel while generating the same output in production volume. The data on this topic, which could be used for evaluation, in combination with fuel cell system assembly is very limited. Therefore, values generated by this methodological approach still need to be validated by practical application and differ a lot from the time values that were discovered within the estimation by JAMES ET AL and the Mercedes-Benz GLC F-Cell assembly.

Further research needs to be carried out regarding the accounting of learning effects through economies of scale when applying MTM by calculation of the time values of assembly contents within the pre-assembly, as the time values where assumed in this model to be static over the time dimension. Additional research can as well be conducted on further modularization [31] of the fuel cell system itself by approaches through design for assembly (DFA [32]), where the design gets adapted to the processes in assembly by engineering. As there were no hybrid structures of manual and automated assembly systems examined in this work, this should be a topic for further investigation. It was concluded that possible assembly tasks to involve automation can be located in tasks, where the stack with its high weight is moved or many screws can be mounted and screwed simultaneously. The subsequent EoL-Testing is an important step within the value chain of the fuel cell system production since it guarantees the quality and therefore needs to be further researched and developed [33]. Further research on optimization of cycle time balancing including mechanisms to enhance disassembly for possible defective parts discovered in EoL-Testing is necessary.

Acknowledgements

This research was funded by Federal Ministry for Economic Affairs and Climate Action, Germany grant number 03EN5026A / AV.

Appendix

Table 1: Bill of Materials for the considered fuel cell system; components are distinguished between the station at which they are mounted and the module to which they belong

Station	Component	Module	Quantity
1	Housing	Stack	1
1	Media Distribution Unit	Stack	1
1	Sealing for Media Distribution Unit	Stack	6
1	Screws	Stack	20
2	Solenoid Valves	Anode	1
2	Hydrogen Pipe (incl. T-pieces)	Anode	7
2	Distributor Valve	Anode	1
2	Hydrogen Injector	Anode	1
2	Recirculation Blower	Anode	1
2	Purge Valve	Anode	1
2	Drain Valve	Anode	1
2	Demister	Anode	1
2	Bracket	Anode	2
2	Screws	Anode	20
2	Cable (Power)	Anode	1
2	Cable (Data)	Anode	6
2	Cable Ties	Anode	20
3	Sealing (Compressor/Turbocharger)	Cathode	4
3	Compressor/Turbocharger	Cathode	1
3	Power Distribution Unit	Electric	1
3	Fuel Cell Control Unit	Electric	1
3	Screws	Cathode/Electric	18
3	Cable (Power)	Electric	1
4	Air Inlet	Cathode	1
4	Air Outlet	Cathode	1
4	Pipe	Cathode	11
4	Resonator	Cathode	2
4	Air Filter	Cathode	2
4	T-piece	Cathode	2
4	Bypass Valve	Cathode	1
4	Air Intercooler	Cathode	1

4	Humidifier	Cathode	1
4	Demister	Cathode	2
4	Sealings	Cathode	18
4	Hose Clamps/Clips	Cathode	24
4	Bracket	Cathode	2
4	Screws	Cathode	28
4	Cable (Data)	Cathode	4
4	Cable Ties	Cathode	8
5	Cooling Hoses	Cooling	12
5	T-piece	Cooling	3
5	Hose Clamps/Clips	Cooling	25
5	Sealings	Cooling	23
5	Locking Valve	Cooling	1
5	Ion Exchanger	Cooling	1
5	Coolant Pump	Cooling	1
5	Control Valve	Cooling	1
5	3-way Valve	Cooling	1
5	Compensating Reservoir	Cooling	1
5	Cable (Power)	Cooling	1
5	Cable (Data)	Cooling	8
5	Cable Ties	Cooling	16
6	Cable (Power)	Electric	2
6	Cable (Data)	Electric	3
6	Screws	Electric	10
6	Cable Ties	Electric	36
		Total	370

Table 2: Example for determining TMU values with the MTM data map for manually joining of a generic pipe – component section (no usage of tools)

Description of motion sequence	Information relevant for time assignment	Code	Time value [TMU]	Time value [seconds]
Movement to the material commission and way back	Walking / 6 m	KA6	150	5.40
Grabbing and placing of pipe	Component < 1kg, loose placing / range of motion between 50 and 80 cm	AE3	70	2.52

Grabbing of component and joining with pipe	Component < 1kg, narrow placing	AF3	80	2.88
Visual control	Visual control	VA	15	0.54
Put workpiece aside	Component < 1kg, loose and approximate placing	AA3	50	1.80
Total	-	-	365	13.14

References

[1] Kampker, A., Heimes, H., Kehrer, M., Hagedorn, S., Reims, P., 2022. Brennstoffzellensystemkosten durch Skaleneffekte senken. maschinenbau (3), 28–31.

[2] Wang, J., Wang, H., Fan, Y., 2018. Techno-Economic Challenges of Fuel Cell Commercialization. Engineering 4 (3), 352–360.

[3] James, B., Huya-Kouadio, J., Houchins, C., DeSantis, D., 2018. Mass Production Cost Estimation of Direct H2 PEM Fuel Cell Systems for Transportation Applications: 2018 Update. https://www.researchgate.net/profile/Brian-James-5/publication/341407810_Final_SA_2018_Transportation_Fuel_Cell_Cost_Analysis_-2020-01-23/links/5ebea64ba6fdcc90d675d7b4/Final-SA-2018-Transportation-Fuel-Cell-Cost-Analysis-2020-01-23.pdf. Accessed 11 July 2023.

[4] Heimes, H., Kehrer, M., Hagedorn, S., Biegler, S., Krieger, G., Müller, J., 2022. PRODUKTION VON BRENNSTOFFZELLENSYSTEMEN. PEM RWTH Aachen; VDMA AG Brennstoffzellen, Aachen. https://www.pem.rwth-aachen.de/global/show_document.asp?id=aaaaaaaabxhbbde.

[5] Marcinkoski, J., James, B.D., Kalinoski, J.A., Podolski, W., Benjamin, T., Kopasz, J., 2011. Manufacturing process assumptions used in fuel cell system cost analyses. Journal of Power Sources 196 (12), 5282–5292.

[6] Deppe, P., 2018. BLICK AUF DIE BRENNSTOFFZELLEN-SYSTEMMONTAGE AM DAIMLER STANDORT KIRCHHEIM-NABERN. mbpassionblog. https://mbpassion.de/2018/03/blick-auf-die-brennstoffzellen-systemmontage-am-daimler-standort-kirchheim-nabern/. Accessed 11 July 2023.

[7] Preiss, H., 2018. Brennstoffzelle passt für alle: Mercedes GLC F-Cell - ist er der Heilsbringer? n-tv Nachrichtenfernsehen GmbH. https://www.n-tv.de/auto/Mercedes-GLC-F-Cell-ist-er-der-Heilsbringer-article20345077.html.

[8] YOUCAR, 2018. Mercedes Hydrogen Engine Factory. https://www.youtube.com/watch?app=desktop&v=aScDGQQcMv8. Accessed 11 July 2023.

[9] Bauernhansl, T., Miehe, R., 2020. Industrielle Produktion – Historie, Treiber und Ausblick, in: Bauernhansl, T. (Ed.), Management in der Produktion. Springer Vieweg, Berlin, Heidelberg, pp. 1–33.

[10] Sethi, A., Sethi, S., 1990. Flexibility in manufacturing: A survey. Int J Flex Manuf Syst 2 (4).

[11] Bebersdorf, P., Huchzermeier, A., 2022. Variable Takt Principle: Mastering Variance with Limitless Product Individualization. Springer International Publishing; Imprint Springer, Cham, 86 pp.

[12] Fechter, M., Dietz, T., 2020. Bewertung der Wandlungsfähigkeit eines Produktionssystems, in: Bauernhansl, T., Fechter, M., Dietz, T. (Eds.), Entwicklung, Aufbau und Demonstration einer wandlungsfähigen (Fahrzeug-) Forschungsproduktion. Springer Vieweg, Berlin, Heidelberg, pp. 11–17.

[13] Staehr, T., Stricker, N., Lanza, G., 2020. Autonomous planning tool for changeable assembly systems. Procedia CIRP 88, 104–109.

[14] MTM ASSOCIATION e. V. MTM-UAS Basic Operations. https://mtm.org/fileadmin/user_upload/MTM-UAS_data_card_basic_operations_2019_EN.pdf. Accessed 11 July 2023.

[15] Deuse, J., Busch, F., 2012. Zeitwirtschaft in der Montage, in: Lotter, B., Wiendahl, H.-P. (Eds.), Montage in der industriellen Produktion. Ein Handbuch für die Praxis ; mit 18 Tabellen, 2. Aufl. ed. Springer Vieweg, Berlin, Heidelberg, pp. 79–107.

[16] Finsterbusch, T., Kuhlang, P., 2021. Position der MTM ASSOCIATION e. V. zur Anwendung des Prozessbausteinsystems MTM-UAS: MTM-Schriftenreihe Industrial Engineering. 16.

[17] REFA - Verband für Arbeitsgestaltung, Betriebsorganisation und Unternehmensentwicklung, 2016. Industrial Engineering: Standardmethoden zur Produktivitätssteigerung und Prozessoptimierung, 2. Auflage ed. Hanser; Ciando, München, 1279 pp.

[18] Proton Motor Fuel Cell GmbH, 2019. Meilenstein für Technologie-Marktführer Proton Motor Fuel Cell GmbH: Offizielle Inbetriebnahme der neuen Brennstoffzellen-Fertigungsanlage. https://www.proton-motor.de/meilenstein-fuer-technologie-marktfuehrer-proton-motor-fuel-cell-gmbh-offizielle-inbetriebnahme-der-neuen-brennstoffzellen-fertigungsanlage-%E2%97%8F-bayerischer-staatsminister-hubert-aiwanger-starte/. Accessed 3 August 2023.

[19] AUTOMOBIL INDUSTRIE, 2022. Vorreiter bei der Brennstoffzelle. https://www.automobil-industrie.vogel.de/vorreiter-bei-der-brennstoffzelle-a-3c56076084474263db37cf5c2581c61b/. Accessed 3 August 2023.

[20] Challen, J., 2021. Assembling Electric Vehicle Motors: Engineers are scrambling to find cost-effective ways to mass-produce EV motors. https://www.assemblymag.com/articles/96393-assembling-electric-vehicle-motors. Accessed 11 July 2023.

[21] Michaelis, S., Rahmizei, E., Kampker, A., Heimes, H., Offermanns, C., Locke, M., Löbberding, H., Wennemar, S., Thielmann, A., Hettesheimer, T., Neef, C., Kwade, A., Haselrieder, W., Blömeke, S., Doose, S., Drachenfels, N. von, Drees, R., Fröhlich, A., Gottschalk, L., Hoffmann, L., Kouli, M., Leithoff, R., Rahlfs, S., Rickert, J., Schmidt, L., Schoo, A., Thomitzek, M., Turetskyy, A., Vysoudil, F., 2021. Roadmap Batterie-Produktionsmittel 2030: Update 2020. VDMA Batterieproduktion, Frankfurt am Main. https://www.vdma.org/c/document_library/get_file?uuid=6037f526-9679-43a2-35a1-513090abd700&groupId=34570. Accessed 11 July 2023.

[22] Sharma, A., Zanotti, P., Musunur, L.P., 2019. Enabling the Electric Future of Mobility: Robotic Automation for Electric Vehicle Battery Assembly. IEEE Access 7, 170961–170991.

[23] Kampker, A., 2014. Montagetechnik für Elektrofahrzeuge, in: Kampker, A., Nowacki, C. (Eds.), Elektromobilproduktion. Springer Vieweg, Berlin, Heidelberg, pp. 235–285.

[24] D'Souza, R., Patsavellas, J., Salonitis, K., 2020. Automated assembly of Li-ion vehicle batteries: A feasibility study. Procedia CIRP 93, 131–136.

[25] Mayr, A., Weigelt, M., Lindenfels, J. von, Seefried, J., Ziegler, M., Mahr, A., Urban, N., Kuhl, A., Huttel, F., Franke, J., 2018. Electric Motor Production 4.0 – Application Potentials of Industry 4.0 Technologies in the Manufacturing of Electric Motors, in: 2018 8th International Electric Drives Production Conference (E|DPC). 4 and 5 December 2018, Schweinfurt, Germany : proceedings. 2018 8th International Electric Drives Production Conference (EDPC), Schweinfurt, Germany. 12/4/2018 - 12/5/2018. IEEE, Piscataway, NJ, pp. 1–13.

[26] Kampker, A., Schuh, G., Swist, M., Ivanescu, S., 2011. Future assembly structures for electric vehicles. ATZ Autotechnol 11 (2), 58–63.

[27] ANews-Mobility, 2022. ANews-Mobility - Reportage chez Hyvia: l'hydrogène pour véhicules, selon Renault et Plug-Power… https://www.youtube.com/watch?app=desktop&v=JY_vC6d0LH4. Accessed 11 July 2023.

[28] Planet Car News, 2022. Renault HYVIA Plant: Assembly and Test of fuel cell modules based on Plug Power. https://www.youtube.com/watch?v=56L4xf9uf6c. Accessed 11 July 2023.

[29] Jiang, J., Huang, Z., Bi, Z., Ma, X., Yu, G., 2020. State-of-the-Art control strategies for robotic PiH assembly. Robotics and Computer-Integrated Manufacturing 65, 101894.

[30] HYVIA, 2021. HYVIA UNVEILS ITS FIRST HYDROGEN PROTOTYPES. https://media.renaultgroup.com/hyvia-unveils-its-first-hydrogen-prototypes/.

[31] Pilley, S., Morkos, B., Alfalahi, M., 2018. Integration and Modularity Analysis for Improving Hybrid Vehicles Battery Pack Assembly, in: SAE Technical Paper Series. WCX World Congress Experience. APR. 10, 2018. SAE International400 Commonwealth Drive, Warrendale, PA, United States.

[32] Boothroyd, G., Alting, L., 1992. Design for Assembly and Disassembly. CIRP Annals 41 (2), 625–636.

[33] 2021. Positionspapier „Brennstoffzelle“: AG 4 - ZWISCHENBERICHT. https://www.plattform-zukunft-mobilitaet.de/wp-content/uploads/2021/04/NPM_AG4_Positionspapier_Brennstoffzelle.pdf. Accessed 11 July 2023.

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 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. From March 2019 to 2023, he was PEM's Executive Chief Engineer before being appointed Professor.

Mario Kehrer (*1990) studied electrical engineering and information technology at Karlsruhe Institute of Technology (KIT). He joined the chair “Production Engineering of E-Mobility Components” (PEM) of RWTH Aachen University in 2017, where he became chief engineer of the Fuel Cell and Electrification Engineering division in 2021.

Sebastian Hagedorn (*1992) 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.

Julius Hausmann (*1995) is research associate at the Chair of Production Engineering of E-Mobility Components (PEM) at RWTH Aachen University. He studied mechanical engineering with a focus on chemical engineering at RWTH Aachen University.

Johann von Harling (*1998) studied industrial engineering with a focus on energy engineering at RWTH Aachen University. He works as a research assistant during his master’s degree at the Chair of Production Engineering of E-Mobility Components (PEM) at RWTH Aachen University.

CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
CPSL 2023-2

5th Conference on Production Systems and Logistics

Ecological Evaluation Of H_2 Energy Supply In Industry

Yvonne Eboumbou Ebongue[1], Felix Schnell[1], Alexander Emde[1], Alexander Sauer[1,2]

[1]Institute for Energy Efficiency in Production EEP, University of Stuttgart, Nobelstr. 12, 70567 Stuttgart, Germany
[2]Fraunhofer Institute for Manufacturing Engineering and Automation IPA, Nobelstr. 12, 70569 Stuttgart, Germany

Abstract

Limiting climate change through global CO_2 emissions is one of the central challenges of the 21st century. This requires a profound transformation of our energy systems and a far-reaching switch to innovative and emission-free technologies in all sectors, from power generation to the major energy consumption sectors of industry, transport and building heating. Hydrogen will play a significant role in a future energy and economic system.

In this paper, H_2 energy supply scenarios are developed, evaluated and compared as an alternative to a reference scenario that uses conventional technologies to meet electricity, heating and cooling needs. The H_2 energy supply scenarios are evaluated with both purchased and self-produced hydrogen. Both the different colours of the hydrogen and the CO_2 intensity of the electricity mix are considered. To cover the electricity and heat demand, different hydrogen technologies are considered and combined to different H_2 energy supply scenarios. Subsequently, the scenarios are evaluated with regard to their sustainability and compared with the reference scenario. The evaluation shows that blue and green hydrogen have an environmental advantage over natural gas, but availability is limited. Therefore, it is advisable to produce hydrogen oneself. Compared to natural gas, however, this only has an ecological advantage if the emission factor of the electricity mix is reduced through the use of renewable energies.

Keywords

H_2 energy supply; CO_2 emissions; hydrogen technologies; sustainability, ecological evaluation

1. Introduction

Hydrogen (H_2) is considered an important energy carrier for implementing the energy transition to achieve the climate goals by science, industry, and politics [1]. Industry is responsible for a significant proportion of global energy consumption and associated greenhouse gas emissions. It faces the challenge of making its processes more environmentally friendly [2]. In this context, the use of hydrogen as an energy carrier for industrial energy supply is becoming increasingly important. Hydrogen offers a promising alternative to conventional fossil fuels, as its combustion with oxygen produces only water vapour and no carbon dioxide (CO_2) emissions [3]. Moreover, hydrogen can be produced via electrolysis from renewable energy sources, ensuring this technology's long-term sustainability [4,5]. Using hydrogen in industry allows heating, electricity, and cooling in an environmentally friendly way makes an important contribution to reducing CO_2 emissions and achieving climate targets [6]. The environmental assessment of H_2 energy supply scenarios in industry is crucial to make informed decisions on the implementation of this technology.

In this paper, H_2 energy supply scenarios are developed, evaluated, and compared as an alternative to a reference scenario that uses conventional technologies to meet electricity, heating, and cooling needs. The

DOI: https://doi.org/10.15488/15316
ISSN: 2701-6277

methodological approach to energy system planning developed by Emde was used to develop and evaluate the H_2 energy supply scenarios [7]. The H_2 energy supply scenarios are evaluated with both purchased and self-produced hydrogen. Both, the different colours of the hydrogen and the CO_2 intensity of the electricity mix are considered. To meet the electricity and heat demand, different hydrogen-based technologies are considered and combined into different H_2 energy supply scenarios. The scenarios are then evaluated from an environmental perspective. The results are compared with the reference scenario. From this, it can be concluded how hydrogen technologies for industrial energy supply can be an environmentally sound alternative to conventional technologies today and in the future.

2. Fundamentals

The following chapter explains the basics for understanding CO_2 intensity and introduces hydrogen technologies.

2.1 Carbon intensity of hydrogen and electricity

Carbon intensity refers to the amount of CO_2 emissions produced per unit of energy produced or consumed [8,9]. It is a measure of the environmental impact of a particular energy source, activity or sector in terms of its emissions. A lower carbon intensity means that a given energy production or consumption results in fewer CO_2 emissions, which is desirable from an environmental perspective [10].

2.1.1 Colours of hydrogen

In the field of hydrogen production, different colours are used. Grey hydrogen is the dominant technology today. In the standard steam reforming process, hydrogen is produced by using natural gas [8,9]. It is currently the most cost-effective process, but large amounts of CO_2 are released in the process. Direct emissions from grey hydrogen average 398 g CO_2/kWh [8]. Blue hydrogen is produced via steam reforming with subsequent CO_2 capture and storage [8,9]. In this process, 85 % to 95% of the CO_2 emissions can be captured and stored in natural gas reservoirs [1]. Therefore, blue hydrogen can only be partially decarbonised. On average, blue hydrogen produces a greenhouse gas impact of 143 g CO_2/kWh to 218 g CO_2/kWh [8,11]. Green hydrogen aims at the complete decarbonisation of hydrogen production [8,9]. In electrolysers, electricity is used to break down water into its components hydrogen and oxygen. The process releases no CO_2 if the used electricity was produced without emissions. Green hydrogen produced with green electricity can be made available with emissions as less as 26 g CO_2/kWh [8,11]. Currently, around 0,7 % of the world's hydrogen is produced via electrolysis, powered by renewable energies [12]. Figure 1 shows the global hydrogen demand and the available quantities of blue and green hydrogen in TWh today and in the future [13]. It can be seen that the demand for hydrogen significantly exceeds the availability.

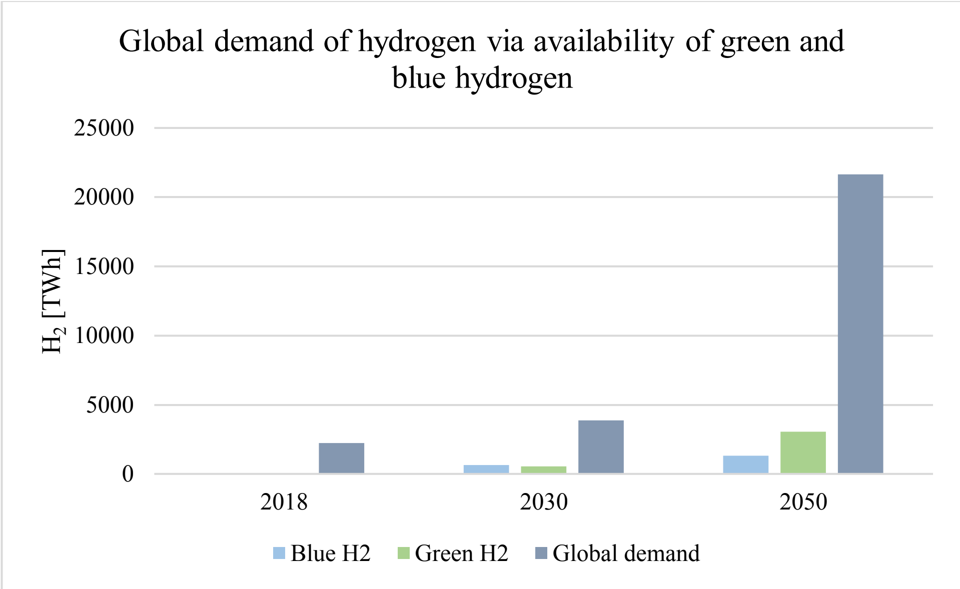


Figure 1: Global demand of hydrogen and availability of green and blue hydrogen [13]

2.1.1 Carbon intensity of electricity

Specific CO_2 emissions from electricity vary depending on the type of electricity generation and the energy mix of a country or region. In general, there are several sources of CO_2 emissions from electricity generation, including for example fossil fuels and renewable energy sources [10]. A worldwide overview of the specific CO_2 emissions of electricity is given in Figure 2. Worldwide, producing one kWh of electricity emits about 436 g CO_2 [10].

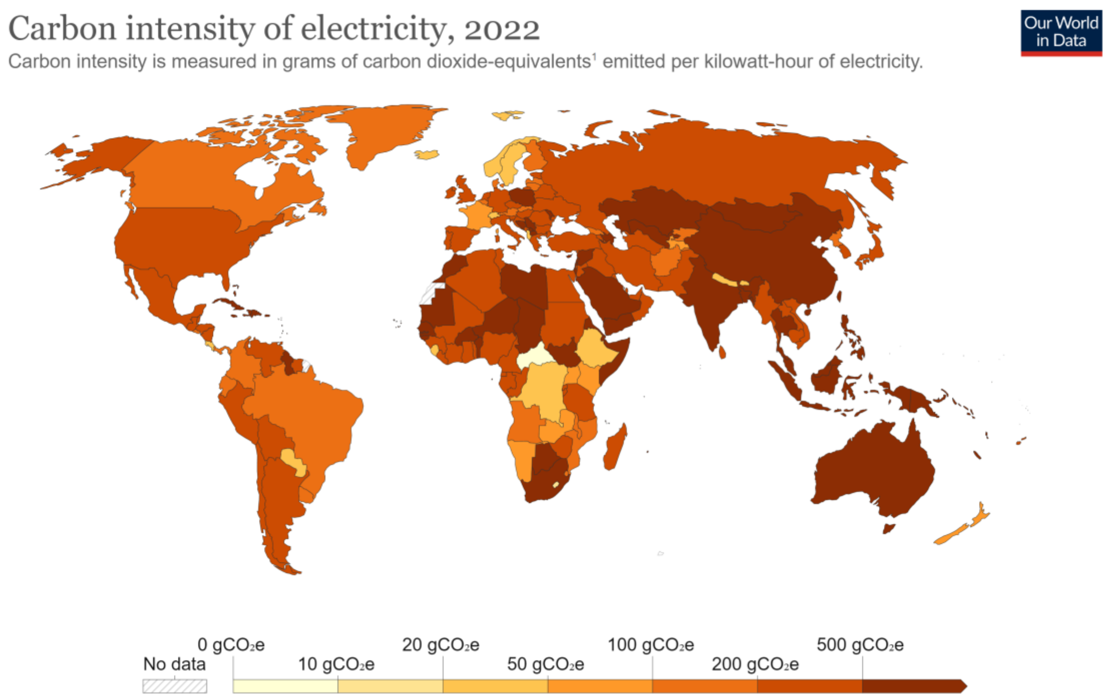


Figure 2: Worldwide overview of the specific CO_2 emissions of electricity [10]

2.2 Hydrogen technologies

Numerous hydrogen technologies were researched and considered for the evaluation. The technologies explained in more detail here prove to be the technically most suitable for the energy supply scenarios investigated to cover the electricity and heat demand.

2.2.1 PEM Electrolysis

Water electrolysis is a process in which water is broken down into its components, hydrogen and oxygen, with the help of electricity [14]. PEM (proton exchange membrane) electrolysis is a special form of water electrolysis in which a proton exchange membrane is used as the electrolyte. The reaction at the electrodes and the electrolyte leads to heat energy generation [6]. This heat must be dissipated to keep the operating temperatures of the electrolysis cells at an optimal level. PEM electrolysers operate in the temperature range from about 20 ◦C to 100 ◦C and the efficiency varies between 67 % and 82 % [15]. PEM electrolysis is used because of its advantages over other types of electrolysis in terms of compactness, scalability, high dynamics and overload capability [6].

2.2.2 PEM Fuel Cell

The fuel cell is an electrochemical energy converter that converts the chemically bound energy of a fuel directly into electrical energy and heat. A PEM fuel cell belongs to the category of low-temperature hydrogen fuel cells. Its central component is the proton exchange membrane, which allows the passage of protons but blocks the passage of electrons. PEM fuel cells operate in the temperature range from about 0 ◦C to 80 ◦C and the electrical efficiency varies around 40 % and the thermal efficiency around 55 % [15]. The PEM fuel cell is used because of its advantages over other types of fuel cell in terms of fast start-up, high power density, and their ability to control operating temperatures [16]. On the other hand, a PEM fuel cell needs a certain amount of time to allow the electrochemical reactions to take place and generate energy.

2.2.3 Hydrogen Burner

The hydrogen burner is a system for generating heat by burning hydrogen to provide process heat. Hydrogen is supplied to a hydrogen burner as fuel and mixed with oxygen [17,18]. A hydrogen burner generates heat immediately as soon as the hydrogen reacts exothermic with the oxygen in the air. The thermal efficiency varies around 90 %. The combustion reaction can take place relatively quickly, providing rapid heat in a temperature range from hundreds to several thousand degrees Celsius [17,18]. Heat energy is used, for example, to heat water and generate steam. Advantages are low pollutant emission values, high efficiency, and flexibility.

3. Hydrogen energy supply scenarios

The reference scenario exemplifies a medium-sized company's electricity, heating in low temperature range and cooling supply in southern Germany over a one-year period. An overview of the reference scenario's processes is given in Figure 3.

To cover its electricity needs, the company obtains electricity from the public grid. Electricity is also used to operate the compression chiller with a power output of 1 000 kW_{th} to cover the company's cooling requirements. A natural gas burner with a power output of 1 200 kW_{th} is used to cover the heat demand. This obtains fuel from the public natural gas supplier. First, the scenario is evaluated with an electricity mix and then with green electricity. In the following, three alternative energy supply scenarios are created, all using hydrogen. The aim is to compare whether, and under which conditions, the use of hydrogen to cover the electricity and heat demand offers ecological advantages compared to the reference scenario.

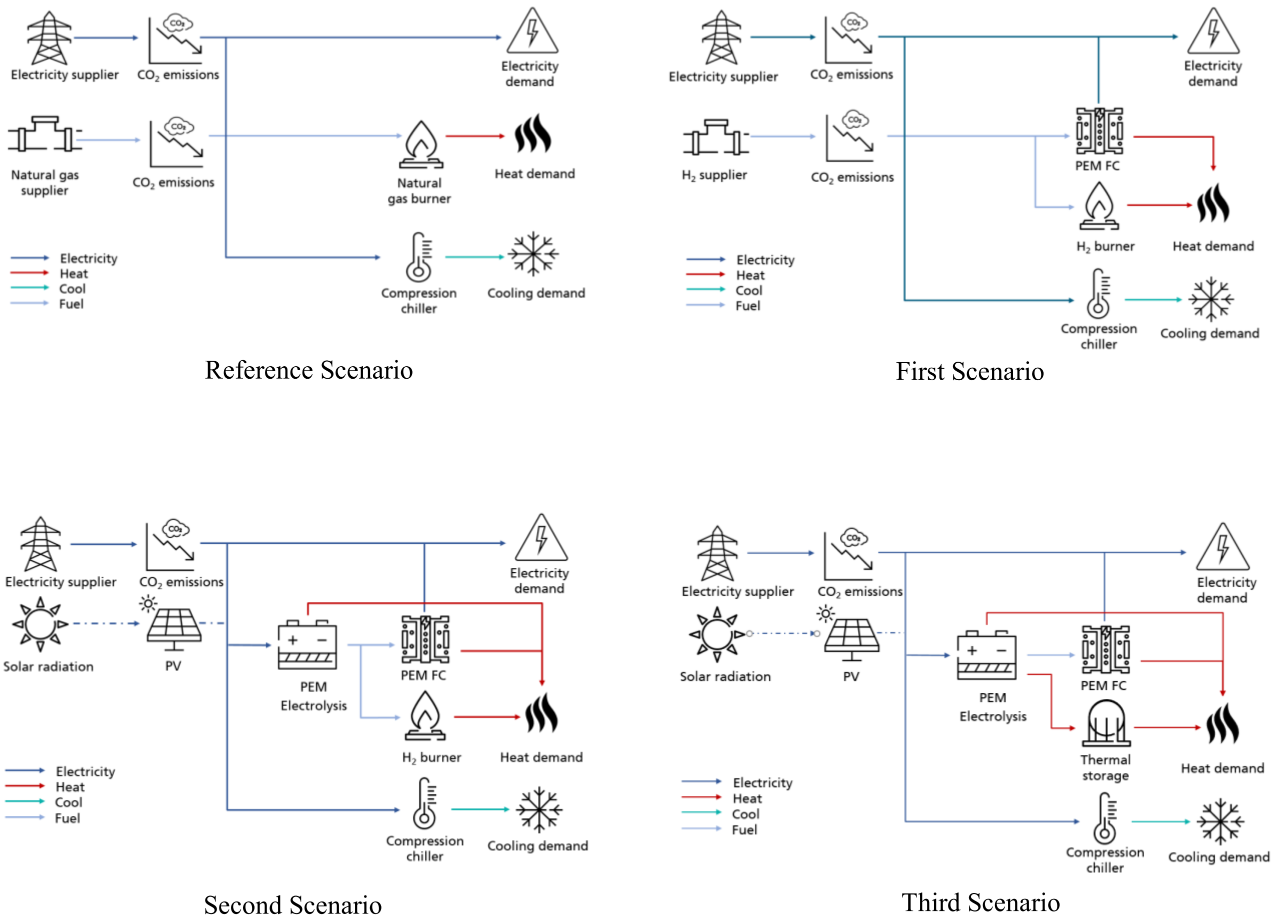


Figure 3: Overview of the processes of the evaluated scenarios

In the first scenario, the company obtains hydrogen from the public hydrogen grid to supply the PEM fuel cell and the hydrogen burner. The PEM fuel cell is designed for 800 kW_{el} and covers both the company's heat and electricity demand. Since the hydrogen burner can generate heat faster than the PEM fuel cell, it is added to the scenario to cover the peak heat demand. This is designed for a capacity of 150 kW_{th}. The hydrogen burner is only used to cover the peak load, as the hydrogen burner does not like to operate at partial load. In addition to the power supply from the PEM fuel cell, the company draws an electricity mix from the public grid to cover the peak loads of the electricity demand. To cover the cooling demand, the compression chiller is operated with a capacity of 1 000 kW_{th}, primarily powered by the electricity produced by the PEM fuel cell and secondarily with electricity mix from the public electricity grid. In this scenario, both grey, blue, and green hydrogen are considered. First, the scenario is evaluated with an electricity mix and then with green electricity. The processes of the second scenario continues to consist of a PEM fuel cell with an output of 400 kW_{el} to cover the base load of the heat and electricity demand and a hydrogen burner with an output of 200 kW_{th} to cover the peak load of the heat demand. Hydrogen is produced via PEM electrolysis. This is also operated with electricity from the public grid and designed for 1 700 kW_{el}. The hydrogen produced is added to the PEM fuel cell and the hydrogen burner. The resulting waste heat from the PEM electrolysis plant is also used to cover the heat demand. The compression chiller covers the cooling demand. It is primarily powered by the electricity produced by the PEM fuel cell and secondarily by electricity from the public grid. First, the scenario is evaluated with electricity mix and then with green electricity. The second scenario is then expanded to include a photovoltaic (PV) system on a roof area of over 7 700 m^2 with an output of 1 400 kW_p primarily to cover the electricity demand. In addition, the PV system drives the PEM electrolysis system and the compression chiller, which is designed for 1 000 kW_{th}. This expansion is also evaluated first with an electricity mix and then with green electricity. In the third scenario, a thermal storage unit replaces the hydrogen burner with a capacity of 500 kWh. This covers the peak heat demand that can be met neither by the PEM electrolysis nor the PEM fuel cell. In this scenario, the PEM electrolysis is designed for 1 700 kW_{el} and the PEM fuel cell for 500 kW_{el}. First, the scenario is evaluated with an electricity mix and then with green electricity. Subsequently, the third scenario is also expanded to include a PV system with an output of 1 400 kW_p. This expansion is also evaluated first with an electricity mix and then with green electricity.

4. Ecological comparison

For all the scenarios, the CO_2 emission values listed in Table 1 are used.

Table 1: Overview of CO_2 emission values for the evaluation

	Emission value [g CO_2/kWh]	Source
Electricity mix Germany	420	Federal Environment Agency [19]
Green power Germany	16	Federal Environment Agency [19]
Natural gas Germany	247	Federal Environment Agency [20]
Grey H_2 Germany	400	Greenpeace energy [8]
Blue H_2 Germany	140	Greenpeace energy [8]
Green H_2 Germany	26	Greenpeace energy [8]

The first scenario is evaluated for grey, blue and green hydrogen as well as with an electricity mix and with green electricity. The total CO_2 emissions can be divided into electricity-related and fuel-related CO_2 emissions. The results of the evaluation of the first scenario can be seen in Figure 4. The CO_2 emissions of the individual evaluations are related to the CO_2 emissions of the reference case with an electricity mix. In the reference case, electricity-related CO_2 emissions account for about 70 % of total CO_2 emissions. These can be reduced to less than three percent by using green electricity.

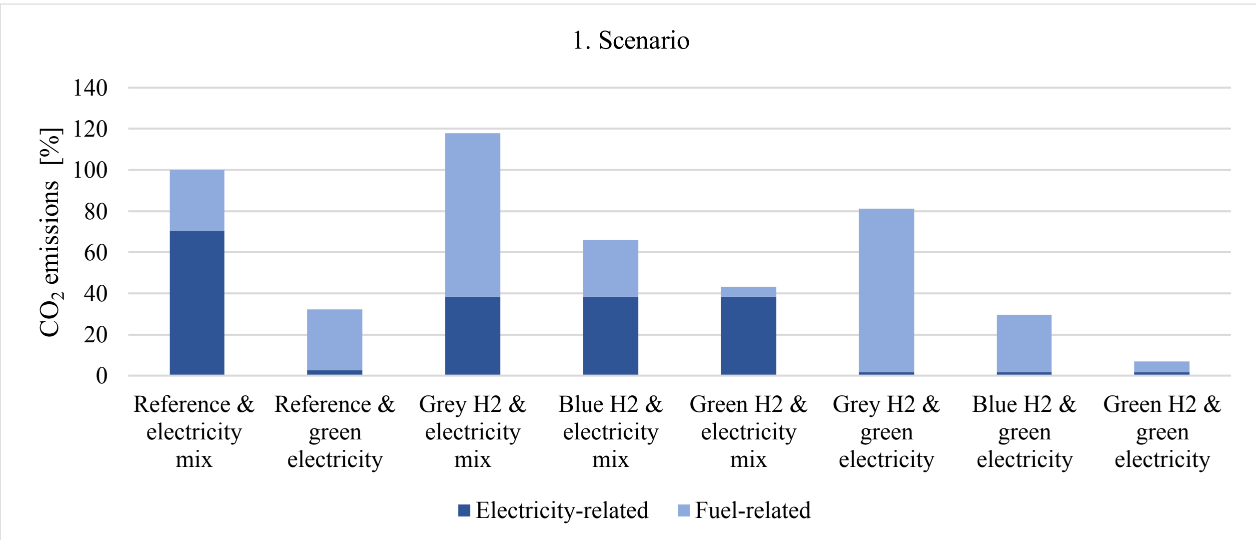


Figure 4: CO_2 emissions in percent of the first scenario compared to the reference scenario

It is striking that the fuel-related CO_2 emissions for the use of grey hydrogen are more than twice as high as for the use of natural gas. However, using PEM fuel cell generates electricity, which is why less electricity is needed from the public grid. Therefore, the electricity-related CO_2 emissions decrease. When using an electricity mix, they fall by about half; when using green electricity, they fall to less than two percent in relation to the reference case. The fuel-related CO_2 emissions for using blue hydrogen are slightly below those of the reference case. However, since using PEM fuel cell saves electricity-related CO_2 emissions, this case offers ecological advantages compared to the reference scenario. The fuel-related CO_2 emissions from the use of green hydrogen fall to about five percent relative to the reference case. In combination with the reduction of electricity-related CO_2 emissions, the use of green hydrogen saves almost 60 % of the emissions compared to the reference scenario.

The second scenario is assumed with and without the feed-in of the PV system as well as with electricity mix and with green electricity. The results of the scenarios are shown in Figure 5.

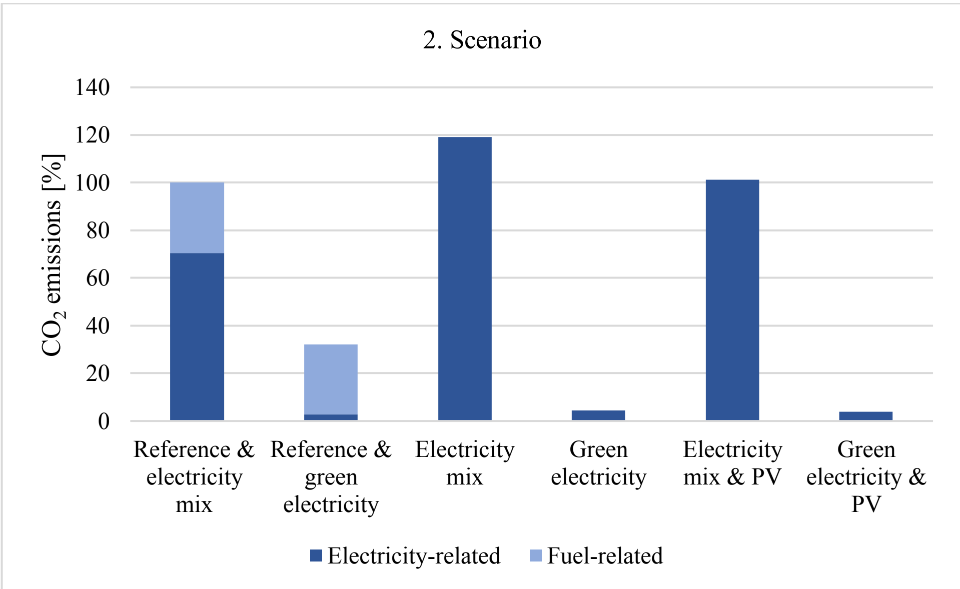


Figure 5: CO_2 emissions in percent of the first scenario compared to the reference scenario

The CO_2 emissions of the individual evaluations are again related to the CO_2 emissions of the reference case with an electricity mix. In the second scenario, the use of PEM electrolysis for the self-production of hydrogen eliminates fuel-related CO_2 emissions. However, the PEM electrolysis requires more electricity than is produced by the PEM fuel cell, which is why the electricity consumption from the grid increases. When using an electricity mix, the total CO_2 emissions increase by almost 20 %. The emission factor of the electricity mix must drop by 16 % to 350 g CO_2/kWh for the emissions to correspond to the reference. By using green electricity, about 95 % of the CO_2 emissions can be saved compared to the reference scenario. The use of a PV system for the self-generation of electricity shows ecologic advantages. When using the electricity mix and PV, emissions are 1 % higher than in the reference scenario, but fall by over 17 % compared to the electricity mix alone. With the use of green electricity and PV, the CO_2 emissions are reduced by more than 97 % compared to the reference scenario.

The third scenario is assumed with and without feed-in from the PV system as well as with electricity mix and with green electricity. The results of the scenarios are shown in Figure 6.

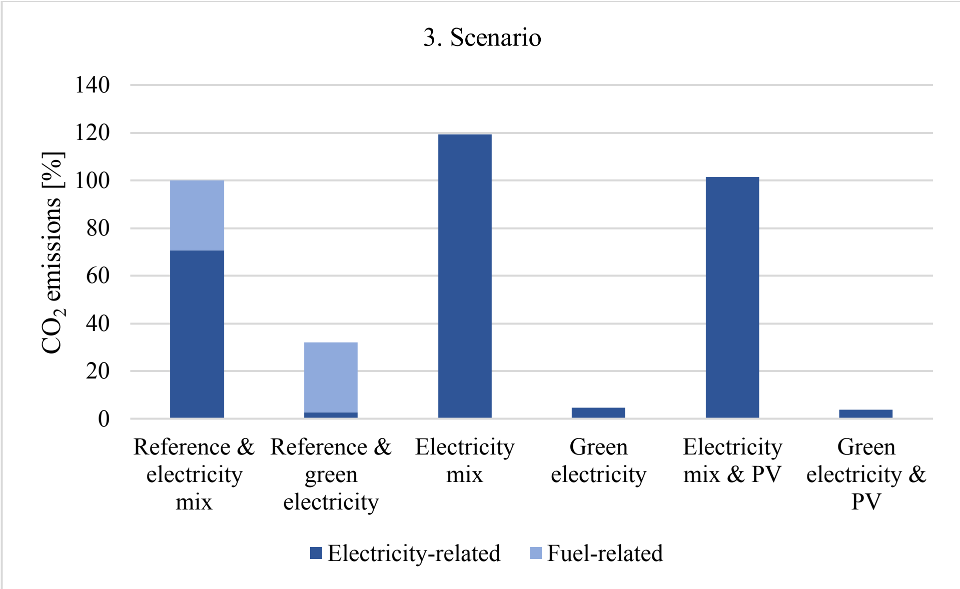


Figure 6: CO_2 emissions in percent of the first scenario compared to the reference scenario

The CO_2 emissions of the individual evaluations are again related to the CO_2 emissions of the reference case with an electricity mix. The third scenario behaves similarly to the second scenario. By using PEM electrolysis for the self-production of hydrogen, the fuel-related CO_2 emissions are eliminated. PEM electrolysis again requires more electricity than is produced by the PEM fuel cell, which is why electricity consumption from the grid increases. When using the electricity mix, the total CO_2 emissions increase by almost 20 %. The emission factor of the electricity mix must drop by 16 % to 350 g CO_2/kWh for the emissions to correspond to the reference. By using green electricity, more than 95 % of the CO_2 emissions can be saved compared to the reference scenario. Once again, using a PV system for the self-generation of electricity shows ecological advantages. With the electricity mix and PV, emissions are 1% higher than in the reference scenario but more than 17% lower than with the electricity mix alone. The use of green electricity and PV reduces CO_2 emissions by more than 97% compared to the reference scenario.

5. Evaluation and Conclusion

Scenario 1 shows that using blue and green hydrogen has environmental advantages compared to the reference case. Companies should thus aim to increase the use of blue and green hydrogen. However, as shown in Figure 1, the availability of blue and green hydrogen today and in the future is low compared to the demand. Therefore, self-production of hydrogen by electrolysis is recommended to cover the hydrogen demand. Companies can consider investing in electrolysis plants to produce their own hydrogen. This allows greater independence from external hydrogen suppliers and contributes to the reduction of CO_2 emissions, especially if electrolysis is coupled with renewable energies such as PV plants. On average, both the use of grey hydrogen and the use of the electricity mix for the self-production of hydrogen through PEM electrolysis do not show any ecological advantages compared to the reference scenario. For hydrogen self-production to make environmental sense compared to the reference scenario, the emission factor of the public grid must be very low. The emission factor of the electricity mix must be 350 g CO_2/kWh or less in the evaluated scenarios for hydrogen self-production through electrolysis to have an ecological advantage over the reference scenario. This value lies below the world average. The CO_2 intensity of the electricity mix must drop to 185 g CO_2/kWh for hydrogen produced by electrolysis to have the same emission factor as the heat supply using natural gas. The CO_2 intensity of the electricity mix must decrease to 75 g CO_2/kWh so that hydrogen produced by electrolysis has the same emission factor as blue hydrogen. Companies should take measures to reduce the CO_2 emission factor of the electricity used for electrolysis to produce hydrogen. This can be done by using renewable energies such as PV systems or purchasing green electricity. This reduces the CO_2 intensity of the hydrogen produced and achieves environmental benefits compared to the reference scenario. Since industrial companies cannot influence this emission factor of the public grid, local measures should be taken into account to reduce the CO_2 emission factor of the electricity used for electrolysis to produce hydrogen. Depending on the location, different measures may be required to reduce the CO_2 intensity of the hydrogen produced. Therefore, it is important to analyse the specific conditions on site and to develop appropriate emission reduction strategies. Since this paper focuses on the environmental benefits of hydrogen integrated energy supply, further work should subsequently address the environmental and technical feasibility of the H_2 energy supply scenarios

Acknowledgements

The authors would like to thank the German Federal Ministry of Education and Research (BMBF) for funding and supervising theWAVE-H2 research project and thus this work.

References

[1] Gerhardt, N., Bard, J., Schmitz, R., Pfennig, M., Kneiske, T., 2020. Wasserstoff im zukünftigen Energiesystem: Fokus Gebäudewärme: Studie zum Einsatz von H2 im zukünftigen Energiesystem mit dem besonderen Fokus auf die Gebäudewärmeversorgung. https://publica-rest.fraunhofer.de/server/api/core/bitstreams/6f08118c-98fb-4d13-8e4e-29bf0ce0956c/content. Accessed 27 June 2023.

[2] Crippa, M., Guizzardi, D., Banja, M., Solazzo, E., Muntean, M., Schaaf, E., Pagani, F., Monforti-Ferrario, F., Olivier, J., Quadrelli, R., Risquez Martin, A., Taghavi-Moharamli, P., Grassi, G., Rossi, S., Jacome Felix Oom, D., Branco, A., San-Miguel-Ayanz, J. and Vignati, E, 2022. CO2 emissions of all world countries. https://publications.jrc.ec.europa.eu/repository/handle/JRC130363. Accessed 27 June 2023.

[3] Agert, C., Brand, U., Dyck, A., Lorenz, T., Naegler, T., Pregger, T., Rieder, T., Riedel, U., Steck, F., Vogt, T., 2020. Wasserstoff als ein Fundament der Energiewende: Teil 2: Sektorenkopplung und Wasserstoff: Zwei Seiten der gleichen Medaille. Deutsches Zentrum für Luft- und Raumfahrt e. V. (DLR). https://elib.dlr.de/139867/#:~:text=Der%20vorliegende%20zweite%20Teil%20%2D%20Sektorenkopplung,systemisch%20wichtigen%20Aspekt%20der%20R%C3%BCckverstromung. Accessed 27 June 2023.

[4] Deutscher Bundestag, 2020. Kosten der Produktion von grünem Wasserstoff: Dokumentation. https://www.bundestag.de/resource/blob/691748/01a954b2b2d7c70259b19662ae37a575/WD-5-029-20-pdf-data.pdf. Accessed 27 June 2023.

[5] Leiblein, J., Bär, K., Graf, F., Kühn Michael, Müller, S., Bäuerle, M., Benthin, J., 2020. Bewertung von alternativen Verfahren zur Bereitstellung von grünem und blauem H2. https://www.dvgw.de/medien/dvgw/forschung/berichte/g201824-abschlussbericht-d1.1-rmg2050-h2-Bereitstellung.pdf. Accessed 27 June 2023.

[6] Töpler, J., Lehmann, J., 2017. Wasserstoff und Brennstoffzelle. Springer Berlin Heidelberg, 369 pp.

[7] Emde, A., Schnell, F., Sauer, A., 2023. Methodisches Vorgehen zur Energiesystemplanung, wt Werkstattstechnik online 113 (01-02), 13–17.

[8] Bukold, S., 2020. Blauer Wasserstoff: Perspektiven und Grenzen eines neuen Technologiepfades. https://green-planet-energy.de/fileadmin/docs/publikationen/Studien/blauer-wasserstoff-studie-2020.pdf. Accessed 27 June 2023.

[9] Bullmann, T., Gollnick, Christian, Schropp, J., 2020. Wasserstoff DIHK-Faktenpapier. https://www.dihk.de/resource/blob/24872/fd2c89df9484cf912199041a9587a3d6/dihk-faktenpapier-wasserstoff-data.pdf. Accessed 28 June 2023.

[10] University of Oxford, 2023. Carbon intensity of electricity, 2022. https://ourworldindata.org/grapher/carbon-intensity-electricity. Accessed 30 June 2023.

[11] Bukold, S., Huneke, F., Claußner, M., 2020. Grün oder Blau?: Wege in die Wasserstoff-Wirtschaft 2020 bis 2040. https://green-planet-energy.de/fileadmin/docs/pressematerial/Gruen_oder_blau_Wege_in_die_Wasserstoffwirtschaft_final.pdf. Accessed 27 June 2023.

[12] Birol, F., 2019. The Future of Hydrogen: Seizing today's opportunities. https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf. Accessed 29 June 2023.

[13] La Camera, F., 2020. Global renewables outlook: Energy transformation 2050. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Apr/IRENA_Global_Renewables_Outlook_2020.pdf. Accessed 1 July 2023.

[14] Jahn, M., 2023. Industrielösungen Wasserstofftechnologien. Fraunhofer-Institut für keramische Technologien und Systeme. https://www.ikts.fraunhofer.de/de/industrieloesungen/wasserstofftechnologien.html. Accessed 27 June 2023.

[15] Lehmann, J., Luschtinetz, T., 2014. Wasserstoff und Brennstoffzellen. Springer Berlin Heidelberg, 149 pp.

[16] Weichenhain, U., Lange, S., Koolen, J., Benz, A., Hartmann, S., 2020. Potenziale der Wasserstoff- und Brennstoffzellen-Industrie in Baden-Württemberg. https://um.baden-wuerttemberg.de/fileadmin/redaktion/m-um/intern/Dateien/Dokumente/6_Wirtschaft/Ressourceneffizienz_und_Umwelttechnik/Wasserstoff/200724-Potentialstudie-H2-Baden-Wuerttemberg-bf.pdf. Accessed 27 June 2023.

[17] SAACKE GmbH, 2022. Wasserstoff-Brenner für die industrielle Dekarbonisierung: Jetzt bereit sein für die Revolution in der Feuerungstechnologie! https://www.saacke.com/fileadmin/saacke/pdf/SAACKE-Whitepaper-H2-01-Web.pdf. Accessed 28 June 2023.

[18] Salchenegger, S., 2006. Emissionen von Wasserstofffahrzeugen: Abschätzung der Emissionen von wasserstoff- und brennstoffzellenbetriebenen Fahrzeugen. https://www.umweltbundesamt.at/fileadmin/site/publikationen/rep0012.pdf. Accessed 17 July 2023.

[19] Icha, P., Lauf, T., 2022. Entwicklung der spezifischen Treibhausgas-Emissionen des deutschen Strommix in den Jahren 1990 - 2021. https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2022-04-13_cc_15-2022_strommix_2022_fin_bf.pdf. Accessed 29 June 2023.

[20] Juhrich, C., 2020. CO2-Emissionsfaktoren für fossile Brennstoffe. https://www.umweltbundesamt.de/sites/default/files/medien/479/publikationen/cc_28-2022_emissionsfaktoren-brennstoffe_bf.pdf. Accessed 29 June 2023.

Biography

Yvonne Eboumbou Ebongue, M.Sc. is a research assistant at the Fraunhofer Institute for Manufacturing Engineering and Automation IPA in the Industrial Energy Systems department. She studied Sustainable Electrical Energy Supply at the University of Stuttgart with a focus on storage technology for electrical energy. Her work focuses on energy efficiency, energy flexibility, energy management, hydrogen technologies and decarbonisation.

Felix Schnell, M.Sc. is a research assistant at the Fraunhofer Institute for Manufacturing Engineering and Automation IPA in the Industrial Energy Systems department. His work focuses on sustainable industrial energy supply, energy management, energy flexibility, energy efficiency and hydrogen technologies.

Dr. Alexander Emde did his doctorate in the field of techno-economic analysis of hybrid energy storage systems across different energy carriers. He is group leader of the group Planning integrated energy systems at the Fraunhofer Institute for Manufacturing Engineering and Automation IPA in the Industrial Energy Systems department.

Prof. Dr.-Ing. Dipl.-Kfm. Alexander Sauer, studied mechanical engineering and business administration at RWTH Aachen University and earned his doctorate there. 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.

CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
CPSL 2023-2

5th Conference on Production Systems and Logistics

Simulation Game Concept For AI-Enhanced Teaching Of Advanced Value Stream Analysis And Design

Mick Geisthardt[1], Lutz Engel[1], Monika Schnegelberger[1]
[1]Institute for Production and Service Systems/ Jade University of Applied Sciences, Wilhelmshaven, Germany

Abstract

Value stream analysis and design is employed globally by improvement teams within industrial settings to maximize value creation and eliminate waste. For ending methodical time-centricity, research expanded the methodology to incorporate diverse facets like material flow cost accounting, information logistics, and external influence factors. These enhancements, along with increasing data volumes, are prompting a re-evaluation of how professional improvement teams should think and operate. Consequently, a transformation of the pedagogical approach used for educating students and professionals necessitates novel solutions. Conventional teaching methods such as expository lectures are widely considered inadequate in promoting knowledge retention and engagement. So far, existing research has not yet resulted in a solution that can effectively impart the methodological complexity of advanced value stream analysis and design in a motivating and vivid fashion. To address this gap, this paper applies a tailored CRISP gamification framework to develop a simulation game concept. These concept enables AI-enhanced teaching of advanced value stream analysis and design focusing on identification of multi-stage resource-efficient optimization strategies. Through integration of game-based learning with AI a trained reinforcement learning agent can act either competitively or cooperatively, creating a unique form of teaching accounting the aspects personalization, adaptive feedback, content creation, and analysis and assessment.

Keywords

Advanced Value Stream Analysis and Design; CRISP Gamification Framework; Simulation Game; Artificial Intelligence; Game-based Learning; Resource-efficient Thinking

1. Introduction

By advancing the methodology of value stream analysis and design—a concept originating from lean management—to embrace aspects such as material flow cost accounting [1], information logistics [2], and the integration of external influencing factors [3] novel opportunities as well as challenges emerge. Major aspects such as material and energy-based waste, digitalization, but also the sales market, labour market, procurement market, and other external aspects like policy and trends can be included in analysis and design through advanced key performance indicators, thus enabling holistic optimizations.

Arising diversity within the methodology consequences an aggregate growth in application complexity and available data volumes, which changes how improvement teams should think and operate in industrial setting. Thus, also educational training of students and professionals must adapt, necessitating the development of novel solutions. It is broadly acknowledged that conventional pedagogical methods, like e.g., expository lectures, lack efficiency regarding knowledge retention and engagement. A minority of researchers expresses scepticism that gamified learning effects can be transferred to non-game contexts

DOI: https://doi.org/10.15488/15262
ISSN: 2701-6277

through the process of gamification [4, 5]. Meta-analyses have proven that gamification in formal education yields significant positive effects on cognitive, motivational, and behavioural aspects of learning [6, 7].

Current research has applied gamification to cultivate understanding of several facets of lean management [8, 9, 10]. These efforts have not yet yielded an approach that successfully encapsulates and conveys the methodology of advanced value stream analysis and design in a motivating and vivid fashion. To fill the identified gap, this paper employs a tailored six-step CRISP gamification framework. The resulting simulation game concept encourages players to develop multi-stage resource-efficient strategies reinforcing sustainable thinking. Enhancing the simulation game concept by game-based learning with AI enables the integration of an agent trained via reinforcement learning. Its deployment can be either competitively or cooperatively, creating a unique form of teaching accounting personalization, adaptive feedback, content creation, and analysis and assessment.

This paper initially introduces the theoretical background of the simulation game. Next, the six-step CRISP gamification framework is applied while the substance focuses on results, i.e., game preparation and game modelling. Detailed derivation and explanation of the CRISP gamification framework will be part of an individual publication currently in preparation. Lastly, conclusion and an outlook on further research is presented.

2. Theoretical Background

2.1 Advance Value Stream Analysis and Design

Within application of value stream analysis and design initially an improvement team maps the current value stream of a relevant product family and illustrates it utilizing standardized value stream elements (value stream analysis) [11]. Subsequently, wastes are identified applying the concepts of “muda”, “mura”, and “muri” [12]. By eliminating identified wastes and applying value stream design guidelines the improvement team designs a target value stream which is optimized in terms of lead time (value stream design) [11, 13]. Ubiquitously guiding within all activities is the ideal state known from the toyota production system, also referred to as the “north star”, consisting of 0 defects, 100 % value creation, one piece flow to customer demand and safety for people [14].

By research, the methodology of value stream analysis and design is advanced by diversifying input and output features [15, 16, 17]. Within this paper, the concept of advanced value stream analysis and design refers exclusively to the advancements by material flow cost accounting [1], information logistics [2] and the consideration of external influencing factors [3]. Figure 1 exemplifies a current value stream of this advanced form of value stream analysis and demonstrates the methodological complexity that is to be conveyed via the simulation game concept to be developed.

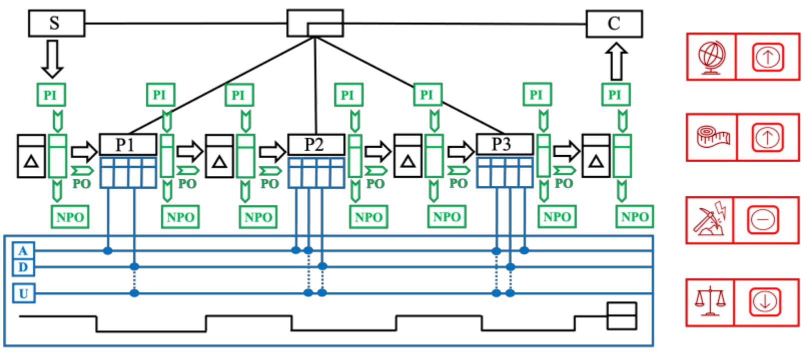


Figure 1: Exemplary Illustration of a Current Value Stream Utilizing Advanced Value Stream Analysis

Lead time centered elements of the conventional value stream analysis including suppliers (S), processes (P), inventories, customers (C), and the lead time ladder are illustrated in black. For resolving the fact of incomplete improvements solely favouring the lead time, the consideration of material and energetic wastes such as excessive energy consumption or material waste is made available via material flow cost accounting according to DIN EN ISO 14051:2011 [18]. Illustrated in green, input and output of a process is differentiated into product input (PI), product output (PO), and non-product output (NPO). The costs of product input, product output and non-product output are structured via material costs, energy costs, system costs, and waste management costs. Additionally, key performance indicators like absolute monetary value creation, relative monetary value creation, and degree of value creation can be used for representation [1].

The integration of information logistics facilitates tracking of activities and key performance indicators information flow via analog (A) and digital storage media (D) and their utilization (U), illustrated in blue. Evaluation can be based on the key performance indicators digitization rate, data availability, and data usage. Especially media discontinuities between the storage media become visible and thus enabling the initiation of selective optimization projects in the context of digitization [2].

Value stream analysis and design primarily according to internal factors may not always be effective. For example, if the geopolitical situation of crucial suppliers is critical coupled with long supply chains, a lack of material availability can quickly lead to costly production restrictions. Therefore, external influencing factors, illustrated in red, derived from sales market, labour market, procurement market, and other external factors such as politics, social area, technology, and general trends should be included to empower holistic optimization [3].

2.2 Gamification Frameworks

Through applying gamification frameworks to lean management tools, like advanced value stream analysis and design, efficiency can be improved in lean initiatives while raising employee engagement. Cross-linking can enable benefits as e.g., boosting enthusiasm, encouraging collaboration, and promoting creativity [19].

Games are voluntarily engaging and formally organised activities with objectives and rules, which might be physical or mental, and can be used to lead players into competition, education, or entertainment. Simulated environments are used to experiment with systems in simulation games, a specific category of game that can be used to teach [20]. Gamification is the process of incorporating game mechanics and strategies into non-game environments to engage and encourage players. To increase interest and participation, it utilizes scoring systems, leaderboards, and awards [21, 22]. Interactive digital or analog games with educational or informational objectives are referred to as serious games which are fostering social connection, transmit knowledge, or train skills [23]. Using specifically created games knowledge is imparted and skills are developed incorporating game elements with educational material [24].

For designing games, various frameworks and models exist, such as the six steps to gamification [25], the mechanics-dynamics-aesthetics (MDA) framework [26], and the octalysis gamification framework [27]. Beyond that, principles unrelated to gamification, such as design thinking, can be used within the creativity processes of game development [28]. Distinct gamification frameworks and models are frequently combined to create unique solutions for specific tasks. Combining gamification principles with software development models, for example, can help to depict complex processes in a game while promoting player participation [29]. Overall, gamification frameworks can provide a foundation for the development of games and gamified applications. In context of lean management tools like advanced value stream analysis and design, there is a necessity for an updated and comprehensive solutions that embrace the core idea of gamification while representing complex methodologies.

2.3 Game-based Learning with Artificial Intelligence

Game-based learning with AI can be applied in the context of lean management to enhance training, problem-solving, and decision-making in organizations within activities related to lean six sigma, kaizen, manufacturing, leadership, and inventory management [19, 30].

Artificial intelligence (AI) game-based learning is an educational technique that combines AI technology with interactive games to enhance the overall learning process. Giving users an intense and individualized learning experience, this method blends fun and motivational aspects of games with intelligence and adaptability of AI. Objective is to encourage engagement, problem solving, critical thinking, and knowledge retention to make learning more enjoyable and effective [31]. Core elements of game-based learning with AI are personalization, adaptive feedback, content creation, and analysis and assessment [32]. AI algorithms stay astute during gameplay, providing players with real-time feedback when they encounter obstacles or make mistakes. These timely cues, ideas, or explanations from the AI act as guiding beacons, directing learners to the appropriate solutions. Embracing a growth mindset, adaptive feedback fosters an environment that encourages continuous improvement of the player [33].

AI can enable develop dynamic and diverse gaming content, continually generating new levels, challenges, or scenarios. Such adaptability aids in preventing boredom and successfully retaining players attention and motivation throughout their educational experience [34]. AI-driven analytics play a vital role in monitoring users progress, effectively pinpointing areas of strength and weakness. Armed with data, educators and developers gain invaluable insights into learners performance, allowing them to refine the learning content and overall experience, thereby fostering continuous enhancement [35]. In essence, the integration of AI and game-based learning transforms the educational environment by making the process appealing, dynamic, and customized to player’s needs. Fusion of gaming features and artificial intelligence in this instructional technique not only enthralls but also empowers students, reigniting their enthusiasm for academic advancement and knowledge acquisition.

2.4 Related Work

In existing research, few efforts been made to leverage presented frameworks and models to develop full-fledged simulation games in the context of advanced value stream analysis and design. Different approaches were followed to generally gamify different lean management tools such as shopfloor management [8], the SMED method [9], or the 5S method [10], or to simply model and simulate the process of value stream analysis [36, 37, 38]. In scope of advanced value stream analysis and design, there is limited application of gamification frameworks. Existing solutions are outdated and do not fully consider the methodological requirements and the core idea of gamification, namely, to generate engagement and motivation, while at the same time adequately representing the complex methodology of advanced value stream analysis and design. Therefore, there is a need for innovative approaches to effectively develop games in this context.

3. Methodology

Objective of this paper is to develop a concept for a computer-based simulation game. This simulation game aims to convey the complex methodology of advanced value stream analysis and design to students and professionals in cooperation and competition with an artificial intelligence (AI) in a motivating and vivid fashion – thus departing from inefficient expository lectures.

In accordance with the lean start-up philosophy and the concept of the minimum viable product [39], the simulation game of this paper should be conceptualized in a cost-efficient and agile manner. To realize this objective, this paper adapts a new six-step CRISP gamification framework, which is illustrated in Figure 2. This tailored procedure model results from merging the six steps to gamification by Werbach and Hunter [25] and the CRISP-DM model by Wirth and Hipp [40]. Contrasting other widespread gamification frameworks such as mechanics-dynamics-aesthetics (MDA) [26] or octalysis [27], this novel model offers a cyclical IT-oriented approach that provides a continuous development flow from conceptual design to the digital realization of a computer-based simulation game. The derivation and detailed explanation of this framework will be part of a separate publication currently in preparation. The CRISP-DM approach is applied in big data and data science, developing solutions that deal with large data sets and probabilities – aspects that also occurs in simulation games. Especially suitability of the new framework and its transfer to the new domain needs to be investigated and discussed in detail.

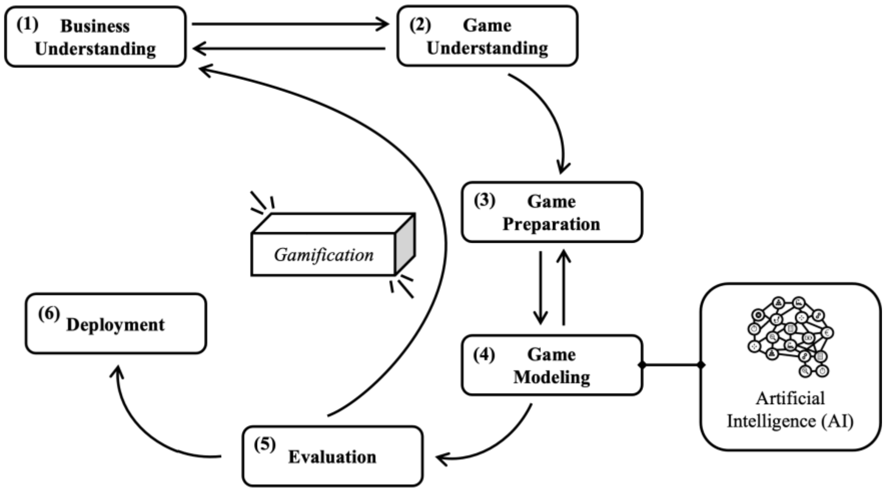


Figure 2: Six-Step CRISP Gamification Framework

The application of the six-step CRISP gamification framework starts with business understanding (1), in which the business context is described and immediate business goal of the system to be gamified is defined, checked for relevance, and evaluated. In subsequent game understanding (2), the target behaviour within the game is specified in bi-directional alignment with the business understanding as well as the player target group is characterized. During game preparation (3), the fundamental framework of the game is conceptualized utilizing the concepts of activity cycles and progression stairs. This preparation is subsequently used in game modelling (4) via creativity processes with appropriate tools to model the simulation game with AI. Lastly, the developed game is logically checked, tested, validated, and compared with the defined business objective in the context of evaluation (5). If the game meets the business objective, it can be deployed (6), if not, the game development is continued iteratively.

4. Implementation and Results

To understand the business context as part of business understanding, the explanations presented in section two on theoretical background should be viewed as foundation of the simulation game. Thereby, overall objective of the game is to enable vivid and motivating teaching of methodological knowledge with AI while explicitly encouraging the development of multi-stage resource-efficient strategies and sustainable thinking.

The target behavior of a player within the simulation game associated with game understanding involves application of traditional and advanced value stream design guidelines to design and model optimized target value streams towards the "north star" – including understanding the implications across a variety of scenarios while strategically deploying resources. It is crucial that the target player group, consisting of lean management affine male and female students and professionals, not solely understand the method, but can understand the real-world complexity and are able to implement the concept over the long-term achieving superior improvements in competition with AI [41].

4.1 Game Preparation

After clarifying the simulation game objective, player target behavior and player characterization, the simulation game can be generally conceptualized within game preparation. Following Figure 3 illustrates the simulation game concept by applying concepts of progression staircase and activity cycle [25] on the theoretical background of advanced value stream analysis and design. The simulation game concept aims to teach advanced value stream analysis and design in a gamified context and to reinforce resource-efficient thinking. The progression stairs of the game's graphical user interface (GUI) show players progress through a total of five game turns, which are also highlighted on the turn pointer, within which players start at the starting point and compete to reach the target point "north star". The five-step activity cycle (step 0 to step 5) runs turn-based and allows players to choose from random sets of actions in each round, resulting in positive or negative feedback from the payout generator. After five turns, the player who manages resources most efficiently and gets closest to the "north star" wins.

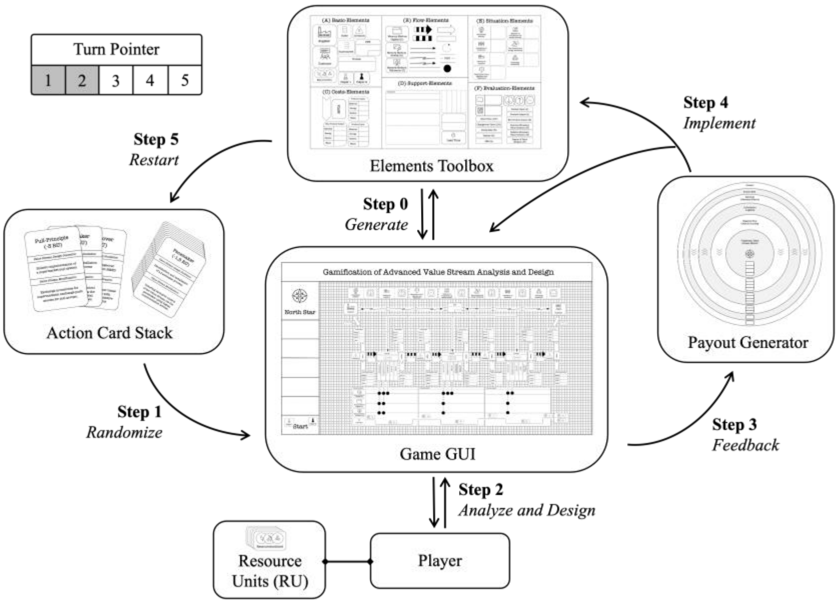


Figure 3: Five-Step Simulation Game Concept Including Progression Stairs and Activity Cycle

Game setup initiation is executed via the computer-based generation of a value stream, as analysis and design object, at the game GUI using preparate value stream elements from the elements toolbox and value stream patterns. Player's game figure starts at the starting point on the progression stairs of the game GUI, and each player receives a defined amount of resource units (RU) (e.g 10 pieces) to be invested for advanced value stream design during the five turns of the simulation game. After the action card stack (e.g. 25 pieces) is shuffled and a defined number of cards (e.g. 5 pieces) is randomly distributed to each player. The action cards represent traditional and advanced value stream design guidelines including name, resource costs for activation, description, and modification instructions. Players generally are keeping their cards secret from each other, creating elements of uncertainty and competition.

Subsequently, within analysis and design players strategically choose based on the made-up value stream at the game GUI and their available cards which action card to activate and place it face up. Each player can only activate one card per turn and must pay the resource unit cost for its activation. In accordance with the combination of the value stream pattern and the played action cards, the payout generator determines the players individual reward via similarities in underlying complex graph networks. The player with highest turn-reward wins the current game turn and can advance one step closer to the "north star" on the progression stairs of the game GUI. The value stream design guideline associated with the turn-winning player's card is implemented into the existing value stream using modification information from the action card and value stream elements from the elements toolbox.

At the turns end all remaining action cards are collected and shuffled for the next turn. The game proceeds for five consecutive turns, allowing players to make resource-efficient decisions over long term to achieve outstanding multilevel improvements in a competitive environment. The objective of the simulation game goes beyond maximizing rewards in a single round; it emphasizes strategic resource management to achieve long-term success and come closest to the "north star". This game-based learning concept encourages players to make well thought-out decisions and fosters continuous learning and improvement.

4.2 Game Modelling and AI Integration

While preparation reveals functionality of the simulation game concept, modeling how the simulation game can be played in competition or in collaboration with an AI to enable self-learning follows. It is well known that AI-based robots have already beaten grandmasters in the games such as "chess" and "go" [42]. Recent developments allow today not only to reach but to exceed human expert-level performance even in complex games like "stratego" with 10^{535} possible states [43]. To achieve such a performance, but also to enable training with and against AI-based robots, different types of reinforcement learning (RL), i.e., model-free multiagent reinforcement learning, can be utilized.

Reinforcement learning enables an agent to learn how to maximize rewards in the future by experiencing rewards and punishments. As basis for application, the agent-environment interface required for the RL model consists of the five key components: agent, actions, environment, rewards, states, and policy [44]. Figure 4 illustrates how the five key components are integrated into the simulation game concept, enabling the training of an agent. Training of the agent's neural network follows the game process and progression. From the action card stack, which reflects various optimization measures, randomly five cards are assigned to the agent. These represent the actions for this turn and activate the neurons. Within the environment, consisting of game GUI and elements toolbox, the present value stream on the game GUI is transformed into a value stream graph with nodes and edges according to graph theory. Referring to this value stream graph (value stream pattern), the agent selects one of its actions and activates it. The agent receives feedback via the reward function of the payout generator. The payout generator is embodied by a complex value stream graph network consisting of value stream pattern variations in combination with actions and corresponding rewards. Through a similarity analysis within the complex value stream graph network versus the present value stream graph and the activated action, the reward can be determined and transferred to the agent. Using the value stream modification information associated with the action, optimization action can be implemented into the environment, resulting in a new state for the next game turn. The overall agent's policy results from the already described game objective, target behavior, and the five-round game process and specifies the rules according to which the agent acts and learns. Alongside the rules and regulations, comprehensibility and fairness are key factors of the policy. The agent implemented in the simulation game concept can be deployed not only primarily as an opponent or duplicated as multiple opponents to facilitate learning. Secondarily, it can also be integrated as an ally in the learning process. The application mode and level of difficulty can be further customized, thus enabling a novel form of teaching featuring personalization, adaptive feedback, content creation, and analysis and assessment.

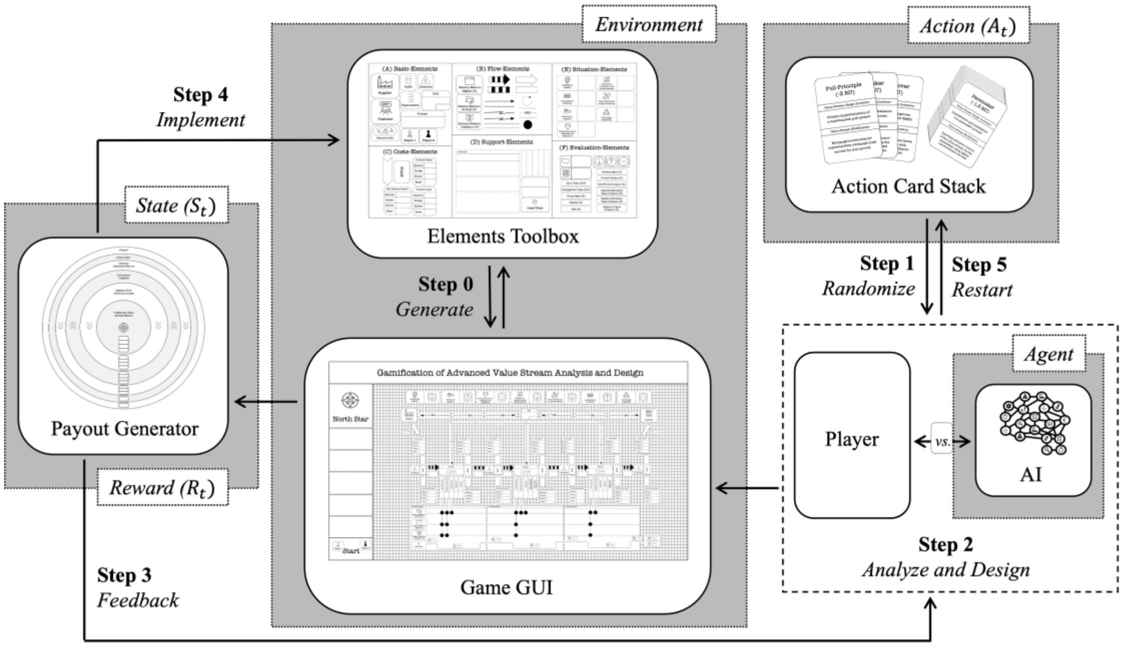


Figure 4: Five-Step Simulation Game Concept for Game-Based Learning with AI

4.3 Evaluation and Deployment

Considering the size of the game board, the possibilities of moves, the behavior of the opponent, the phases of the game, and the random factor, the game concept presented features more possible states than “stratego”. Major driver being value stream graphs variations in the complex value stream graph network associated with the reward function. Resulting complexity of the simulation game is a challenge for traceability of results, computing performance, and practical application. To counteract this complexity, the rules of the game must be designed precisely, the effect of the action cards must be balanced, and transparency must be enhanced to further refine the concept.

For future evaluation of the simulation game concept for AI-enhanced teaching advanced value stream analysis and design presented in this paper, an empirical investigation of the usability components effectiveness, efficiency, and satisfaction according to ISO 9241-11 is planned [45]. For this purpose, an evaluation procedure in three steps is intended, while testing the simulation game within the lecture “Digital Lean Manufacturing” in the 5th semester of the program “Engineering and Management” at the Jade University of Applied Sciences. The evaluation procedure initially relevant value criteria and expected performance standards are formulated for the application of the simulation game in teaching. Afterwards, the simulation game is applied with AI-enhanced teaching of advanced value stream analysis and design as component of the designated lecture. As part of the analysis of effectiveness, efficiency, and satisfaction, the students are surveyed, e.g., according to the procedure of Kaiser [46]. Lastly, the survey-based findings are synthesized, and a uniform value judgement is drawn up. This three-step approach allows a first evaluation of the concept and a closer examination of the underlying limitations of the simulation game. Once these have been considered, a second three-stage evaluation in a similar style is to be carried out to validate results, upon success allowing the simulation game to be transferred to full deployment.

5. Conclusion and Outlook

Within this paper the development of a computer-based simulation game concept using game-based learning with AI, which enables advanced value stream analysis and design to be taught to students and professionals in a vivid and motivating fashion, was presented. Objective being to convey methodological knowledge considering AI while explicitly encouraging the development of multi-stage resource-efficient strategies and sustainable thinking. For achieving this objective, a tailored six-step CRISP gamification framework, resulting from merging the six steps to gamification and the CRISP-DM model, was utilized. Discussing of this framework will be part of an individual publication currently in preparation.

Resulting simulation game concept is composed of five-steps including generation, randomization, analysis and design, feedback, implementation, and restart while applying the game components game GUI, elements toolbox, action card stack, and payout generator. To enable game-based learning with AI, these game components were conceptually leveraged to implement five core components of a reinforcement learning model into the simulation game concept. Prospectively, the trained agent can, according to learning preference, be duplicated and be deployed either competitively or cooperatively, creating a unique form of teaching considering personalization, adaptive feedback, content creation, and analysis and assessment.

In continuation of this paper, it is intended to address the challenge of complexity and evaluate the presented simulation game concept featuring game-based learning with AI in accordance with the usability components effectiveness, efficiency, and satisfaction. The evaluation will be carried out as part of the lecture "Digital Lean Manufacturing" and deliver insights into potential limitations by means of an empirical investigation. After a second evaluation, the simulation game can be deployed and enable teaching of advanced value stream analysis and design using incentives such as competitive spirit, success, social exchange and of cause fun factors while promoting cognitive, motivational, and behavioural learning.

Acknowledgements

The authors gratefully acknowledge the Jade University of Applied Sciences for funding the present work through the Jade2Pro PhD scholarship program.

References

[1] Engel, L., Kranhold, M., 2021. Lean Management wird zum Green Management, Um Materialflusskosten erweiterte Wertstromanalyse. Deutsches Ingenieurblatt 2021(6), 1-6.

[2] Meudt, T., 2020. Wertstromanalyse 4.0 - Eine Methode zur integrierten Erfassung und Analyse von Material- und Informationsflüssen in Wertströmen. Dissertation Technische Universität Darmstadt. Shaker Verlag, Düren.

[3] Zanker, C., Reisen, K., 2015. Stabilitäts- und Flexibilitätsanforderungen an Produktionssysteme. In: Kötter, W., Schwarz-Kocher, M., Zanker, C. (eds.) Balanced GPS, Ganzheitliche Produktionssysteme mit stabil-flexiblen Standards und konsequenter Mitarbeiterorientierung. Springer Fachmedien, Wiesbaden.

[4] Boulet, G., 2012. Gamification: The Latest Buzzword and the Next Fad. eLearn Magazine 2012(12).

[5] Klabbers, J. H., 2018. On the architecture of game science. Simulation & Gaming 49(3), 207-24.

[6] Sailer, M., Homner, L., 2020. The Gamification of Learning: A Meta-analysis. Educational Psychology Review 32, 77-112.

[7] Huang, R., Ritzhaupt, A.D., Sommer, M., 2020. The impact of gamification in educational settings on student learning outcomes: a meta-analysis. Educational Technology Research Development 68, 1875-1901.

[8] Bloechl, S. J., Michalicki, M., Schneider, M., 2017. Simulation game for lean leadership–shopfloor management combined with accounting for lean. Procedia Manufacturing 9, 97-105.

[9] Bárdy, M., Kudrna, J., Šrámková, B., Edl, M., 2014. Interactive game supporting SMED method. Applied mechanics and materials 474, 141-146.

[10] Gomes, D. F., Lopes, M. P., de Carvalho, C. V., 2013. Serious games for lean manufacturing: the 5S game. IEEE Revista Iberoamericana de Tecnologias del Aprendizaje 8(4), 191-196.

[11] Rother, M., Shook, J., 2011. Sehen lernen, Mit Wertstromdesign die Wertschöpfung erhöhen und Verschwendung beseitigen. Version 1.4., Lean Management Institute GmbH, Mülheim.

[12] Ohno, T., 2013. Das Toyota-Produktionssystem. 3rd edn. Campus Verlag, Frankfurt/Main.

[13] Erlach, K., 2013. Wertstromdesign, Der Weg zur schlanken Fabrik. 2nd edn. Springer-Verlag, Berlin.

[14] Rother, M., 2009. Toyota Kata: Managing People for Improvement, Adaptiveness and Superior Results. McGraw-Hill Global Education Holdings LLC, New York.

[15] Balsliemke, F., 2015. Kostenorientierte Wertstromplanung, Prozessoptimierung in Produktion und Logistik. Springer Gabler, Wiesbaden.

[16] Braglia, M., Carmignani, G., Zammori, F., 2006. A new value stream mapping approach for complex production systems. International journal of production research 44(18-19), 3929-3952.

[17] Cai, Y., You, J., 2008. Research on value stream analysis and optimization methods. In: 4th International Conference on Wireless Communications, Networking and Mobile Computing, 1-4.

[18] Deutsches Institut für Normung e.V., 2011. DIN EN ISO 14051:2011-12, Umweltmanagement – Materialflusskostenrechnung – Allgemeine Rahmenbedingungen (ISO 14051:2011). Beuth Verlag, Berlin.

[19] Pedro, J., Martínez, J., Fuentes, J., 2017. Learning to Teach Lean Management through Games: Systematic Literature Review. WPOM-Working Papers on Operations Management, 8, 164-170.

[20] Wixon, D., 2015. What is a game?. Interactions 13(2), 37.

[21] Brauer, H., Jent, S., Janneck, M., 2019. Einsatz und Potenzial von Gamification in digitalen Trainingsplattformen. Gesellschaft für Informatik e.V., Bonn.

[22] Schmidt, R., Niesenhaus, J., Schering, S., 2015. Press Play² - Gamification in Wissenschaft und Praxis. In: Weisbecker, A., Burmester, M., Schmidt, A. (eds.) Mensch und Computer. De Gruyter Oldenbourg, Berlin.

[23] Freyermuth, G.S., Wallenfells, F., Wessely, D., 2013. Serious games, exergames, exerlearning zur Transmedialisierung und gamification des wissenstransfers. Transcript Verlag, Bielefeld.

[24] Ahrens, D., 2018. Serious games, Lassen Sich Arbeit und Lernen Spielerisch Verknüpfen? Ein Beispiel aus der Hafenwirtschaft, Bildung 2.1 für Arbeit 4.0?, 287-302.

[25] Werbach, K., Hunter, D., 2020. For the win, revised and updated edition, The power of gamification and game thinking in business, education, government, and social impact. University of Pennsylvania Press, Pennsylvania.

[26] Hunicke, R., LeBlanc, M., Zubek, R., 2004. MDA: A formal approach to game design and game research. Proceedings of the AAAI Workshop on Challenges in Game AI 4(1), 1722.

[27] Chou, Y. K., 2019. Actionable gamification, Beyond points, badges, and leaderboards. Packt Publishing Ltd., Birmingham.

[28] Hung, A. C. Y., 2018. Gamification as Design Thinking. International Journal of Teaching and Learning in Higher Education 30(3), 549-559.

[29] Herrmanny, K., Schmidt, R., 2014. Ein Vorgehensmodell zur Entwicklung von Gameful Design für Unternehmen. Mensch & Computer 2014.

[30] Dorota, S., Deif, M., 2019. A gamification approach application to facilitate lean manufacturing knowledge acquisition. Management and Production Engineering Review.

[31] Yu, D., Glazieva, A., 2022. Game based learning with artificial intelligence and immersive technologies: an overview. In CEUR workshop proceedings 3077, 146-159.

[32] Ma, J., Zhang, Y., Bin, H., Wang, K., Liu, J., Gao, H. 2022. The Development of Students' Computational Thinking Practices in AI Course Using the Game-Based Learning: A Case Study, 2022 International Symposium on Educational Technology (ISET), Hong Kong, 273-277.

[33] Samiha, M., Akram, B., Barnes, T., Price, T., 2022. Adaptive Immediate Feedback for Block-Based Programming: Design and Evaluation. IEEE-Transactions on Learning Technologies 15(2022), 406-420.

[34] Élise, L., Monterrat, B., Desmarais, B., George, S., 2019. Adaptive Gamification for Learning Environments. IEEE Transactions on Learning Technologies 12 (2019), 16-28.

[35] Christos, T., Krouska, A., Virvou, M., 2020. Using a Multi Module Model for Learning Analytics to Predict Learners' Cognitive States and Provide Tailored Learning Pathways and Assessment. Machine Learning Paradigms.

[36] McDonald, T., Van Aken, E. M., Rentes, A. F. 2002. Utilising simulation to enhance value stream mapping, a manufacturing case application. International Journal of Logistics 5(2), 213-232.

[37] Solding, P., Gullander, P, 2009. Concepts for simulation-based value stream mapping. In Proceedings of the 2009 Winter Simulation Conference 2231-2237 IEEE.

[38] Lian, Y. H., Van Landeghem, H, 2002. An application of simulation and value stream mapping in lean manufacturing. In Proceedings 14th European Simulation Symposium 1-8, SCS Europe BVBA.

[39] Lenarduzzi, V., Taibi, D., 2016. MVP explained: A systematic mapping study on the definitions of minimal viable product. In 42th Euromicro Conference on Software Engineering and Advanced Applications (SEAA), 112-119.

[40] 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 1, 29-39.

[41] Kato, I., Smalley, A., 2010. Toyota Kaizen methods: Six steps to improvement. CRC press.

[42] Hsu, F. H., Anantharaman, T., Campbell, M., Nowatzyk, A., 1990. A grandmaster chess machine. Scientific American, 263(4), 44-51.

[43] Perolat, J., 2022. Mastering the game of Stratego with model-free multiagent reinforcement. learning.Science 378, 990-996.

[44] Sutton, R. S., Barto, A. G., 2018. Reinforcement learning: An introduction. MIT press.

[45] Hegner, M., 2003. Methoden zur Evaluation von Software. (IZ-Arbeitsbericht, 29). Bonn: Informationszentrum Sozialwissenschaften.

[46] Kaiser, R., 2014. Qualitative Experteninterviews, Konzeptionelle Grundlagen und praktische Durchführung. Springer Fachmedien, Wiesbaden.

Biography

Mick Geisthardt, M. Eng has been a researcher at the Institute for Production and Service Systems (IPD) at the Jade University of Applied Sciences and a Jade2Pro doctoral scholar at the Department Very Large Business Applications (VLBA) of the Carl von Ossietzky University of Oldenburg since 2022. His research focuses on digital value stream analysis and design, gamification, artificial intelligence, and resource-efficient production.

Prof. Dr. -Ing. Lutz Engel has been professor for Production, Quality Management and Work Science in the Department Management, Information, Technology at the Jade University of Applied Sciences in Wilhelmshaven since 2016 and head of the Institute for Production and Service Systems (IPD) since 2020. His application-oriented industrial research has received multiple federal and state grants and focuses on production management and technology, work science, and lean management.

Monika Schnegelberger, M. Eng. has been a researcher at the Institute for Production and Service Systems (IPD) at Jade University of Applied Sciences since 2021 and works as research assistant at the Department of Management, Information, Technology since 2020. Additionally, she and manages an OER project at Carl von Ossietzky University Oldenburg since 2023 and is an experienced game developer and data scientist.

CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
CPSL 2023-2

5th Conference on Production Systems and Logistics

On The Effectiveness Of Bottleneck Information For Solving Job Shop Scheduling Problems Using Deep Reinforcement Learning

Constantin Waubert de Puiseau[1], Lennart Zey[2], Merve Demir[1],
Hasan Tercan[1], Tobias Meisen[1]

[1]Institute for Technologies and Management of Digital Transformation der Bergischen Universität Wuppertal , Wuppertal, Germany
[2]Lehrstuhl für Produktion und Logistik der Bergischen Universität Wuppertal, Wuppertal, Germany

Abstract

Job shop scheduling problems (JSSPs) have been the subject of intense studies for decades because they are often at the core of significant industrial planning challenges and have a high optimization potential. As a result, the scientific community has developed clever heuristics to approximate optimal solutions. A prominent example is the shifting bottleneck heuristic, which iteratively identifies bottlenecks in the current schedule and uses this information to apply targeted optimization steps. In recent years, deep reinforcement learning (DRL) has gained increasing attention for solving scheduling problems in job shops and beyond. One design decision when applying DRL to JSSPs is the observation, i.e., the descriptive representation of the current problem and solution state. Interestingly, DRL solutions do not make use of explicit notions of bottlenecks that have been developed in the past when designing the observation. In this paper, we investigate ways to leverage a definition of bottlenecks inspired by the shifting bottleneck heuristic for JSSPs with DRL to increase the effectiveness and efficiency of model training. To this end, we train two different DRL base models with and without bottleneck features. However, our results indicate that previously developed bottleneck definitions neither increase training efficiency nor final model performance.

Keywords

Production Scheduling; Reinforcement Learning; Bottleneck Identification; Operations Research; Artificial Intelligence

1. Introduction

Scheduling problems occur in every sector of the manufacturing industry and often have substantial optimization potential. Industrial scheduling problems are classified as combinatorial optimization problems [1], which are prohibitively computationally expensive to solve optimally at the scale of real-world scenarios. Consequently, they have been studied for many years, especially in the fields of operations research (OR) and computer science. The result of these research efforts are numerous priority dispatching rules (PDRs) [2] and (meta-)heuristics that are still under very active development [3, 4]. All solution methods cover different spectrums in the trade-off between computation time and optimality of the found solution. Generally, PDRs are fast and interpretable, but the solutions are often more than 20% worse than the optimum [5, 6], whereas (meta-)heuristics obtain more optimal solutions at the cost of more computation time. In the last five years the application of deep reinforcement learning (DRL) has gained popularity in the scheduling domain [7, 8], driven by the increasing availability of computation and rapidly improving learning algorithms. DRL has already shown competitive results for standardized scheduling problems, such as the Job Shop Scheduling Problem (JSSP) [6, 9]. Since learning-based solutions like DRL have the inherent

DOI: https://doi.org/10.15488/15306
ISSN: 2701-6277 publish-Ing.

ability to adapt to different environments during training, the driving long-term hypothesis of researchers in the field is that DRL will lead to better results than manually tailored heuristics, require less manual effort for the mathematical description of the production environment and will generalize well to stochasticity in production lines [10, 11].

Existing DRL-based solutions can be roughly divided into two research directions. One computes information-rich, simple features for the agents' observation space, such as remaining processing times of jobs, and relies on small and shallow neural network topologies. The second trains much more elaborate neural network topologies on raw and high-dimensional problem state representations. However, neither research direction makes explicit use of the intuition and work that has been build and done over the course of many decades by the operations research (OR) community when designing observation spaces. For example, the notion of bottlenecks is very common in the OR literature and builds the foundation of one of the most cited heuristics for the JSSP, the shifting bottleneck heuristic (SBH) [12]. Yet, bottleneck features are not commonly found within DRL-based solution approaches. Therefore, in this paper, we investigate whether there is a benefit to the incorporation of bottleneck features into DRL. Building upon the definition of a bottleneck in the SBH for the design of an input feature for DRL agents, we combine established knowledge and new, powerful learning algorithms. We hypothesize that the use of the bottleneck feature leads to faster training and/or more optimal plan generation by agents, as it provides useful information about the problem instance and the current scheduling situation. The main contributions of this paper are:

- The design of a bottleneck feature inspired by the SBH that can be integrated into DRL-based solution methods.
- The analysis of the effectiveness of this feature for DRL-based scheduling methods by integrating the feature into two different existing approaches: a self-designed, comparatively small-scale DRL-based approach that relies on engineered features, and a state-of-the-art approach with an end-to-end architecture.

The remainder of this paper is structured as follows: We begin with a brief introduction to the background of this study with respect to DRL for the JSSP and definitions of bottlenecks. Next, we discuss related work with respect to bottleneck definitions and their integration into DRL-based solution approaches. In section 3, the methods and experiments are detailed, followed by the results in section 4. Section 5 concludes the study and offers perspectives for future work.

2. Background and Related Work

2.1 Deep Reinforcement Learning and Job Shop Scheduling

DRL is a machine learning paradigm, in which deep learning models are trained through interaction with an environment by sampling experience data and autonomously deriving action sequences which maximize a cumulative reward signal across a task [13]. In theory, the DRL paradigm can be applied to any sequential decision problem that can be formulated as a Markov decision process (MDP), i.e., in which a given problem state is independent of the way in which the problem state was reached. In practice, the success of the application of DRL to industrial use-cases depends on a combination of the fit of the used DRL algorithm, the neural network topology and other design decisions, such as the actions an agent can take and the reward signal, to the underlying problem. In some use cases, such as robotic control [14, 15], warehouse management [16] or load carrier control [17], DRL has already achieved impressive results. Since scheduling problems can also be formulated as MDPs, much interest has emerged in recent years to address scheduling problems with DRL as well.

In a JSSP, J jobs must be processed on M machines, where every job consists of M operations and has to be processed once on every machine in a fixed order and with different processing times. Only one job may be processed on any machine at once and, once started, an operation may not be interrupted [1]. JSSP problem sizes are often abbreviated as JxM JSSP, meaning that a JSSP with six jobs and six machines is abbreviated as 6x6 JSSP. The objective of the combinatorial optimization often is the minimization of the makespan, i.e., the timespan between the start of the first operation and the end of the last operation in the schedule. The JSSP cannot be solved in polynomial time, making it infeasible to find exact solutions for large problem settings in acceptable time.

Considerable research effort has already been put into addressing the JSSP with DRL. Although first breakthroughs date back to 2016 [18], solutions that outperform rule-based dispatching strategies by larger margins have only recently been discovered. Therein, DRL is used in one of two ways: firstly, as stand-alone solution for constructive scheduling [5, 6, 9, 19], meaning that schedules are constructed such that Gantt charts are created from left to right. Secondly, and less frequently, DRL is used to guide improvements on already existing solutions [20, 21]. As mentioned before, a crucial part of the algorithm design is the definition of a suitable problem representation as input, called observation, for the DRL-agent. Many researchers make use of features like the remaining processing times of jobs and machines, or the number of remaining operations, which are also used by common priority dispatching rules [5, 19, 22, 23]. The most competitive observation designs, however, are raw problem descriptions of the scheduling instance and current solution state that leverage neural network topologies that capture the structure of the underlying problem through graph networks [6] or recurrent architectures [9]. Surprisingly, we found no work using more elaborate features like bottleneck information, which has proven useful in OR problem descriptions and advanced heuristics.

2.2 The Concept of Bottlenecks

In general terms, bottlenecks in production scenarios are resources or jobs which have a large impact on the final scheduling performance. Logically, it is common to identify these resources or jobs and prioritize them in one way or another. Therefore, when relying on the notion of bottlenecks, the tasks are to identify bottlenecks and to prioritize them effectively [1, 24]. For example, Zhang and Wu identified constraining bottleneck machines and jobs through statistical analysis of multiple simulations and applied this information to various genetic algorithms [25–27]. Definitions regarding resource utilization, queue lengths, and average waiting times are also common [28, 29]. To the best of our knowledge, only one DRL-based solution approach actively incorporates a bottleneck identification step. In this work, Thomas et al. propose two agents, one to classify resources as bottlenecks and the other to schedule operations [30]. However, the goal of their study was to adjust machine capacities, not to schedule on a fixed machine park. One of the most widely known effective use of the bottleneck concept is the shifting bottleneck heuristic (SBH) [12]. On an abstract level, it iterates over all machines in the problem following three steps:

1. *Identification of the bottleneck machine* of this iteration step based on the current problem state.
2. Determining the order of operations on this bottleneck machine.
3. Incorporating this order of operations on the bottleneck machine into the current problem state.

Evidently, the identification of the bottleneck machine is a central step of the SBH. For a detailed description of each step and the overall algorithm, we refer to the original publication by Adams at al. [12] and the textbook version by Pinedo [1]. Our adaption of the bottleneck identification step as feature for a DRL-agent is described in the following section 3.1.

3. Methods and Experiments

This section firstly provides details of the suggested bottleneck information. Then, the description of the self-designed and adapted base models is given, including how these models are augmented with the bottleneck information as feature, and how the models are trained.

3.1 Bottleneck Information

The bottleneck information calculation procedure we propose is closely related to the bottleneck identification step in the SBH. The abbreviated pseudo-code of the algorithm we discuss in this section is presented in Algorithm 1. The bottleneck information is calculated in every step of the DRL-based schedule generation and should provide information on the current situation. For simplicity, we refer to all non-complete solutions (including solutions without any operation scheduled) as partially solved from here on.

The algorithm starts from a partially solved schedule. In the first step, as in the SBH, we determine the lower-bound of the makespan, $makespan_{LB}$, of the current schedule. We do so under the artificial assumption that all machines can process all unscheduled operations at the same time but while still adhering to already fixed orders of operations in the schedule and to precedence constraints within jobs (see [12]). Next, from $makespan_{LB}$, we can infer pseudo release dates, being the time when operations start in the partial solution, as well as pseudo due dates that tell us when each operation would have to be finished to fulfill the lower-bound makespan.

After this preliminary calculation, we calculate the bottleneck information for each machine separately. To do so, we assume that the sequence of operations on the considered machine is not (partially) fixed. We then determine a sequence of operations minimizing the maximum tardiness on that machine, given the previously calculated release dates and due dates. In practice, we solve this one-machine tardiness minimization problem with the algorithm developed by Carlier [31]. The solution to the one-machine tardiness minimization problem returns the minimal tardiness, $tardiness_{MIN}$. It can be shown that the sum of the $makespan_{LB}$ and the $tardiness_{MIN}$ is a valid lower-bound makespan for the regarded machine [12]. As in the SBH, we interpret this makespan as an indication for the bottleneck machine, since a machine with a large lower-bound makespan is likely to have a larger influence on the final makespan. Having calculated this bottleneck information for every machine, we finally min-max scale across all bottleneck information values to the range [0, 1]. How this bottleneck information is inserted into the observation of each DRL base model is described in the respective sections 3.2.1 and 3.2.2.

Algorithm 1: Calculation of the bottleneck information list

Algorithm 1: Bottleneck Information Calculation

Input: current schedule;
bottleneck_info_list ← []
$\text{makespan}_{\text{LB}}$ ← find lower-bound makespan
calculate pseudo due dates
for *every machine* **do**
    $\text{tardiness}_{\text{MIN}}$ ← minimize tardiness of the one-machine-problem
    bottleneck_info ← $\text{makespan}_{\text{LB}}$ + $\text{tardiness}_{\text{MIN}}$
    bottleneck_list.append(bottleneck_info)
end
min-max(bottleneck_info_list)
Output: bottleneck_info_list

3.2 Base Models and Bottleneck Feature Integration

In this paper, we experiment with two different DLR models: a self-designed model architecture, that relies on engineered features and a small neural network, as well as a large model architecture proposed by Iklassov et al. [9], that uses both raw data and features to achieve state-of-the-art results. In both cases, we modify the existing base model such that the additional bottleneck feature can be added as input. To ensure that differences in the model performances with and without the bottleneck feature can be attributed to the effect of the feature, we overwrite the bottleneck feature vector with zeros whenever the bottleneck features are not used. This way, the number of model parameters remains the same with and without the additional bottleneck feature. All experiments were conducted on 6x6 and 10x10 JSSPs and repeated with three random seeds.

3.2.1 Self-designed Base Model

In the self-designed base model, the DRL-agent interacts with its environment by choosing from the next operations that can be scheduled per job, thereby iteratively constructing a schedule starting with the first operations of jobs. Once scheduled, the resulting starting and ending times of operations remain unchanged. The design choices, features and hyperparameters were found in extensive preliminary experiments and resulted in a stable learning behavior and competitive makespans compared to the common priority dispatching rules *most-tasks-remaining*, *shortest-processing-time-first* and randomly generated schedules. As DRL algorithm we use Proximal Policy Optimization (PPO) [32] with action masking [33] to avoid impossible action suggestions such as scheduling an operation of a finished job. The policy and value networks in PPO are feedforward neural networks with two hidden layers of size 256 and Tanh activation function. Both networks are separate networks, meaning that they do not share parameters. The used feature vector contains concatenated information on the next operations to be scheduled per job. Each one of these next operations is described by:

- its processing time
- the remaining processing time of the corresponding job
- the number of remaining operations of the corresponding job
- the remaining processing time on the required machine
- the number of remaining operations on the required machine
- the earliest starting time for the task given the current planning status

In addition, an MTR-feature is calculated, named after the common *most-tasks-remaining* dispatching rule. It is a vector of the element-wise comparison between the number of remaining operations of all jobs, where a 1, -1, and 0 indicate if there are more, less, or equal remaining operations, respectively. The bottleneck feature is also used as descriptive feature per next operation by inputting the calculated bottleneck feature of the machine processing the next operation. The data flow from problem state to the action and value predictions is depicted in Figure 1.

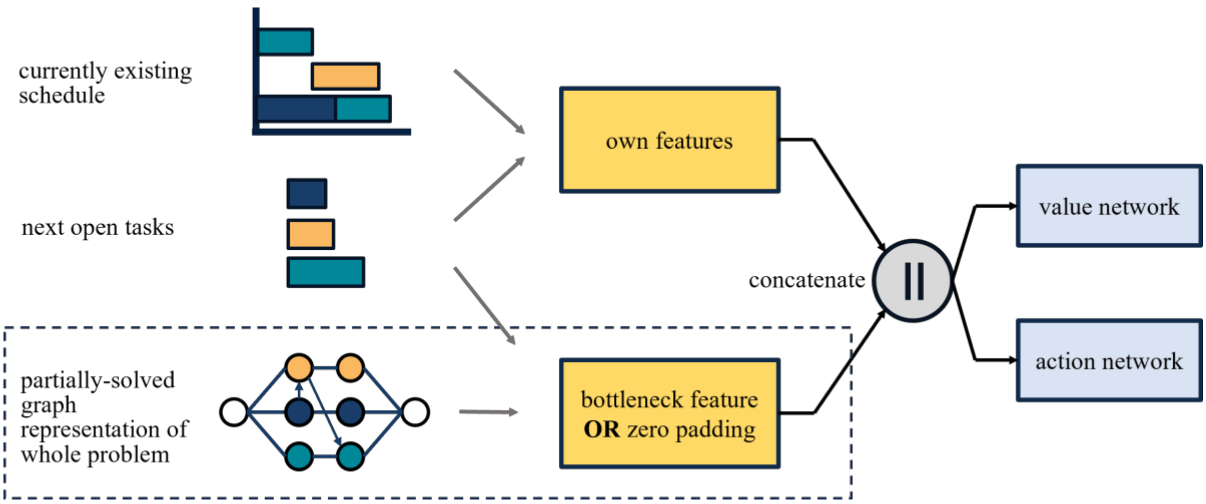


Figure 1: Data flow in the self-developed base model. Content in dashed box indicates the additions that were made in this study.

The implementation of masked PPO as well as the training and testing datasets and procedures are adapted from the *schlably* framework for DRL base production scheduling experiments [34]. The training instances were generated by randomly assigning machines to operations within a job and with operation times determined from integers uniformly distributed in the interval [1, 11]. Training was performed on a fixed set of 1,200 training instances. The model was validated on ten separate instances every 30,000 training steps and the model that performed best on the validation data during training was finally tested on 40 test instances. Training was ended after 4,000,000 time steps for the 6x6 JSSP and 700,000 time steps for 10x10 JSSPs, as no further improvement was observed through further training in preliminary experiments. All used hyperparameters are given in Appendix Table 1.

3.2.2 Learning-To-Generalize (l2g) Base Model

Our learning-to-generalize base model that we use in this study is adapted from a recent publication by Iklassov et al. [9], which achieves state-of-the-art results for all DRL-based JSSP solutions, where the model iteratively constructs a schedule operation by operation, similarly to our approach described above (see section 3.2.1). We deploy the best reported performing configuration and hyperparameters but modify the algorithm in two ways to fit it to the objective of our experiments: First, we solely train the 6x6 JSSP model on 6x6 JSSP training instances and the 10x10 model 10x10 training instances instead of training instances of multiple sizes per model. This minimizes the required training time per model, because training on much larger instances increases the calculation time significantly, due to the calculation time of the bottleneck feature that scales faster than quadratically with increasing problem sizes. We accept here that this may lead to a worse overall performance of the models, since our primary interest lies in the comparison between models trained with and without the bottleneck feature. The second modification is with respect to the input features. The bottleneck features are added as a fourth dynamic feature category next to the information about the last processed operations per job, the machine status and remaining processing times, as illustrated in Figure 2. To this end, the bottleneck features, like the other dynamic features, are expanded to the embedding size 128 through a linear layer, concatenated with the static input embedding and passed through a recurrent set2set model [35], before entering the actor and critic networks.

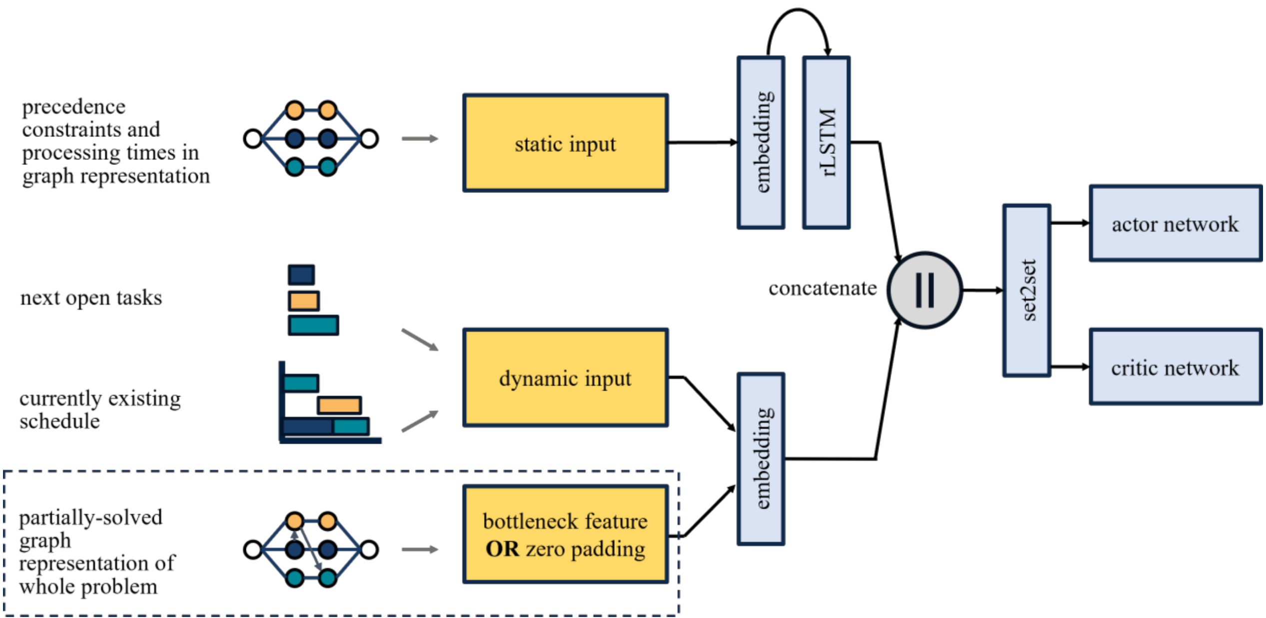


Figure 2: Data flow in the l2g base model. Content in dashed box is the addition that was made for this study.

Adhering closely to the original training procedure, all instances consist of operations with processing times sampled uniformly from the interval [0, 100]. This has the benefit that the bottleneck features is not only tested on multiple base models but varying JSSP settings. For every episode, new training instances are randomly created. Evaluations during training are carried out every 100 episodes on ten fixed evaluation instances. Finally, the best performing model on the evaluation instances is tested on separate test instances.

Training was stopped after 2,800 episodes and 1,100 episodes for the 6x6 and 10x10 JSSPs, respectively, because no further improvement was observed after this point in preliminary experiments.

4. Results

We first analyze the training behavior of the DRL agents to verify the working hypothesis that the bottleneck feature is a useful addition to the observation space. To this end, the achieved makespans on the evaluation instances are plotted over the number of instances seen during training. Every plot in Figure 3 shows the evaluation makespans averaged across three seeds for models trained with the bottleneck feature (blue) and without the bottleneck feature (orange) as solid lines. Shaded areas represent the standard deviation across the three seeded training runs per model. Generally, the evaluation results drop fast in the beginning and then plateau after a few hundred training instances. Critically, we cannot identify significantly faster learning, nor significantly lower plateaus, nor other striking differences between any of the two lines per plot. Therefore, the bottleneck feature does not seem to qualitatively change the learning behavior, which falsifies our working hypothesis.

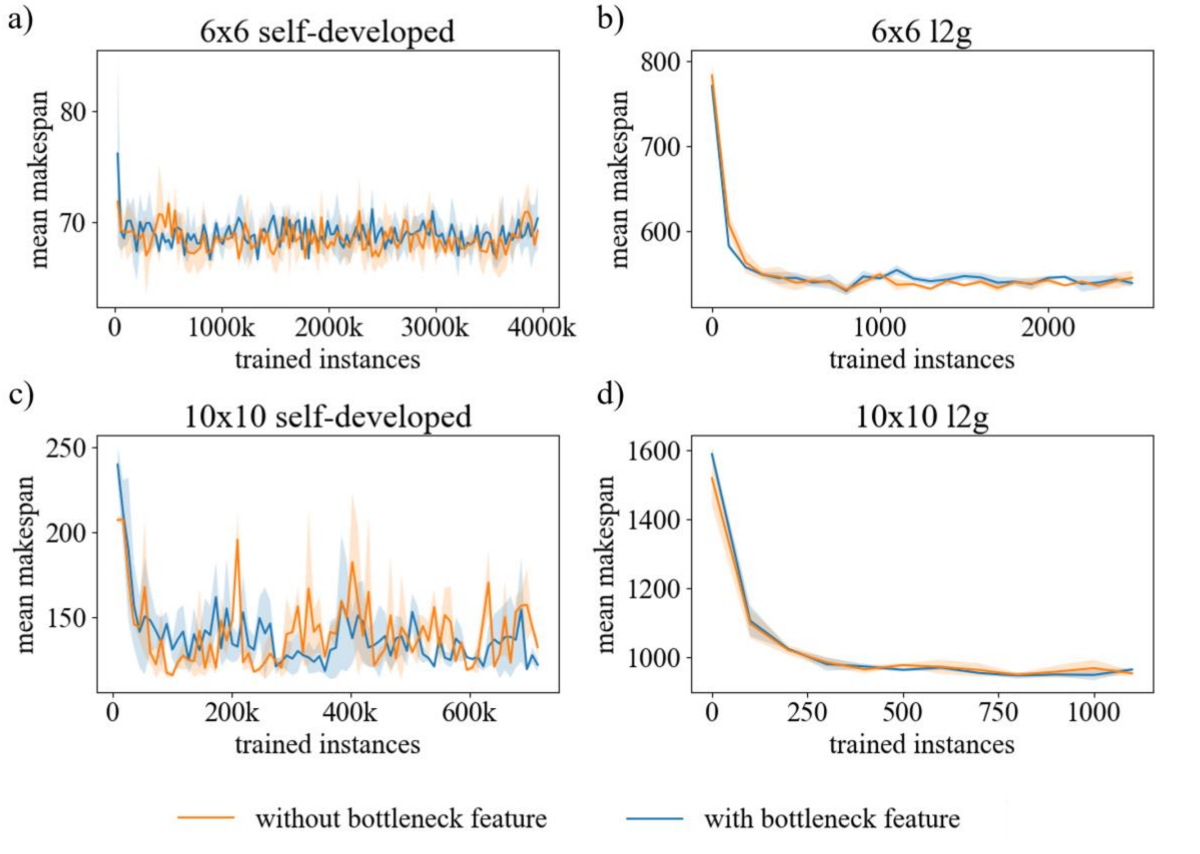


Figure 3: Learning curves of evaluation runs, averaged across seeds. a) Self-developed base model on 6x6 JSSP; b) L2g base model on 6x6 JSSP; c) Self-developed base model on 10x10 JSSP; d) L2g base model on 10x10 JSSP

The second part of the analysis aims at the evaluation of the performance of the final trained models. The averaged results across the three training seeds on the test instances are reported in Table 1. The column *optimal* represents the average makespans of optimal solutions that were calculated using the CP-SAT solver of the OR Tools library [36]. The percentual gap to the optimum is reported in the column *opt.-gap*. The other columns show the average makespans achieved through common PDRs: *MTR*, “most-tasks-remaining”, always selects the next unscheduled operation that belongs to the job with the most unscheduled operations, with ties resolved by the smallest assigned job id. *SPT*, “shortest-processing-time”, selects the next unscheduled operation with the shortest processing time, with ties resolved as before. *Random* chooses the next job of which the next operation will be scheduled by sampling the job id from a uniform random distribution. Comparing the PDR results with the results of the agent, all agents except the ones using the self-designed base on the 10x10 JSSP clearly outperform the PDRs. The critical results with respect to our working hypothesis are the differences between the model performances with and without the bottleneck feature. Here, we find that the resulting makespans are very similar and that those models trained without the bottleneck feature even sometimes outperform those trained with the bottleneck feature. The results of individual models can be found in Appendix B.

Table 1: Summary of average test results of the trained models

base model	JSSP size	bottlenck-feature	agent	optimal	opt.-gap	MTR	SPT	Random
self-designed	6x6	yes	69.5 ± 2.1	59	17.8 %	72.1	140.7	98.9
		no	68.7 ± 2		16.4 %			
	10x10	yes	123.7 ± 5.1	96.9	27.5 %	117.2	320.1	165.3
		no	123.9 ± 2.5		27.8 %			
l2g based	6x6	yes	543.7 ± 1.4	494.8	9.9 %	602.2	1209.6	828.625
		no	542.0 ± 3.5		9.5 %			
	10x10	yes	962.2 ± 3.9	827.65	16.3 %	1094.6	2910.0	1599.3
		no	963 ± 2.5		16.4 %			

The experiments were designed to indicate whether the bottleneck feature carries more useful information than zeros. Considering the above-presented results, the additional non-zero features seem to introduce no noise to the experience data rather than to provide useful information for the learning task. It should also be noted that both, the inclusion of the bottleneck feature and that of zeros, had a small detrimental effect on the final agents' performance when compared to models without such extensions. This shows that more seemingly meaningful features and parameters do not necessarily improve model performance. On the contrary, features with little or no informative value lead to worse results. This has been previously mentioned in other studies regarding DRL based scheduling [5, 19], but has never explicitly been shown for the JSSP.

5. Conclusion and Future Work

This paper presented a study on the integration of a novel shifting bottleneck heuristic-inspired feature into the observation space of DRL agents solving JSSPs. The training behavior and final performance of two different solution approaches, both with and without the new feature, were analyzed and compared. From the results, we conclude that the inclusion of the bottleneck feature does not improve the training procedure, but rather leads to slightly worse final performances. In the light of these results and the considerably prolonged training times resulting from the calculation of the feature in every step of the solution generation, it does not seem like a valuable addition to existing approaches. Yet, we believe that there is unexploited potential in established algorithms and intuitions developed by the OR community over the course of decades, which have received enough attention by DRL based solutions. Some work in this area has already shown great success on combinatorial problems [20, 37, 38]. In future work we aim to identify such potentials in local search algorithms for scheduling problems and build upon the underlying insights to optimize given schedules with DRL.

Appendix

Appendix A: Hyperparameters in Accordance with the Implementation in the *schlably* Framework [34]

Appendix Table 1: Hyperparameters in the self-implemented approach

Parameter	**Value**
Algorithm	PPO-masked
Clip-Range	0.2
Batch size	256
Ent_coef	0
Gamma	1
Learning rate	0.02
N_epochs	5
Policy_activation	Tanh
Policy_layer	[256, 256]
Value_activation	Tanh
Value_layer	[256, 256]
Rollout_scale	2048

Appendix B: Detailed Test Results

Appendix Table 2: Test results of the self-developed base model with and without the bottleneck feature on 6x6 JSSP instances

	seeds	**agent**	**optimal**	**opt. - gap**	**MTR**	**SPT**	**Random**
with bottleneck feature	1	72.13	61.03	18 %	75.50	138.20	101.30
	2	69.28	58.93	18 %	71.50	144.05	100.98
	3	67.05	57.05	18 %	69.15	139.98	94.50
	average	69.48	59.00	**18 %**	72.05	140.74	98.93
without bottleneck feature	1	71.43	61.03	17 %	75.50	138.20	101.30
	2	68.15	58.93	16 %	71.50	144.05	100.98
	3	66.53	57.05	17 %	69.15	139.98	94.50
	average	68.70	59.00	**16 %**	72.05	140.74	98.93

Appendix Table 3: Test results of the self-developed base model with and without the bottleneck feature on 10x10 JSSP instances

	seeds	**agent**	**optimal**	**opt. - gap**	**MTR**	**SPT**	**Random**
with bottleneck feature	1	116.6	95.5	22.1 %	115.5	318.4	159.8
	2	126.1	98.0	28.7 %	118.9	320.2	168.6
	3	128.3	97.3	31.9 %	117.2	321.7	167.6
	average	123.7	96.9	**27.5 %**	117.2	320.1	165.3
without bottleneck feature	1	120.4	95.5	26.1 %	115.5	318.4	159.8
	2	125	98	27.6 %	118.9	320.2	168.6
	3	126.2	97.3	29.7 %	117.2	321.7	167.6
	average	123.9		**27.8 %**	117.2	320.1	165.3

Appendix Table 4: Test results of the l2g base model with and without the bottleneck feature on 6x6 JSSP instances

	seeds	agent	optimal	opt. - gap	MTR	SPT	Random
with bottleneck feature	1	541.7	494.8	9.5 %	602.2	1209.6	828.6
	2	544.3	494.8	10.0 %	602.2	1209.6	828.6
	3	545.1	494.8	10.2 %	602.2	1209.6	828.6
	average	543.7	494.8	**9.9 %**	602.2	1209.6	828.6
without bottleneck feature	1	540.0	494.8	9.1 %	602.2	1209.6	828.6
	2	547.0	494.8	10.5 %	602.2	1209.6	828.6
	3	539.2	494.8	9.0 %	602.2	1209.6	828.6
	average	542.0	494.8	**9.6 %**	602.2	1209.6	828.6

Appendix Table 5: Test results of the l2g base model with and without the bottleneck feature on 10x10 JSSP instances

	seeds	agent	optimal	opt. - gap	MTR	SPT	Random
with bottleneck feature	1	965.5	827.7	16.7 %	1094.6	2910.0	1599.3
	2	956.7	827.7	15.6 %	1094.6	2910.0	1599.3
	3	964.5	827.7	16.5 %	1094.6	2910.0	1599.3
	average	962.2	827.7	**16.3 %**	1094.6	2910.0	1599.3
without bottleneck feature	1	962.9	827.7	16.3 %	1094.6	2910.0	1599.3
	2	960.0	827.7	16.0 %	1094.6	2910.0	1599.3
	3	966.1	827.7	16.7 %	1094.6	2910.0	1599.3
	average	963.0	827.7	**16.4 %**	1094.6	2910.0	1599.3

References

[1] Pinedo, M., 2012. Scheduling: Theory algorithms and systems, 4th ed. Springer, New York.

[2] Holthaus, O., Rajendran, C., 1997. Efficient dispatching rules for scheduling in a job shop. International Journal of Production Economics 48 (1), 87–105.

[3] Luo, X., Qian, Q., Fu, Y.F., 2020. Improved Genetic Algorithm for Solving Flexible Job Shop Scheduling Problem. Procedia Computer Science 166, 480–485.

[4] Leonor Hernández-Ramírez, Juan Frausto Solis, Guadalupe Castilla-Valdez, Juan Javier González-Barbosa, David Terán-Villanueva, María Lucila Morales-Rodríguez, 2019. A Hybrid Simulated Annealing for Job Shop Scheduling Problem. International Journal of Combinatorial Optimization Problems and Informatics 10 (1), 6–15.

[5] 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: CPSL2021, 709–718.

[6] Zhang, C., Song, W., Cao, Z., Zhang, J., Tan, P.S., Xu, C., 2020. Learning to Dispatch for Job Shop Scheduling via Deep Reinforcement Learning. 34th Conference on Neural Information Processing Systems.

[7] Panzer, M., Bender, B., Gronau, N., 2021. Deep Reinforcement Learning In Production Planning And Control: A Systematic Literature Review. Proceedings of the Conference on Production Systems and Logistics: CPSL2021, 535–545.

[8] Khadivi, M., Charter, T., Yaghoubi, M., Jalayer, M., Ahang, M., Shojaeinasab, A., Najjaran, H., 2023. Deep Reinforcement Learning for Machine Scheduling: Methodology, the State-of-The-Art, and Future Directions. SSRN Journal.

[9] Iklassov, Z., Medvedev, D., Solozabal, R., Takac, M., 2022. Learning to generalize Dispatching rules on the Job Shop Scheduling. https://arxiv.org/pdf/2206.04423.

[10] Waubert de Puiseau, C., 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.

[11] Rinciog, A., Meyer, A., 2022. Towards Standardising Reinforcement Learning Approaches for Production Scheduling Problems. Procedia CIRP 107, 1112–1119.

[12] Adams, J., Balas, E., Zawack, D., 1988. The Shifting Bottleneck Procedure for Job Shop Scheduling. Management Science 34 (3), 391–401.

[13] Sutton, R.S., Barto, A., 2018. Reinforcement learning: An introduction, 2nd ed. The MIT Press, Cambridge, Massachusetts, London, England.

[14] Gomes, N.M., Martins, F.N., Lima, J., Wörtche, H., 2022. Reinforcement Learning for Collaborative Robots Pick-and-Place Applications: A Case Study. Automation 3 (1), 223–241.

[15] Han, D., Mulyana, B., Stankovic, V., Cheng, S., 2023. A Survey on Deep Reinforcement Learning Algorithms for Robotic Manipulation. Sensors (Basel, Switzerland) 23 (7).

[16] Waubert de Puiseau, C., Nanfack, D.T., Tercan, H., Löbbert-Plattfaut, J., Meisen, T., 2022. Dynamic Storage Location Assignment in Warehouses Using Deep Reinforcement Learning. Technologies 10 (6), 129.

[17] Hadwiger, S., Lavrik, V., Liao, L.X., Meisen, T., 2023. Simulation-to-Reality Transfer of a Two-Stage Deep Reinforcement Learning Controller for Autonomous Load Carrier Approaching. Proceedings of the 2023 IEEE International Conference on Autonomous Robot Systems and Competitions (ICARSC), 232–238.

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

[19] Kuhnle, A., 2020. Adaptive Order Dispatching based on Reinforcement Learning: Application in a Complex Job Shop in the Semiconductor Industry. Shaker Verlag.

[20] Falkner, J.K., Thyssens, D., Bdeir, A., Schmidt-Thieme, L., 2023. Learning to Control Local Search for Combinatorial Optimization, in: . Joint European Conference on Machine Learning and Knowledge Discovery in Databases. Springer, Cham, pp. 361–376.

[21] Chen, X., Tian, Y., 2018. Learning to Perform Local Rewriting for Combinatorial Optimization. https://arxiv.org/pdf/1810.00337.

[22] Luo, S., 2020. Dynamic scheduling for flexible job shop with new job insertions by deep reinforcement learning. Applied Soft Computing 91, 106208.

[23] Altenmüller, T., Stüker, T., Waschneck, B., Kuhnle, A., Lanza, G., 2020. Reinforcement learning for an intelligent and autonomous production control of complex job-shops under time constraints. Production Engineering 14 (3), 319–328.

[24] Wang, Y., Zhao, Q., Zheng, D., 2005. Bottlenecks in production networks: An overview. Journal of Systems Science and Systems Engineering 14 (3), 347–363.

[25] R. Zhang, C. Wu. Bottleneck Machine Identification for Shop Scheduling Problems. 2008 3rd International Conference on Innovative Computing Information and Control 2008, 149.

[26] R. Zhang, C. Wu, 2008. A simulation-based approach to job shop scheduling with bottlenecks, in: 2008 6th IEEE International Conference on Industrial Informatics. 2008 6th IEEE International Conference on Industrial Informatics, pp. 1007–1012.

[27] Rui Zhang, Cheng Wu, 2008. An effective immune particle swarm optimization algorithm for scheduling job shops, in: 2008 3rd IEEE Conference on Industrial Electronics and Applications. 2008 3rd IEEE Conference on Industrial Electronics and Applications, pp. 758–763.

[28] Pollett, P., 2000. Modelling congestion in closed queueing networks. International Transactions in Operational Research 7 (4-5), 319–330.

[29] Law, A.M., Kelton, W.D., 1991. Simulation modmeling and analysis, 2nd ed. Mc Graw-Hill, New York.

[30] Thomas, T.E., Koo, J., Chaterji, S., Bagchi, S., 2018. Minerva: A reinforcement learning-based technique for optimal scheduling and bottleneck detection in distributed factory operations. Proceedings of the 10th International Conference on Communication Systems & Networks, 129–136.

[31] Carlier, J., 1982. The one-machine sequencing problem. European Journal of Operational Research 11 (1), 42–47.

[32] Schulman, J., Wolski, F., Dhariwal, P., Radford, A., Klimov, O., 2017. Proximal Policy Optimization Algorithms. https://arxiv.org/pdf/1707.06347.

[33] Huang, S., Ontañón, S., 2022. A Closer Look at Invalid Action Masking in Policy Gradient Algorithms. Proceedings of the Thirty-Fifth International Florida Artificial Intelligence Research Society Conference, 35.

[34] Waubert de Puiseau, C., Peters, J., Dörpelkus, C., Tercan, H., Meisen, T., 2023. schlably: A Python framework for deep reinforcement learning based scheduling experiments. SoftwareX 22, 101383.

[35] Vinyals, O., Bengio, S., Kudlur, M., 2016. Order Matters: Sequence to sequence for sets. https://arxiv.org/abs/1511.06391

[36] Perron, L., Furnon, V., 2023. Or-Tools. Google.

[37] Hottung, A., Tierney, K., 2020. Neural Large Neighborhood Search for the Capacitated Vehicle Routing Problem. Proceedings of the 24th European Conference on Artificial Intelligence (ECAI2020).

[38] Wu, Y., Song, W., Cao, Z., Zhang, J., Lim, A., 2022. Learning Improvement Heuristics for Solving Routing Problems. IEEE Transactions on Neural Networks and Learning Systems 33 (9), 5057–5069.

Biography

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

Lennart Zey (*1987) holds a doctorate and is a scientific researcher at the chair of production and logistics at the University of Wuppertal since 2014. His research focuses on scheduling algorithms, meta heuristics, and deep reinforcement learning.

Merve Demir (*1994) holds a master's degree from Erzurum Ataturk University in Industrial Engineering. She received a scholarship from the Türkiye Ministry of National Education for her doctoral study. Since 2022, she works at the Institute for Digital Transformation Technologies and Management at the University of Wuppertal. Her research focuses on solving planning and scheduling problems with deep 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 Institute for 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 for Technologies and Management of Digital Transformation 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 chair of the Interdisciplinary Centre for Data Analytics and Machine Learning.

CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
CPSL 2023-2

5th Conference on Production Systems and Logistics

Innovation Management in Manufacturing - A Study on Industrial Application, Deficits and Opportunities

Quirin Gärtner[1], Xuezhou Zhang[1], Fabian Sippl[1]

[1]Institute for Machine Tools and Industrial Management, Technical University of Munich, Garching near Munich, Germany

Abstract

Manufacturing companies are constantly pressured to innovate in an increasingly complex and discontinuous environment. In addition to developing new products and product features, innovation management in manufacturing has become necessary to ensure the competitiveness of technologies and processes in the context of digitalization, human centricity, sustainability and resilience (Industry 5.0). In the study, presented in this paper, companies from various industries participated in an online survey on their approach to incremental and radical innovation in manufacturing and the associated innovation management. In the study, more than 50 participants provide insight into the innovation management of their manufacturing unit and identify specific fields of action as well as challenges in the areas of technology, organization and people. The study results are intended to provide manufacturing innovation managers with an overview of the challenges, deficits and potentials of innovation management in manufacturing and to help them identify and describe challenges in their organization.

Keywords

Manufacturing; Production; Innovation Management; Radical Innovation; Industry 5.0

1. Introduction

In today's dynamic business environment, innovation is critical to the success of manufacturing companies [1]. With the technological advances and the global competition, organizations must constantly seek to innovate and maintain a competitive edge [2]. Innovation, which encompasses the development of new products, processes and business models, has become an essential catalyst to gain competitive advantages, expand into new markets and achieve sustainable growth [3]. In addition to the development and introduction of new products, the competitive, flexible and sustainable manufacture of these products is increasingly important. The manufacturing industry, known to produce tangible goods, has significantly changed recently [4]. Traditional manufacturing practices have focused primarily on efficiency, cost reduction and scale. However, today's landscape demands a shift towards innovation-driven strategies [5]. To maintain the competitiveness of production sites in high-wage countries, it is essential to develop, implement and exploit innovations to gain a technological advantage and secure the prosperity of society. Adopting advanced manufacturing technologies, such as artificial intelligence and the internet of things, can revolutionize manufacturing, enabling greater flexibility, customization and efficiency [6,7]. Despite recognizing the importance of innovation in manufacturing, several challenges remain to be addressed. This study aims to identify these deficits and explore their underlying causes, providing insights into the industry's barriers to effective innovation management. In addition, this study highlights the opportunities to improve innovation management practices. By examining these opportunities, the paper provides practical recommendations and strategies for organizations to effectively leverage innovation management in manufacturing.

DOI: https://doi.org/10.15488/15250
ISSN: 2701-6277

2. Study

2.1 Aim of the study

This study aims to identify the current diffusion, operational use, challenges and opportunities of manufacturing innovation management in the industry. To this end, an online survey was created, asking companies on their approach, challenges and the starting points for the further improvement of innovation management in manufacturing.

2.2 Study design and participants

2.2.1 Study design

The study was designed according to the established guidelines and methods of empirical social research [8]. To reach a large number of experts at relatively low costs and to obtain data quickly, the study was conducted as an online survey using Qualtrics. When designing the survey, special attention was paid to reducing response bias by excluding contradictory statements, having few questions with Likert scales and always providing the opportunity to include additional answers. The survey was divided into three parts. First, general information about the participant and his company was collected. Second, general information about the application and the influencing factors of manufacturing innovation management were derived and relevant terms were defined. Third, specific information on challenges and potentials in manufacturing innovation management from the participants' companies was asked for.

2.2.2 Study participants

The data collection for the study took place over three months, with the online survey being completed in December 2022. Company representatives from the extended industrial network of the Institute for Machine Tools and Industrial Management at the Technical University of Munich were surveyed. The aim was to obtain a representative cross-section of the European industrial landscape, but also to include non-European companies. More than 70 experts in the field of manufacturing innovation management were contacted by email and provided with a link for participation.

A total of 55 responded to the online survey and returned the questionnaire. As shown in Figure 1 (a), 59% of the participants consider their role to be in a planning position (e.g., project manager or managing director) and 41% in an operational position (e.g., technical specialist or team leader). In addition to automotive engineering (39%), consulting (17%) and plant and mechanical engineering (14%), representatives of the electronics industry (8%), metalworking (8%), aerospace (4%), energy supply (4%), medicine (4%) and agricultural engineering (2%) could also be interviewed (see Figure 1 (b)).

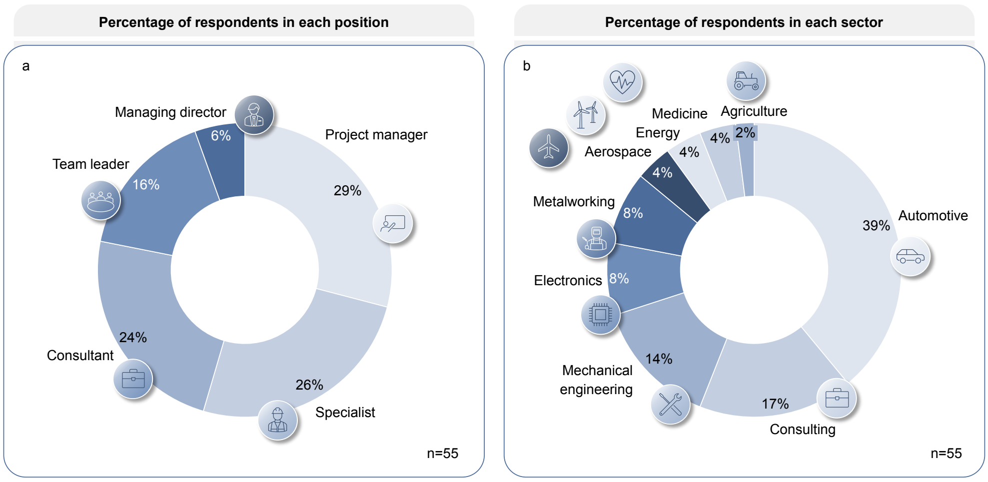


Figure 1: (a) Positions of the study participants; (b) sectors of the study participants

The surveyed experts indicated that their companies operate production facilities in Europe (28%), Asia (26%), North America (18%), Central and South America (15%), as well as Africa (8%) and Oceania (3%) (see Figure 2 (a)). As shown in Figure 2 (b), 40% of the experts represent large companies, 35% medium-sized companies and 25% small and micro companies. In addition, 27% of respondents have more than ten years of professional experience, 37% have between 3 and 10 years, and 36% have less than three years of experience (see Figure 2 (c)).

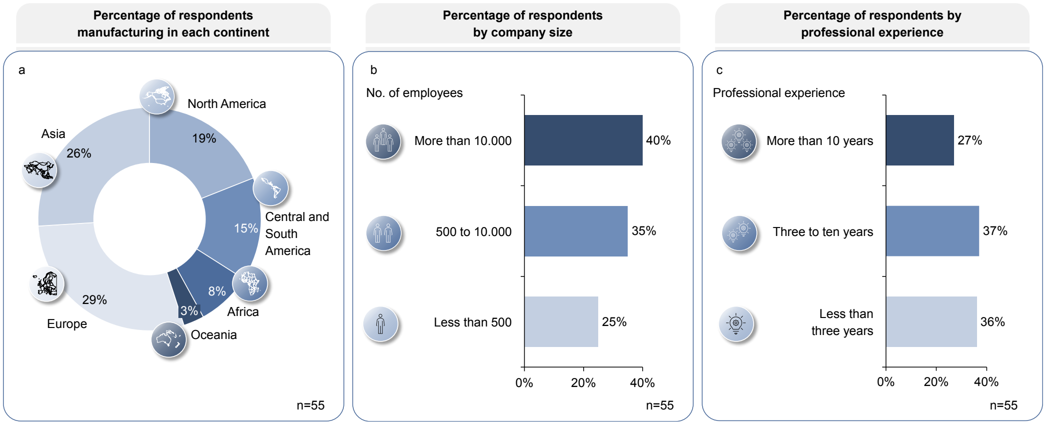


Figure 2: (a) Location of respondents' production sites; (b) Percentage of respondents by company size; (c) Percentage of respondents by professional experience

3. Innovation management in manufacturing

3.1 Terms and definitions

Manufacturing transforms inputs, such as raw materials and resources, into finished goods or services [9]. It involves a series of interrelated activities, which can be divided into value-adding activities, like the production of raw parts and assembly, and non-value-adding activities, like planning, logistics and quality management [10].

Innovation is defined as the generation and successful implementation of new ideas in processes or products that lead to improvements in efficiency, quality or functionality [11]. According to [12], innovation in the context of manufacturing can be defined as the recombination of forces and objects to either produce differently or something different. There are two critical factors in determining an innovation. First, there must be an invention aimed at improving a process. Second, this invention must be followed by a successful implementation in a manufacturing system [13].

Innovations are differentiated in various ways in the literature and different dimensions are repeatedly addressed [14,15]. Concerning the research topic of this study, it is necessary to explain the distinction between incremental and radical innovation. According to [16], a gradual differentiation of innovations can be translated into dichotomies. The most common dichotomy in the literature is the distinction between incremental and radical innovation. Incremental innovation in manufacturing refers to improvements with a high affinity to the existing process [17], unlocking its underlying potential through comparatively minor changes [18], like the accuracy of a laser cutting process. In contrast, radical innovation describes a leap or fundamental change that leads to a breakthrough toward a new technological process (component), environment or organization [19,20], like the introduction of additive manufacturing technologies.

From a process perspective, innovation management involves the identification, idea generation and evaluation, development, integration, adoption and diffusion [21,22] of novel concepts within an organization, leading to improved performance and market advantage. Internal and external stimuli are used to discover innovation needs and opportunities during the identification process. The subsequent generation and evaluation of ideas generate possible solutions and select the most promising ones. Thereafter, the chosen solution is developed until it is suitable for serial production. The implementation and the use of the new solution in the existing or new manufacturing system follow the development. In the final diffusion, the results of the previous stages are fed back into the organization and used for further use cases [21].

Integrating innovation into manufacturing gives rise to the concept of manufacturing innovation management. Effective manufacturing innovation management enables organizations to respond to market changes proactively, capitalize on emerging technologies and continuously improve their products and value-adding processes, ultimately leading to sustainable growth and competitive advantage in quality, cost and time [23]. It involves the use of methods for the systematic planning, coordination and control of innovation processes, including the process activities mentioned above [23].

3.2 Industrial application of manufacturing innovation management

To successfully compete in the market, manufacturing companies have several options. In theory, four basic strategies can be distinguished [24,25]. The differentiation strategy aims to differentiate from competitors by offering unique product quality or functionality. The cost leadership strategy seeks to differentiate itself from competitors by offering a product at a lower price. The niche strategy aims to satisfy the specific needs of a particular customer group through specific product qualities or functionalities to gain market share. Finally, the hybrid strategy includes all combinations of the first three competitive strategies.

The respondents were asked to classify the innovation strategy of their manufacturing unit, which follows the company's competitive strategy. It became clear that most manufacturing units pursue quality differentiation (41%) and a hybrid strategy (28%). The competitive strategies of cost leadership (20%) and niche strategy (11%) are followed by only a small proportion of manufacturing units (see Figure 3 (a)).

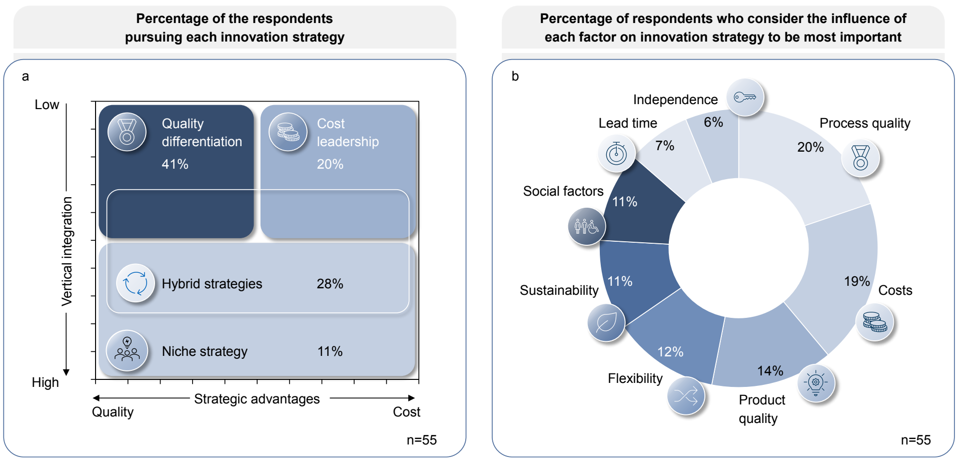


Figure 3: (a) Percentage of the respondents pursuing each innovation strategy; (b) influence factors for the manufacturing innovation strategy

Manufacturing companies strive to continuously align their performance indicators with their competitive strategy through the processes and methods of manufacturing innovation management. Production costs, process and product quality and lead time within the manufacturing process are strongly emphasized to measure this process. These four main objectives are complemented by new strategic orientations in modern manufacturing units, such as flexibility, sustainability, independence or social factors such as employee satisfaction and health. As shown in Figure 3 (b), respondents ranked the influence of these objectives on their manufacturing innovation management according to their perceived importance. It was found that process quality (20%), production costs (19%) and product quality (14%) remain the most critical influencing factors. However, it also became clear that objectives such as flexibility (12%), sustainability (11%) and social factors (11%) are having an impact on the innovation strategy of manufacturing. Lead time (7%) and independence (6%) were rated to have the least influence on the innovation strategy.

Manufacturing companies face external challenges forcing them to rethink their manufacturing operations, including processes, working methods, technologies and organizational structures. Respondents highlighted rising costs (16%), digitalization and artificial intelligence (16%), sustainability (16%), skills shortages (14%) and unstable supply chains (14%) as the most critical challenges to their competitive position. By contrast, demographic change (8%), cyber security (7%), individualization (5%) and the shift in global economic power (4%) are currently of secondary importance to the companies surveyed (see Figure 4 (a)).

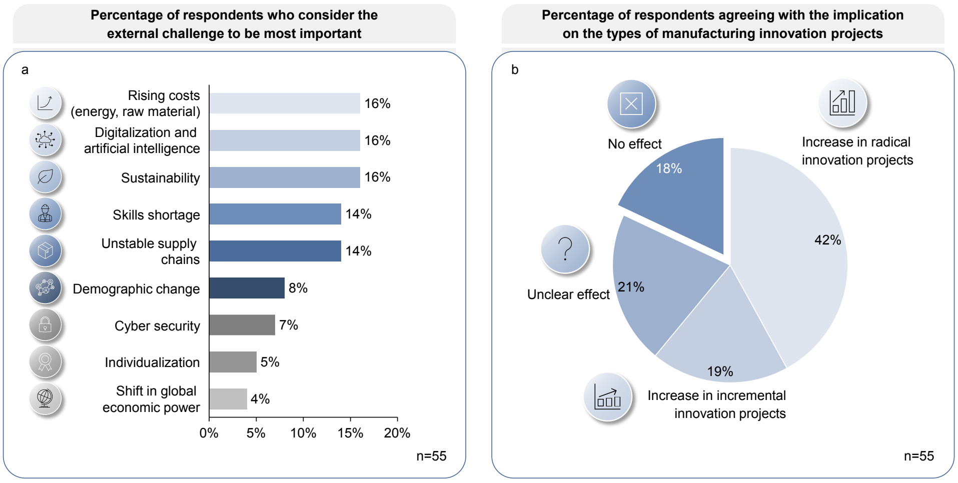


Figure 4: (a) External challenges for manufacturing; (b) implications for manufacturing innovation projects

According to respondents, these external influences affect manufacturing companies' innovation strategy and the types of innovation projects (82%). As Figure 4 (b) shows, most respondents (42%) state that the proportion of radical innovation projects has increased. In contrast, 19% of respondents see an increase in incremental innovation projects or an unclear effect (21%). This suggests that the challenges ahead are so significant that manufacturing units need to address them through radical innovation projects.

3.3 Challenges and deficits of manufacturing innovation management

However, when carrying out innovation projects in manufacturing unplanned complexity is created by challenges. As shown in Figure 5 (a), respondents state that the execution of radical innovation projects is rather complex, while the complexity of incremental innovation projects is rated to be rather moderate.

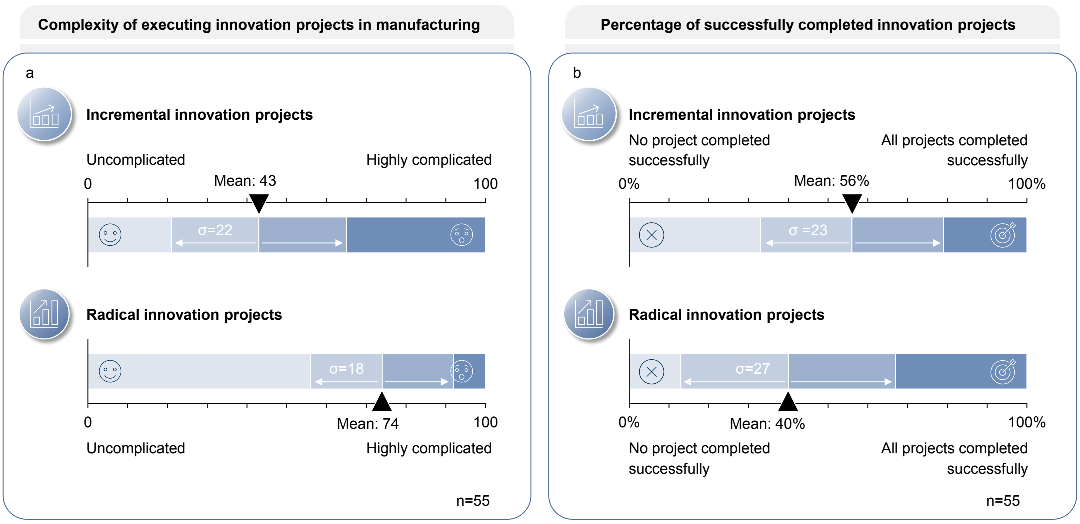


Figure 5: (a) Complexity of innovation projects; (b) Percentage of successfully completed innovation projects

The complexity of radical manufacturing innovation projects becomes even more apparent when comparing the two types of projects (radical and incremental) regarding the percentage of successfully completed projects. Figure 5 (b) shows that, respondents indicate that only 40% of initiated radical manufacturing innovation projects are completed. For incremental innovation projects, this proportion is 56%.

Subsequently, the participants were asked at which stage of the innovation process the challenges occurred most frequently and in which area the challenge originated. The challenge areas were based on [26], dividing the elements of a manufacturing unit into the main categories of technology, organization and people. Participants were then asked to choose which of these three areas presented the most challenges.

Figure 6 shows that, the development (22.5%) and integration (36.3%) phases are where most of the challenges in the manufacturing innovation process occur. The phases of idea generation, evaluation and selection (12.7%) and exploitation (16.7%) are the second most challenging. Demand identification (5.9%) and dissemination (5.9%) are considered by the participants to be relatively unproblematic.

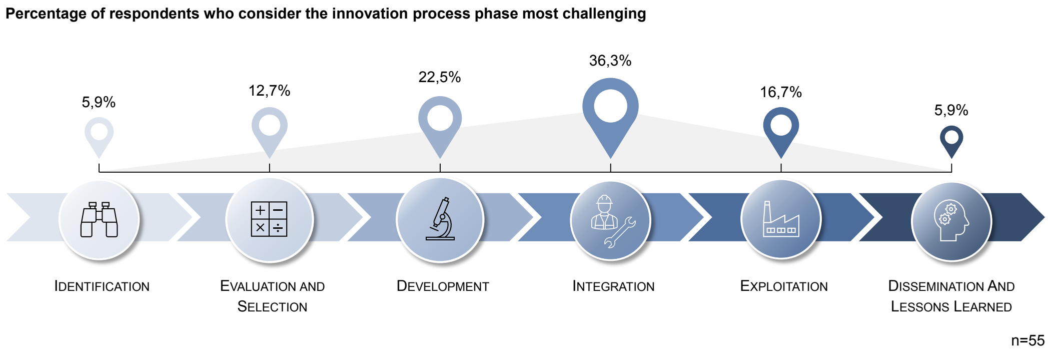


Figure 6: Occurrence of challenges in the manufacturing innovation process

Looking at the areas where challenges arise, it became surprisingly clear that there was not one area where problems occurred most frequently (see Figure 7). The areas of technology (35%), organization (32.5%) and people (32.5%) were rated equally by participants when asked about the causes of challenges.

The study then sought to gain a deeper understanding of the specific challenges in each area. In the area of technology, three key challenges were highlighted by respondents. Firstly, in the context of technological innovation management in manufacturing, challenges are seen in providing appropriate resources for technology development (e.g., facilities, environments, software) as these are often unavailable or difficult to obtain. Secondly, the lack of technological knowledge in the organization to implement technology projects in a targeted and successful way was emphasized. Thirdly, it was stressed that implementation often fails because the integration into the existing manufacturing system is too complex or the technical equipment is insufficient (e.g., IT system, infrastructure).

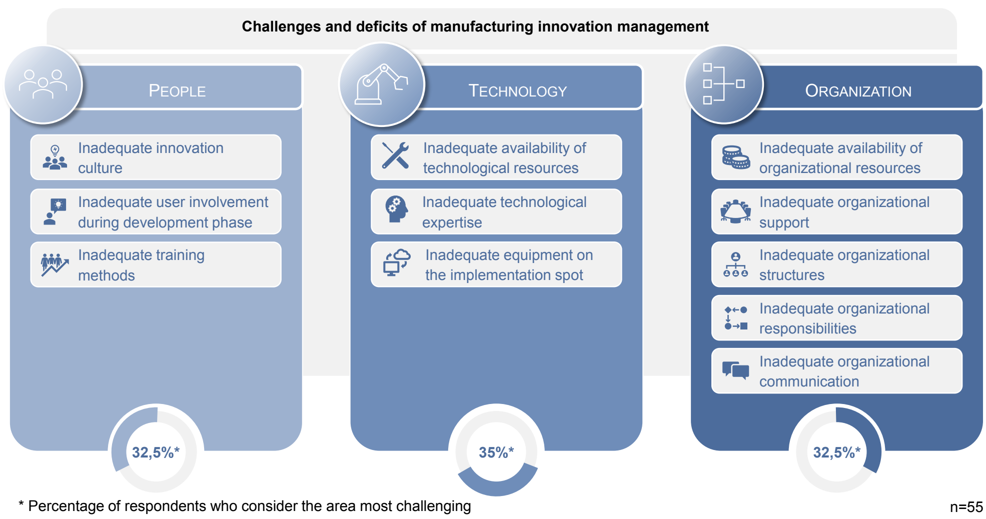


Figure 7: Challenges in manufacturing innovation management

In the area of organization, participants identified five root causes of organizational challenges in manufacturing innovation management. Firstly, a lack of organizational resources (e.g., time and people) was emphasized. Secondly, a lack of organizational support from management or the innovation culture and philosophy of the organization was identified by the participants. Thirdly, inappropriate organizational structures (e.g., hierarchical project structures) were emphasized. Fourthly, unclear managerial responsibilities (e.g., decision rights and process structures) were highlighted. Fifthly, insufficient internal scaling due to a lack of dissemination (communication) or organizational strategy was mentioned.

In the area of people, three critical challenges for innovation management in manufacturing were identified. Firstly, a lack of acceptance of new solutions and willingness to change was emphasized by the participants. Secondly, a lack of user involvement during the innovation development to enable ergonomic application in manufacturing was highlighted. Thirdly, a lack of solutions and methods to familiarize users with new technologies or processes in a targeted, application-oriented and economical way was stated.

3.4 Opportunities for manufacturing innovation management

In addition, the participants were asked about their ideas and opportunities for innovation management in manufacturing. Since most participants stated that the proportion of radical innovation projects in manufacturing is increasing, the opportunities also relate to the implementation of radical projects.

Surprisingly, only under half of the respondents indicated that a distinction is made between incremental and radical innovation projects in their manufacturing unit. However, the vast majority of respondents (91%) indicated that the planning and implementation of radical innovation projects in manufacturing should be handled different from that of incremental innovation projects. Based on the responses, several potential areas for innovation management in manufacturing could be identified (see Figure 8).

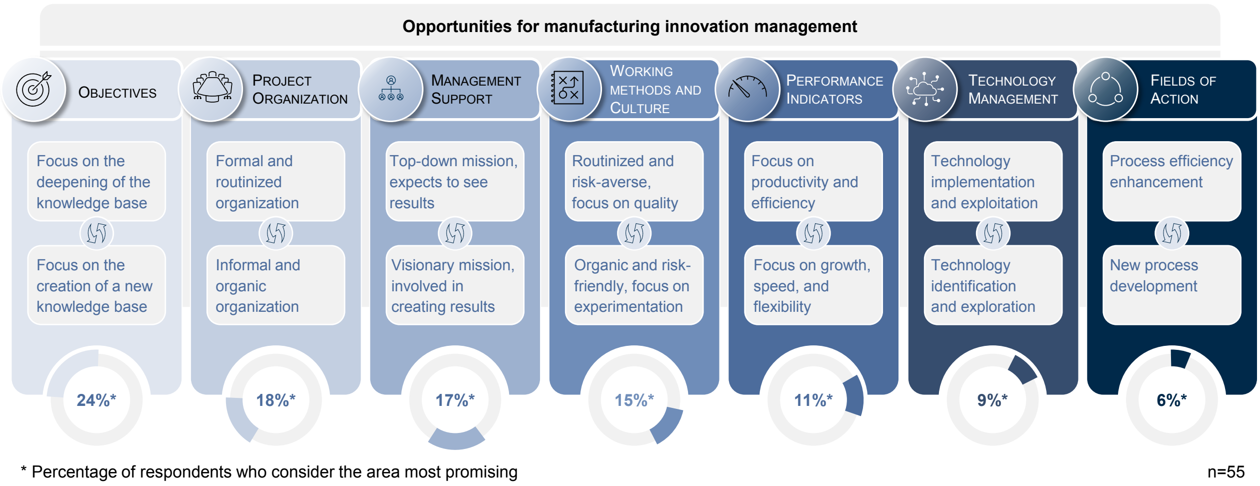


Figure 8: Opportunities for manufacturing innovation management

Differentiation in project objectives (24%) was the most frequently mentioned potential. The objectives of radical innovation projects should focus on creating new knowledge and not on deepening knowledge to reach objectives like quality, costs and lead time in the short run. Secondly, project organization (18%) was seen as another significant potential in differentiation. In line with the challenges identified, respondents highlighted a need for informal and organic organizational structures and process organizations in radical innovation projects in manufacturing. The third potential area concerns the type of management support (17%). According to the respondents, radical innovation projects in manufacturing require a visionary and supportive management to be successfully implemented. The fourth potential area relates to working methods and culture (15%). Respondents emphasize new methods and a risk-friendly culture to implement radical innovation projects in manufacturing. Fifth, the respondents state that measuring the performance of radical innovation projects requires indicators related to growth and speed rather than productivity and efficiency. Concluding, the least potential is seen in technology management (9%) and general fields of action (6%) of innovation projects in manufacturing to differentiate. According to the respondents, the technology management activities for incremental and radical innovation projects can be identical. The same applies to the relevant fields of action.

4. Summary and outlook

In summary, this contribution explores the concept of innovation management in manufacturing, examines its industrial application, identifies shortcomings and uncovers opportunities. Contributing to the existing body of knowledge on innovation management, it provides valuable insights for manufacturing companies navigating the complexities of the modern innovation management.

This study shows that the differentiation through quality and cost remains the most critical innovation strategy in manufacturing. However, it also shows that flexibility, sustainability and social factors increasingly influence these innovation strategies. It became clear that external challenges, like rising material and energy costs, digitalization and artificial intelligence or sustainability, are significantly impacting the innovation activities of manufacturing companies. Further, it was found that these external challenges strongly influence the type of innovation activity, leading to an extreme increase in radical innovation projects in manufacturing. The challenge, however, is that implementing radical innovation projects in manufacturing is almost twice as complex as implementing incremental innovation projects. This complexity occurs mainly during the phases of development and integration. However, it is surprising that the challenges are evenly distributed across the areas of technology, people and organization. On the other hand, opportunities and potentials for innovation management in manufacturing were identified. The study showed that the most significant potential and opportunities lie in defining the objectives, informal project organization, visionary management support, appropriate working methods and suitable performance indicators to enable knowledge generation and short-cycle innovation development.

Looking forward, modern manufacturing units must focus on managing radical innovation projects on a regular basis. Therefore, manufacturing units must learn to adapt their organizational and project structure to radical innovation projects. Second, manufacturing units need to identify and apply the right technologies and methods for these projects in short cycles. Third, manufacturing units and innovation managers need to involve their employees even more, promote active and inclusive communication and create and foster an innovative culture. In all three areas, the scientific and industrial community must develop concepts and methods to strengthen the radical innovation capacity of European manufacturing companies, maintain their technological leadership and thus ensure the prosperity of society.

Acknowledgements

The Bavarian Ministry of Economic Affairs, Regional Development and Energy (StMWi) funds this research and development project "Industrielle und Durchlaufoptimierte Endmontagelinie für Helikopter" (ROB-2-3410.20-04-10-21). We extend our sincere thanks to the StMWi for its generous support.

References

[1] Zhu, M., Gao, H., 2021. The antecedents of supply chain agility and their effect on business performance: an organizational strategy perspective. Operations Management Research 14 (1-2), 166–176.

[2] Ávila, M.M., 2022. Competitive Advantage and Knowledge Absorptive Capacity: The Mediating Role of Innovative Capability. Journal of the Knowledge Economy 13 (1), 185–210.

[3] Visnjic, I., Wiengarten, F., Neely, A., 2016. Only the Brave: Product Innovation, Service Business Model Innovation, and Their Impact on Performance. Journal of Product Innovation Management 33 (1), 36–52.

[4] Backer, K. de, Desnoyers-James, I., Moussiegt, L., 2015. Manufacturing or Services - That is (not) the Question: The Role of Manufacturing and Services in OECD Economies. OECD Science, Technology and Industry Policy Papers 19 (1), 1–53.

[5] Wang, B., 2018. The Future of Manufacturing: A New Perspective. Engineering 4 (5), 722–728.
[6] Huang, Z., Jowers, C., Kent, D., Dehghan-Manshadi, A., Dargusch, M.S., 2022. The implementation of Industry 4.0 in manufacturing: from lean manufacturing to product design. The International Journal of Advanced Manufacturing Technology 121 (5-6), 3351–3367.
[7] Wang, G., Zhang, L., 2022. Simulation Analysis of Dynamic Feedback Correlation Between Advanced Manufacturing Technology (AMT) and Product Innovation Performance. IEEE Engineering Management Review 50 (1), 113–131.
[8] Häder, M., 2015. Empirische Sozialforschung. Springer Fachmedien Wiesbaden, Wiesbaden.
[9] Schuh, G., Schmidt, C., 2014. Grundlagen des Produktionsmanagements, in: Schuh, G., Schmidt, C. (Eds.), Produktionsmanagement. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 1–62.
[10] Soliman, M., Saurin, T.A., 2017. Lean production in complex socio-technical systems: A systematic literature review. Journal of Manufacturing Systems 45, 135–148.
[11] Gärtner, Q., Dorth, A., Reinhart, G., 2022. Concept for ambidextrous management of incremental and radical innovation in manufacturing. Procedia CIRP 107, 475–480.
[12] Schumpeter, J.A., 1934. Theorie der wirtschaftlichen Entwicklung: Eine Untersuchung über Unternehmergewinn, Kapital, Kredit, Zins und den Konjunkturzyklus, 1st ed. Duncker und Humblot, Berlin.
[13] Porter, M., 1990. Competitive Advantage of Nations. Competitive Intelligence Review 1 (1), 1–14.
[14] Green, S.G., Gavin, M.B., Aiman-Smith, L., 1995. Assessing a multidimensional measure of radical technological innovation. IEEE Trans. Eng. Manage. 42 (3), 203–214.
[15] Katila, R., 2011. Measuring innovation performance, in: Neely, A. (Ed.), Business Performance Measurement. Cambridge University Press, Cambridge, pp. 304–317.
[16] Hauschildt, J., Salomo, S., 2010. Innovationsmanagement, 5th ed. Vahlen, München.
[17] Nigg-Stock, A., Bayrle, N., Brecht, L., 2023. Drivers of exploitative and explorative innovation efficiency. Digital Business 3 (2), 100062.
[18] Schallmo, D.R., Brecht, L., 2017. Prozessinnovation erfolgreich anwenden. Springer Berlin Heidelberg, Berlin, Heidelberg.
[19] Brem, A., Nylund, P.A., Schuster, G., 2016. Innovation and de facto standardization: The influence of dominant design on innovative performance, radical innovation, and process innovation. Technovation 50-51, 79–88.
[20] Olivan, P., 2019. Methode zur organisatorischen Gestaltung radikaler Technologieentwicklungen unter Berücksichtigung der Ambidextrie. Dissertation. Universität Stuttgart, Stuttgart.
[21] Hofer, A., Brandl, F., Bauer, H., Haghi, S., Reinhart, G., 2020. A Framework for Managing Innovation Cycles in Manufacturing Systems. Procedia CIRP 93, 771–776.
[22] Spur, G., Gleich, H., Eßer, G., 2013. Modellorientierte Planung von Produktionsinnovationen. Zeitschrift für wirtschaftlichen Fabrikbetrieb 108 (5), 279–282.
[23] Brandl, F.J., Kagerer, M., Reinhart, G., 2018. A Hybrid Innovation Management Framework for Manufacturing – Enablers for more Agility in Plants. Procedia CIRP 72, 1154–1159.
[24] Porter, M., 1985. The Competitive Advantage: Creating and Sustaining Superior Performance. Free Press, New York.
[25] Salavou, H.E., 2015. Competitive strategies and their shift to the future. European Business Review 27 (1), 80–99.
[26] Ulich, E., 1997. Mensch, Technik, Organisation: ein europäisches Produktionskonzept, in: Strohm, O., Ulich, E. (Eds.), Unternehmen arbeitspsychologisch bewerten. vdf Hochschulverlag, Zürich, pp. 5–17.

Biography

Quirin Gärtner (*1994) holds a M.Sc. degree in Mechanical Engineering and Management from the Technical University of Munich. Since 2020 he is a doctoral fellow at the Institute for Machine Tools and Industrial Management (*iwb*) at the University of Munich, Germany. His research areas are Innovation and Technology Management.

Xuezhou Zhang (*1994) holds a B.Sc. degree in Mechanical Engineering from the University of Kassel, Germany. He currently pursues a M.Sc. degree in Automotive Engineering at the Technical University of Munich, Germany. His research areas are Innovation and Technology Management and Automotive engineering.

Fabian Sippl (*1993) holds a M.Sc. degree in Mechanical Engineering from the Technical University of Munich. Since 2018 he is a doctoral fellow at the Institute for Machine Tools and Industrial Management (*iwb*) at the University of Munich, Germany. Since 2021 he is part of the management board of the *iwb* and head of the department for production management and logistics. His research area is Manufacturing Change Management.

5th Conference on Production Systems and Logistics

Bridging The Gap: A Framework For Structuring The Asset Administration Shell In Digital Twin Implementation For Industry 4.0

Monika Risling[1], Henry Himmelstoss[1], Alexander Brandstetter[1], Dachuan Shi[1], Thomas Bauernhansl[1,2]

[1] *Fraunhofer Institute for Manufacturing Engineering and Automation IPA, Nobelstraße 12, 70569 Stuttgart, Germany*
[2] *Institute of Industrial Manufacturing and Management, University of Stuttgart, Allmandring 35, 70569 Stuttgart, Germany*

Abstract

The digital twin is a core technology for implementing Industry 4.0 scenarios in scientific and industrial applications. One upcoming variant of the digital twin is the concept of the asset administration shell, representing an approach to standardization. This approach must be adapted to specific use cases and applied in a target-oriented manner. However, no comprehensive guidance exists on structuring and implementing asset administration shells based on the digital twin in manufacturing environments. This issue pertains to defining and organizing the relevant data and mapping domain-specific limitations and characteristics within the hierarchical structure of the asset administration shell's components. This paper introduces an approach to structuring the asset administration shell to address this gap. This approach capitalizes on domain-specific expertise, industry standards, and established best practices, providing a framework. We validate the presented approach by applying it to the use case of distributed high-rate electrolyser production. The overarching objective of this research is to bridge the gap between theoretical concepts and practical applications.

Keywords

Digital Twin; Asset Administration Shell; Systematic Structuring; Digital Manufacturing; Industry 4.0

1. Introduction

Hydrogen has been identified as one of the relevant energy carriers of the future in the German government's national hydrogen strategy [1]. Thus directly contributing to the EU Green Deal, that states as one of its objectives that no more net greenhouse gases should be emitted by 2050 [2]. The demand for hydrogen is subject to ongoing estimation, and current estimates forecast an increasing demand. According to Fraunhofer ISE's hydrogen roadmap, Europe will have a hydrogen demand of 800 TWh in a low scenario and 2,250 TWh in a high scenario in the year 2050. Meeting these hydrogen requirements will necessitate a proportional expansion of electrolysers capable of producing green hydrogen [3]. This results in the necessity of producing electrolysers in large numbers and with sufficient capacity. Due to its technical properties, PEM electrolysis has proven to be particularly suitable for meeting the dynamic challenges of the future [4]. In principle, high-performance electrolysers are already available on the market, but they are often still assembled by hand in insufficient numbers. Implementing series production of electrolysers is also necessary to counter the cost aspects resulting from time-consuming manual assembly [5].

The H2Giga-FRHY project is dedicated to researching the high-volume production of industrial-grade electrolysers. It involves a diverse group of researchers from various Fraunhofer Institutes located at different sites focusing on different aspects of the high-throughput electrolyser production. The digitalized and

DOI: https://doi.org/10.15488/15286
ISSN: 2701-6277

standardized descriptions of electrolyser production, encompassing product-related information, involved manufacturing resources, production processes, and process data, play a crucial role in the series production of electrolysers. Especially in distributed manufacturing systems, seamless data exchange among disparate systems is imperative. In this sense, digital twin (DT) technologies structure a digital representation of distributed manufacturing systems for electrolyser production.

This paper presents an approach for structuring a digital representation based on the Asset Administration Shell (AAS) for distributed manufacturing systems. This work follows from previous research that has focused on the specification of service functionalities to enable use-case oriented modelling of the AAS [6]. As a result, various relevant norms, industry standards, best practices, and domain-specific expertise are utilized, thereby providing a framework. We validate our approach by applying it to the use case of distributed electrolyser production within the research project H2Giga-FRHY.

2. Initial situation and problem description

The software services within the software-defined manufacturing system (SDMS) that enable high-rate series production require a cross-site and cross-process representation of products and processes. Those are typically engendered and processed through domain-specific software applications in different phases of the product life cycle as a courtesy of various vendors. This scenario consequently leads to the formation of individual data silos. This holds particularly true where data is dispersed across disparate and incompatible systems employing various technologies. It further elaborates on three specific problems. First, data sources and resulting data types are highly heterogeneous. Secondly, there is an insufficiency for standardization of relevant entities, terms, and attributes relationships. And lastly, the semantic context is lacking. Therefore production-specific data is often captured and managed without metadata and context, preventing its use by multiple stakeholders [7]. DTs are expected to disrupt this silo pattern, fostering a more cohesively networked production system. Despite the proposition of numerous DTs of production equipment and systems in the past decade [8], the absence of interoperability between individual DTs and a systematic framework for structuring and implementing networked DTs remains a significant impediment realizing high-rate distributed manufacturing systems.

The AAS is a standard for the DT's standardization and interoperability information framework of the DT. It describes an asset's technological features as a core element of the Reference Architectural Model for Industry 4.0 – also known as RAMI 4.0 [9,10]. The AAS offers prospects for integrating these data silos. It is achieved by employing standardized semantics and syntax. These are given throughout product life cycles, the vertical hierarchy levels within an enterprise, and the horizontal value chain [11].

Structuring a digital representation aims to build information models in a machine- and human-readable form that enables semantic interoperability. However, the information modeling process for developing standardized submodel templates and the standardization of data specifications poses tremendous challenges, as it depends heavily on specific domain expertise and lacks a universal methodology. In practice, a group of domain experts usually develops these. The modeling approach varies depending on the experts and the domain.

With this consideration, a general framework offering guidance on structuring the AAS-based DT could prove beneficial in expediting the procedures of development and standardization. The ultimate goal is to create the AAS-based representation of distributed manufacturing systems that enables end-to-end, cross-process control and product adaptation from development to the end of the manufacturing process.

The proposed framework can also be applied to future production-specific projects, capitalizing on the project's decentralized structure, utilization of modern tools, and the involvement of various stakeholders. This is based on the assumption that when considering discrete manufacturers in the abstract, a relevant number of similarities can be defined as a digital representation that also serves as a basis for deriving further use case-specific DTs. Established standards are used to pick up these similarities in discrete production. The considerations and requirements arising from this project establish an ideal structure for administering the AAS that can be applied to other production-specific endeavours.

3. State of the art of digital twin usage

In scientific investigation and industrial application, diverse viewpoints concerning DT prevail. The concept of DT was first mentioned by Grieves, who defined it as three components. These components consist of the physical product in real space, the virtual product in virtual space, and the link for the data and information flow [12]. Tao et al. built on Grieves' concept and suggested two additional components: data and services [13,14]. There are attempts to describe DT based on several existing descriptions. For example, Kritzinger et al. [15] describe the central common feature that DT represents the digital counterpart to physical objects. Valk et al. [16] conducted an extensive literature review and identified the most cited commonalities. These include, among others, a bi-directional data connection, that the physical object is usually created first, or that it can contain both raw and pre-processed data.

The DT concept is employed in connection with the AAS framework, designating it as a comprehensive digital representation that effectively fulfils a specific set of use cases. The AAS is a repository for recording and delivering production and product-associated data. *IEC 63278* focuses on the general concepts and structure of a single AAS rather than a representative concept of a complex manufacturing system consisting of a heterogeneous landscape of manufacturing assets that are interrelated and interdependent. Data inputs are integrated into our production scenario, establishing it as SDMS [17]. The standardized syntax refers to the standardized meta model of AAS and the standardized submodel templates. These specify the rules and formats determining how the information is structured and represented for the specific use cases. The semantic pertains to the data specifications of the information encapsulated in the AAS. This involves leveraging standardized vocabularies and ontologies defined by the IEC Common Data Dictionary [18] and ECLASS [19]. This ensures consistent interpretation of data across diverse systems and contexts, and facilitates accurate comprehension by humans and machines.

The SDMS that prevails here using the data and use case-based software services provided by DT enables the actors in the system to optimize product and process configurations in continuously faster cycles. For example, by showing correlations between product defects and product characteristics or deviations from target processes. Thus, the SDMS fulfils the characteristics of cloud-based manufacturing and thus takes into account the decentralisation prevailing in the project due to the distributed production locations. Cloud-based manufacturing can be described by characteristics such as connected manufacturing, scalability, IoT, and as-a-service like software-as-a-service, among others [20].

4. Production and manufacturing domain-specific standards and guidelines

This chapter shows relevant standards and guidelines on DT manufacturing and structuring. We describe the reasoning behind the chosen approach and selected standard. In this context, we classify the standards and guidelines and exclude irrelevant standards for systematically structuring production-focused DTs. We then further introduce industry-specific standards that can be adapted to our use. We did not perform a systematic literature review but evaluated the standards described based on relevance in the literature, specifics, generalisation, and suitability for manufacturing.

Currently, DTs are primarily research-based. There are no generally acknowledged standards for developing and deploying DTs [21–23]. However, ongoing standardization initiatives make an effort to standardize several DT components. ISO, IEC, ITU, and IEEE standardizations are among them. Since these organizations could not agree on a definition of DT, Wang et al. [24] identified and categorized them into five main categories: physical entities, virtual entities, data, connections, and services. Wang et al.'s systematic literature review of the technology standards group is our primary source for investigating the appropriate DT standards due to its coverage. The categories chosen for the literature review can be seen in Figure 1, including a classification of the essential DT standards into the mentioned categories. Most of the standards are specific to a single field, such as sensor technology (*IEEE 2888*), data sharing (*IEC 62714-1*), or data on cutting tools. However, many of these are too general compared to the necessity of manufacturing. The AAS described in *IEC 63278-1* ED1 and the general DT norm *ISO 23247* are two standards written for manufacturing. The AAS is described in detail in the chapters before.

ISO 23247 is a multi-layered DT framework standard for manufacturing. The layers describe the observable manufacturing elements, data collection and device control entity, core entity, and user entity. The standard includes a reference architecture, data examples, and network protocols. The standard gives a fundamental and necessary understanding of a DT framework in manufacturing [25].

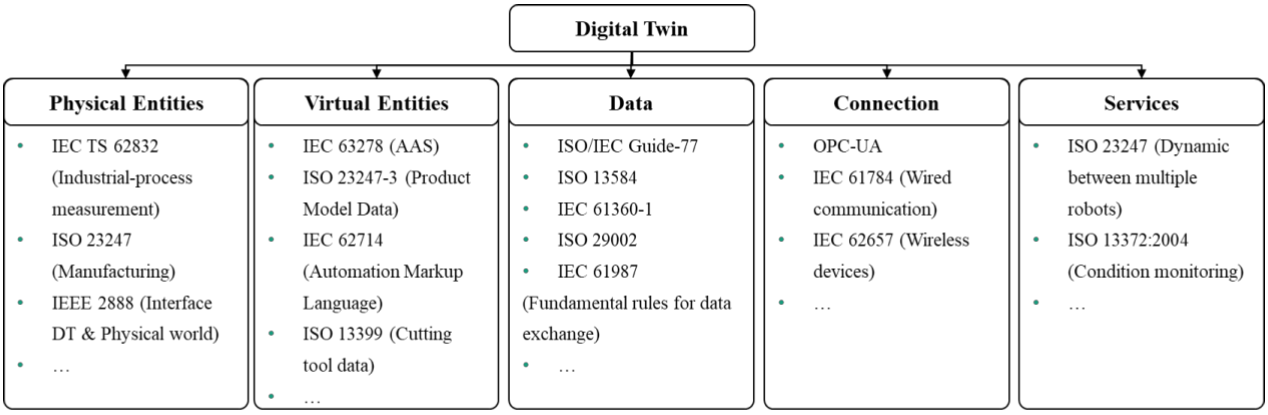


Figure 1. Division of the digital twin into five sections and associated standards excerpt from [24]

The *I4.0 Core Information Model* is a standardized data model specifically designed for the manufacturing domain within the context of Industry 4.0. It provides a comprehensive framework for describing entities, attributes, and relationships relevant to manufacturing processes. By enabling the integration of heterogeneous data sources and supporting analytical use cases, the *I4.0 Core Information Model* facilitates interoperability and data exchange, ultimately enhancing operational efficiency in industrial settings. Similar to the *IEC 62264*, the semantic is divided into product, process segment, product segment, and equipment. It also contains the physical asset model as in the AAS and a parameter model. The *I4.0 Core Information Model* and AAS, both based on resource description framework (RDF), serve distinct purposes in DT design. The *I4.0 Core Information Model* provides a standardized data model for integrating heterogeneous data sources and analytical use cases. At the same time, DT architectures like AAS enable DTs' semantic description and real-time data exchange. Combining these models allows for comprehensive DT solutions, facilitating knowledge graph creation, real-time updates, and advanced control of physical assets within the Industry 4.0 context [7].

Besides DT standardizations, we identified manufacturing-specific norms and standards that are crucial as well. Guidelines and standardizations for manufacturing, as well as enterprise architecture frameworks for structuring the DT can supplement the absence of structure and guidance for a manufacturing use case in the DT. The *IEC 62264* standard provides terminology, information, and activity models for manufacturing operations. Its origins are on the *ANSI/ISA 95* standard that clarifies the functionalities of manufacturing operations management and the associated information usage and defines the terminology and operation models for manufacturing organizations. The standard consists of six parts. To fill the gap in developing enterprise IT architecture in new construction settings, it is vital to pay attention to parts 1 and 3 of the paper since they deal with object models, manufacturing operations attributes, and activity models, respectively [26]. According to Deuter's and Pethig's Digital Twin Theory [27], the productivity increase in the digitalized industry is essentially based on the seamless connectivity of all actors and systems, both horizontally and vertically. The horizontal connectivity of the value chain is achieved through a DT. The improvement of vertical connectivity is based on the hierarchical levels according to *IEC 62264* as well as the procedures and services based on it. For example, horizontal connectivity is improved by enabling development, production and use of a product to be mapped across the DT, while vertical connectivity is improved, for example, by enabling "plug and play" applications [27,26].

Complementary to the Manufacturing Operations Management standard *IEC 62264*, the Association of German Engineers published the manufacturing execution systems (MES) standard *VDI 5600*. It guides a task-oriented description of MES and their potential applications. It provides a view that better reflects the concerns of European manufacturers. The focus of this guideline is to describe the tasks and benefits of MES [28]. *Zachman's methodology*, *TOGAF*, *FEA(F)*, *DoDAF*, and the *Gartner Framework* are the top five enterprise architecture frameworks [29–31]. *TOGAF*, however, is the only framework among these that is appropriate for designing, planning, implementing, and managing systems for SDMS[32]. In [17], the importance of *TOGAF* is shown, *ISO 23247*, and *IEC 62264* for a manufacturing use case. The publication shows the compatibility of the standardizations.

5. Approach to structuring the asset administration shell

The approach can be divided into eight steps: vision and context, stakeholder requirements, use case definition, asset selection, selection of norms and guidelines, comparative analysis with separately modeled submodels, standard mapping to the AAS structure, and the validation of the representation concept. The steps of the structuring approach are based on the *TOGAF* steps like vision, architecture, requirements management, opportunities, and solutions. However, those steps are customized to the needs of the AAS and DT, given by *IEC 63278-1* and *ISO 23247*.

Figure 2 shows the practical implementation of these steps: The first step is the initial description and further detailing of the vision and the context. An initial conceptual idea is meticulously refined, serving as a driving force for the advancement of solution development. The stakeholder requirements establish a foundation for a purpose-driven concept of virtual representation, accommodating domain-specific challenges.

This second step in the approach capsules all pertinent stakeholder requirements, as elaborated in [17]. This includes a systematic formulation, a categorization and bundling to higher-level functionalities of the requirements. The virtual representation concept is a pivotal pillar and enabler of the SDMS. Requirements management is also the center of *TOGAF*.

The third step is executed based on extracting and prioritizing the acquired requirements. The use case definition engages in the comprehensive modeling of use cases. It results in a deeper understanding of the use case and shows all stakeholders involved as well as interaction objects.

This is necessary for the asset selection. It selects significant manufacturing assets for integration into an AAS system based on their alignment with specific use cases. The approach follows an asset-centric orientation, organizing information and services in line with *IEC63278* guidelines. Assets are chosen according to *ISO 23247*'s definition of manufacturing elements, which correlates with *IEC 62264* [33] and predefined information models forming the groundwork for submodel development as per [11].

The fifth step is the selection of norms and guidelines. It conducts comprehensive research and meticulous selection of standards, guidelines, and specifications in alignment with the specific domain like [7]. This step is time-consuming and also requires specific domain knowledge, but it also offers the chance for domain-specific aspects taken into account in the structure of the AAS.

The comparative analysis with separately modeled submodels determines the relevance of standardized submodels for the identified use cases. This step identifies potential gaps and discerns missing structures needed to accommodate data, services, and models that require representation. However, it also presupposes that work on the content of submodels is carried out in parallel. Therefore, it highlights the importance of standards for submodel development in [11]. It will reference pertinent standards and sections on relevant standards in the use case template.

The seventh step, standard mapping to the AAS structure, conducts the mapping of standards, guidelines, and specifications to the structure, ensuring that domain-specific aspects are suitably addressed. Furthermore, this should ensure that previously identified submodels are integrated within the structure.

Lastly, the validation of the representation concept is fulfilled. The validation assesses the achievement of the use case objectives. In the event of a use case behaving differently in practice, it necessitates the modification of both the use case and the structure of the AAS.

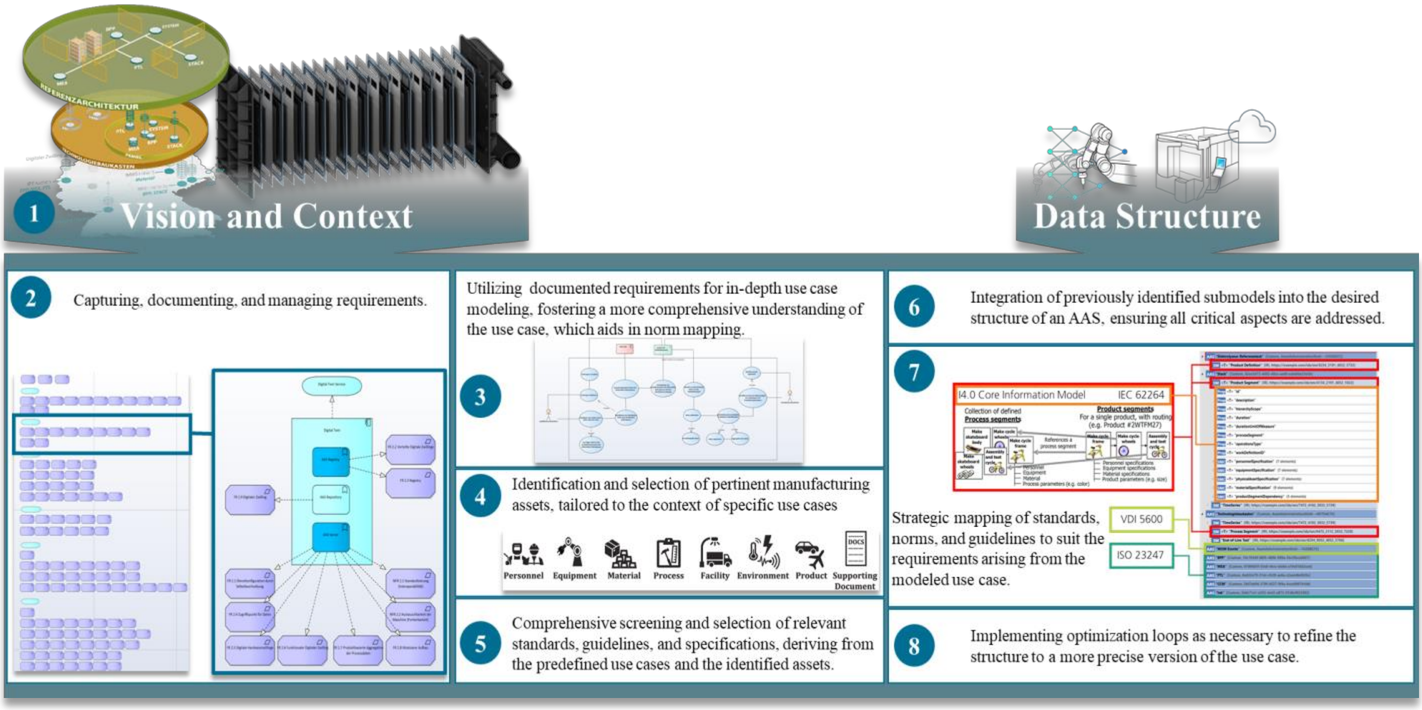


Figure 2: Approach used in the project to structure the asset administration shell

6. Use Case: Digital twin concept in hydrogen production

The proposed procedure in chapter 5 was used and adapted to the H2Giga-FRHY project and is represented in this chapter. The H2Giga-FRHY project includes six process steps for electrolyser production divided among five locations. It aims for a connected distributed production with focus on the subparts bipolar plate (BPP), porous transport layer (PTL), and catalyst-coated membrane (CCM) as part of the membrane electrode assembly (MEA). 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. The manufacturing system of this project is designed according to our definition in [17]. Challenges for the DT of the project include the high-rate scalability, interoperability, and decentralisation of the production through various production sites. Central points of reference for structuring the AAS are the *I4.0 Core Information Model*, based on *IEC 62264*.

In particular, the relationship between product definition, product segment, and process segment is taken up and applied from *IEC 62264*. The product definition is characterized by three aspects: product production, bill of material, and bill of resources. In our case, the product definition represents the reference stack, the central point and benchmark for production activities. Although it is defined, changes can also be made during the project. In turn, the product segment is defined as the information overlap between the product production rules and the bill of resources. The product segment describes a job with one or more work elements. In our case, the product segment represents the actual electrolyser produced. The product definition relates to the product segment, like the product type to the product instance. Therefore, the product definition contains the target values of the electrolyser to be produced, and the product segment contains the actual values of an produced electrolyser. When it says that the product segment consists of work elements, it references process segments in an ordered and defined sequence. The sequence again depends on the requirements of the product definition. The unordered collection of process segments includes all available processes for manufacturing the product and its sub-products. Process segments that have the same task but different properties can also occur. In our case, the collection of process segments is called a technology kit. This contains all the processes considered in the project for producing the electrolyser, the reference stack. Optional, redundant, or potential processes for electrolyser production are also included, described, and documented. In the course of the project, different processes are tested and first defined. Accordingly, the product segments may also change, which is served by the collection of process segments.

Thus, the structure also follows the Common Model of the *I4.0 Core Information Model (orange in Fig.3)*. Figure 3 shows an example of the aspects that can be found in the structure of the AAS and filled with content. On the right you can see the structuring of the AAS of the example project with assigned standards on the left. Among other things, the physical asset is listed as a central component in this model. The structuring according to *IEC 62264,* is divided into three primary components product definition, product segment and process segment (red). In our case, the electrolyser is the most relevant physical asset to map as the main AAS. The product itself is one of the observable manufacturing elements mentioned in *ISO 23247* and, thus, a potential asset for digital representation in the manufacturing context. Therefore, the BPP, MEA, PTL, CCM and Ink sub products are also represented in addition to the reference stack (dark green). The events are described according to *VDI 5600* (light green).

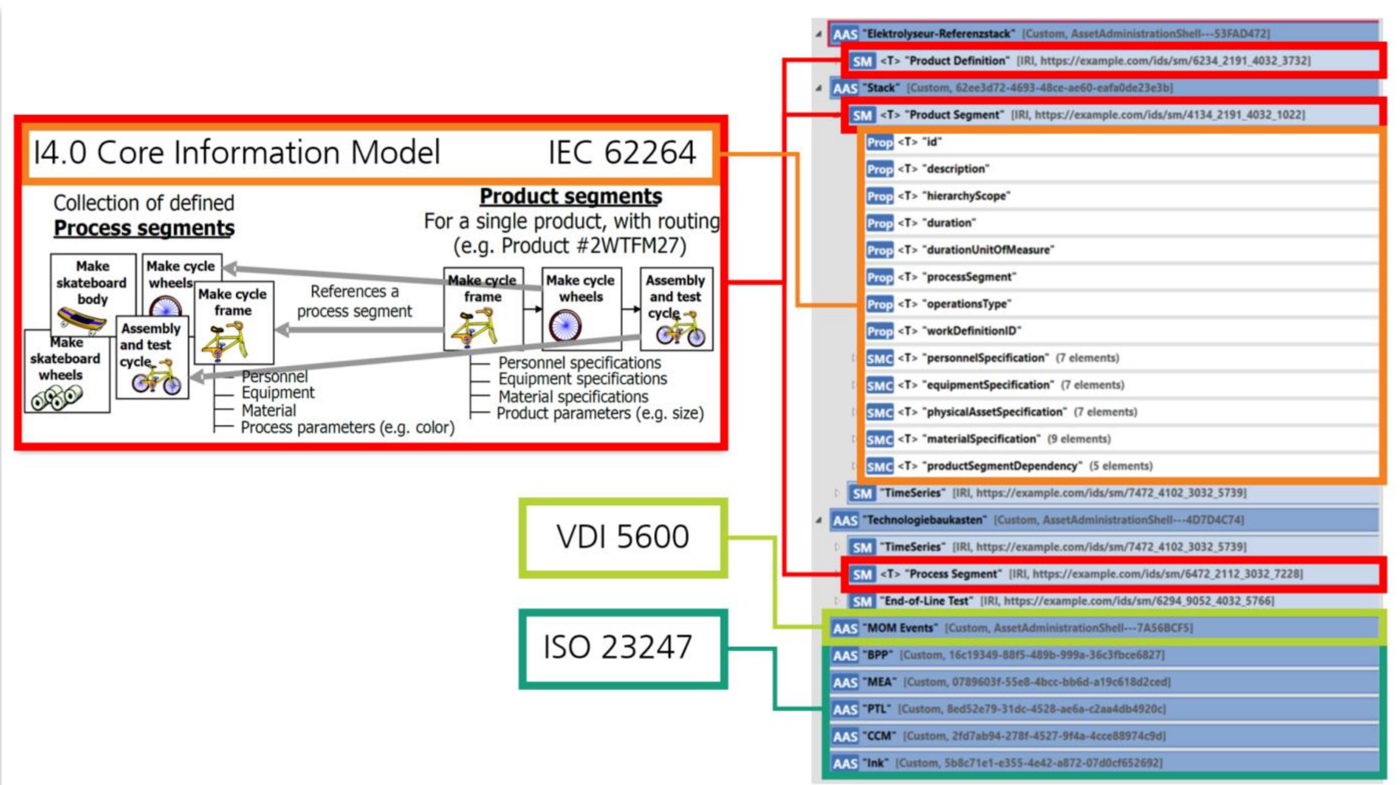


Figure 3: Derivation of a general AAS structure

As a result, we obtain a structure for the AAS that presumably could be applied to multiple use cases in a production-specific context. However, it is recommended to apply the described approach to ensure that all relevant aspects of a specific use case are reflected in the structure of the corresponding AAS.

7. Critical reflection and outlook

The procedure from a production-specific point of view was elaborated, and the AAS was applied in the production environment. The structure was determined by standards typical for it. In the form shown here, it is a reasonably general structure that can be applied similarly to many production-specific use cases. Following such a structure, primarily if it is based on widely used standards, can save time in designing the digital twin. Likewise, structuring the AAS for specific use cases from other domains can follow the approach presented here and thus provide orientation. Still, it also exhibits a few features of more specific domains. With clearly limited knowledge of all the domains that can be mapped in the production context, it is difficult to say to what extent there are always appropriate standards to incorporate specific characteristics into the structure.

The widespread adoption of AAS in industrial applications, the significance of shared data spaces, and the necessity for operability across diverse assets will be crucial to its success. A procedure for structuring the AAS according to domain-specific requirements can serve as orientation for users and thus improve the acceptance of the concept. It also facilitates that all necessary aspects are considered in the modeling and no element is left out. In addition, a structured approach can save time in modelling a digital twin and thus also pays off on the cost aspect.

With the presented approach, a possible structure of the AAS was derived. More value can be generated if the systematic development of the content complements the systematic development of the structure. The effectiveness of the approach presented here and the structure of the AAS derived for the project must also be reviewed for optimization potential when it comes to the technical realization and implementation of the project. An adequate method for this could be a gap analysis to check whether the AAS enables the use cases to be realized. There also needs to be a fundamental look at the system to discuss which asset in that very system needs an AAS.

Acknowledgements

This research was carried out as part of the H2Giga-FRHY project funded by the German Federal Ministry of Education and Research (BMBF) since 2021 under grant number 03HY112C. This involved cooperation with the InterOpera project (project number 13I40V006C).

References

[1] Presse- und Informationsamt der Bundesregierung, 2022. Wasserstoff – Energieträger der Zukunft: Nationale Wasserstoffstrategie. Bundesregierung. https://www.bundesregierung.de/breg-de/schwerpunkte/klimaschutz/wasserstoff-technologie-1732248#:~:text=Die%20Bundesregierung%20hat%20im%20Juni,Wirtschaft%20und%20erschlie%C3%9Ft%20neue%20M%C3%A4rkte. Accessed 6 July 2023.

[2] Vertretung der Europäischen Kommission in Deutschland. The Green Deal in Germany: The European Green Deal will help Germany protect its environment and achieve its climate-neutral goals. Europäische Union. https://germany.representation.ec.europa.eu/strategie-und-prioritaten/eu-politik-deutschland/der-grune-deal-deutschland_de?etrans=en. Accessed 6 July 2023.

[3] 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.

[4] Töpler, J., Lehmann, J., 2017. Wasserstoff und Brennstoffzelle. Springer Berlin Heidelberg, Berlin, Heidelberg.

[5] Project Management Jülich, 2021. How the H2Giga flagship project aims to mass produce electrolysers for the production and scale-up of hydrogen. Federal Ministry of Education and Research (BMBF). https://www.wasserstoff-leitprojekte.de/projects/h2giga. Accessed 6 July 2023.

[6] Himmelstoß, H., Hall, R., Thieme, P., Bauernhansl, T., 2023. Designing Smart Services for a Component Manufacturer Based on a Digital Twin. Procedia CIRP 119, 950–956.

[7] Ameziane, S., Grangel-Gonzalez, I., Janik, P., Keller, M., Loesch, F., Massari, F., Molin, D., Wilhelm, N., 2022. Industry 4.0 Core Information Model: A publication by the Open Manufacturing Platform. Open Manufacturing Platform. https://openmanufacturingplatform.github.io/. Accessed 8 July 2023.

[8] Leng, J., Wang, D., Shen, W., Li, X., Liu, Q., Chen, X., 2021. Digital twins-based smart manufacturing system design in Industry 4.0: A review. Journal of Manufacturing Systems 60, 119–137.

[9] Abdel-Aty, T.A., Negri, E., Galparoli, S., 2022. Asset Administration Shell in Manufacturing: Applications and Relationship with Digital Twin. IFAC-PapersOnLine 55 (10), 2533–2538.

[10] 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 (ETFA). 2017 22nd IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), Limassol. 12.09.2017 - 15.09.2017. IEEE, pp. 1–8.

[11] DIN German Institute for Standardization, 2022-07-00. Asset Administration Shell for industrial applications: Part 1: Asset Administration Shell structure (IEC 65/867/CD:2021). Beuth Verlag GmbH,VDE-VERLAG GMBH IEC 63278. https://www.iec.ch/dyn/www/f?p=103:38:25763300038578::FSP_ORG_ID,FSP_APEX_PAGE,FSP_PROJECT_ID:1250,23,103536#. Accessed 21 July 2023.

[12] Grieves, M., 2016. Origins of the Digital Twin Concept.

[13] Tao, F., Zhang, H., Liu, A., Nee, A.Y.C., 2019. Digital Twin in Industry: State-of-the-Art. IEEE Trans. Ind. Inf. 15 (4), 2405–2415.

[14] Tao, F., Zhang, M., 2017. Digital Twin Shop-Floor: A New Shop-Floor Paradigm Towards Smart Manufacturing. IEEE Access 5, 20418–20427.

[15] 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.

[16] van der Valk, H., Haße, H., Möller, F., Arbter, M., Henning, J.-L., Otto, B., 2020. A Taxonomy of Digital Twins, in: AMICS 2020 proceedings, AIS eLibrary.

[17] Brandstetter, A., Himmelstoss, H., Risling, M., Schel, D., Oberle, M., 2023. Towards A Design Of A Software-Defined Manufacturing System Based On A Systematic Literature Review For Enabling A Decentralised High-Rate Electrolyser Production. Hannover : publish-Ing.

[18] International Electrotechnical Commission, 2016. IEC/SC 65E - Test - Common Data Dictionary (CDD - V2.0016.0001). https://cdd.iec.ch/cdd/iec61987/cdddev.nsf/TreeFrameset?OpenFrameSet.

[19] ECLASS, 2023. Search the ECLASS content. https://eclass.eu/en/eclass-standard/search-content.

[20] Thames, L., Schaefer, D., 2016. Software-defined Cloud Manufacturing for Industry 4.0. Procedia CIRP 52, 12–17.

[21] Jones, D., Snider, C., Nassehi, A., Yon, J., Hicks, B., 2020. Characterising the Digital Twin: A systematic literature review. CIRP Journal of Manufacturing Science and Technology 29, 36–52.

[22] Semeraro, C., Lezoche, M., Panetto, H., Dassisti, M., 2021. Digital twin paradigm: A systematic literature review. Computers in Industry 130, 103469.

[23] Singh, M., Fuenmayor, E., Hinchy, E., Qiao, Y., Murray, N., Devine, D., 2021. Digital Twin: Origin to Future. ASI 4 (2), 36.

[24] Wang, K., Wang, Y., Li, Y., Fan, X., Xiao, S., Hu, L., 2022. A review of the technology standards for enabling digital twin. digitaltwin 2, 4.

[25] Moreno-Díaz, R., Pichler, F., Quesada-Arencibia, A., 2022. Computer Aided Systems Theory – EUROCAST 2022. Springer Nature Switzerland, Cham.

[26] Oberle, M., Yesilyurt, O., Schlereth, A., Risling, M., Schel, D., 2023. Enterprise IT Architecture Greenfield Design Combining IEC 62264 and TOGAF by Example of Battery Manufacturing. Procedia Computer Science 217, 136–146.

[27] Deuter, A., Pethig, F., 2019. The Digital Twin Theory. I40M 2019 (1), 27–30.

[28] Association of German Engineers VDI, 2016. VDI 5600: Manufacturing execution systems (MES).

[29] 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.

[30] Dumitriu, D., Popescu, M.A.-M., 2020. Enterprise Architecture Framework Design in IT Management. Procedia Manufacturing 46, 932–940.

[31] Qurratuaini, H., 2018. Designing enterprise architecture based on TOGAF 9.1 framework. IOP Conf. Ser.: Mater. Sci. Eng. 403, 12065.

[32] Ansyori, R., Qodarsih, N., Soewito, B., 2018. A systematic literature review: Critical Success Factors to Implement Enterprise Architecture. Procedia Computer Science 135, 43–51.

[33] DIN German Institute for Standardization, 2014. Enterprise-control system integration: Part 1: Models and terminology (IEC 62264-1:2013). Beuth Verlag GmbH,VDE-VERLAG GMBH IEC 62264.

Biography

Monika Risling (*1997) is a research associate at the Fraunhofer Institute for Manufacturing Engineering and Automation IPA since 2021 where she has been working in the department Competence Centre for Digital Tools in Manufacturing and in the field of smart manufacturing. She focuses on data and applications for digital production based on her studies in Industrial Engineering with focus on Digital Production Management and Computer Science.

Henry Himmelstoß (*1991) is a research associate and project leader at the Fraunhofer Institute for Manufacturing Engineering and Automation IPA in Stuttgart, Germany. Since 2019 he has been working in the department Competence Centre for Digital Tools in Manufacturing.

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.

Dachuan Shi (*1990) is working at Fraunhofer Institute for Manufacturing Engineering and Automation IPA as a postdoctoral researcher since 2022. His research focuses on digital twin and predictive maintenance for industrial applications.

Prof. Dr.-Ing. Thomas Bauernhansl (*1969) has been head of the Fraunhofer Institute for Manufacturing Engineering and Automation IPA in Stuttgart and the Institute for Industrial Manufacturing and Factory Management IFF at the University of Stuttgart since September 2011. Bauernhansl studied mechanical engineering at the RWTH Aachen and received his doctorate in 2002. He then worked for Freudenberg, most

recently as Director of the Technology Centre at Freudenberg Sealing Technologies. His scientific focus areas include personalized production, the biological transformation and Industry 4.0.

5th Conference on Production Systems and Logistics

A Framework For The Domain-Driven Utilization Of Manufacturing Sensor Data In Process Mining: An Action Design Approach

Jonathan Brock[1], Niclas Rempe[1], Sebastian von Enzberg[1], Arno Kühn[1], Roman Dumitrescu[2]

[1]*Fraunhofer Institute for Mechatronic System Design IEM, Zukunftsmeile 1, 33102 Paderborn, Germany*
[2]*Heinz Nixdorf Institute, University of Paderborn, Fürstenallee 11, 33102 Paderborn, Germany*

Abstract

Manufacturers install and rely on a large number of sensors to operate and control their processes. However, the collected sensor data is rarely used to analyse and improve the higher-level, aggregated business processes. Process mining (PM) appears to be a promising solution, with the ability to automatically generate and analyse business process models based on data. However, the atomic events of sensor measurements need to be refined, aggregated, and enriched to properly represent a business process. In this paper, we propose a novel framework to make manufacturing sensor data analysable with PM. The framework allows manufacturers with batch and continuous processes (BCP) to systematically enrich their sensor data to use it for optimization purposes. Following the action design research, we demonstrate the applicability of the framework in a use case study using sensor data from a BCP beverage production.

Keywords

Process Mining; Manufacturing; Sensor Data; Framework; Real-World

1. Introduction

Manufacturers need to constantly analyse and optimize their value generating processes, in order to save costs and stay competitive [1]. Traditionally, they deploy a variety of tools and methodologies to achieve this, such as lean management [1,2]. More recently, digitalization has proven to be a viable optimization possibility [3]. While this digitalization often had no effect on the sensor and actor IT-layer, recent trends like the industrial internet of things steadily increase the availability of data from this layer [4,5]. In the intersection between the need for optimization and the availability of data, process mining (PM) has emerged in recent years as a promising technology [6]. PM describes "[…] techniques, tool and methods to discover, monitor and improve real processes […]." [7]. Manufacturers can particularly profit from PM through increased transparency, measurement of process performance, or the creation of digital twins [8,9]. The minimum requirement for data in PM is a case ID (e.g. an order number), an activity name (e.g. drilling) and a timestamp [7]. Data with at least these three features is called an event log [7]. PM is typically applied to data generated from process aware IT-systems, such as Enterprise Resource Planning (ERP), where for example workflows easily provide the necessary data structure [6].

However, in many real-world scenarios, sensors and actors are not necessarily aware of the current case that is being processed [10]. This has to do with the prevalent, classical pyramid style IT-architecture in

DOI: https://doi.org/10.15488/15267
ISSN: 2701-6277

manufacturing companies, where machine sensors and actors are often decoupled from higher hierarchy IT-systems in order to ensure real-time capability [4,5]. Consequently, when working with sensor data in PM, problems like a lack of process notion (i.e., missing case IDs or activity names), the mapping of fine granular sensor data to (human) activities, and the aggregation of sensor data to process activities, arise [11,10,12]. Various authors call for further research on the utilization on sensor data for PM [13–15]. In this paper, we derive a framework to make manufacturing data from the sensor and actor layer usable in PM. The framework is designed through Action Design Research (ADR), meaning that we iteratively work on the manufacturing sensor data from a real-world organization [16]. Our main contribution is the framework consisting of six phases with an emphasis on applicability in industry, meaning that it draws from existing domain expertise. Additionally, we contribute an activity grouping scheme and case ID inheritance algorithm, which allows other organizations to apply PM on their manufacturing sensor data.

The remainder is structured as follows. In section 2 we introduce the application scenario and existing solutions for sensor abstraction. Section 3 will explain our research methodology ADR. In section 4, the framework for will be introduced and applied to the application scenario. In section 5 we will discuss our results, before concluding the paper in section 6.

2. Need for action on manufacturing sensor data utilization in process mining

In this section we will introduce the application scenario (section 2.1) and existing solutions to it in the state of the art (section 2.2). In section 2.3 these two will be compared to motivate the need for further research.

2.1 Application scenario and objective of Big Beverage Inc.

Big Beverage Inc. is a family owned and run manufacturer of drinks, with around 400 employees in Germany. Their production resolves around mixing raw fluids, which are then later combined, and finalized with water. Their machinery setup as well as the collected data are displayed in Figure 1. The machine layer displays how the organization utilizes different tanks and pipes to produce their drinks.

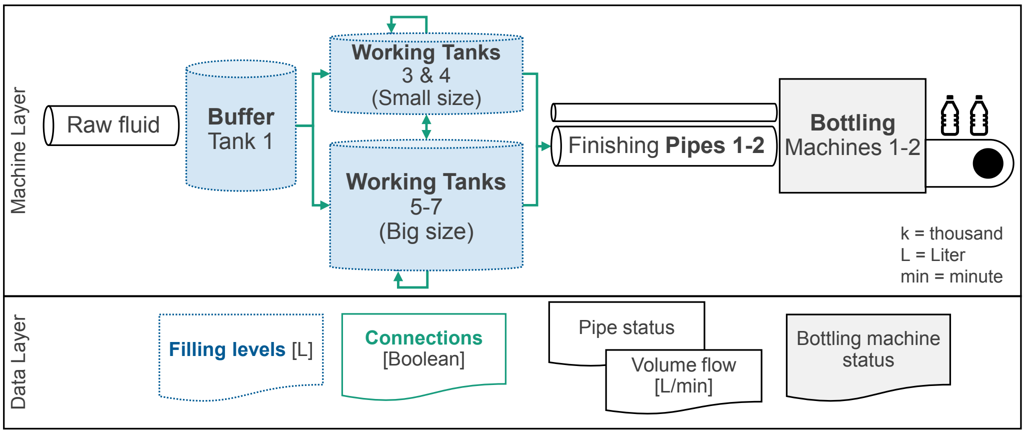


Figure 1 The machinery and data at the Big Beverage Inc.

Figure 1 shows that initially raw fluids run into a buffer tank, which then distributes the material into one or multiple working tanks (No. 4 to 7). The working tanks have different volumes. Before sending the final good to one of two bottling machines through a finishing pipe, the raw fluid might be re-distributed to other tanks or combined with other raw fluids. The raw fluid will always be finalized by adding water before they are bottled. From a production perspective, some elements of this process are a batch process (e.g. moving an entire tank filling), while others are a continuous process (e.g. the finishing pipe) [17]. From a data perspective, the filling levels of all tanks are measured. Additionally, it is registered if any of the tanks are connected to one another or to any of the two finishing pipes as a boolean value (i.e. True/False). For the finishing pipes and bottling machines, the status (e.g. production) is registered. Additionally, the current volume flow for the pipes is measured. All sensor data is measured every 30 seconds. The manufacturer is faced with a rapid increase in orders, while keeping their production resources constant in the past years. Therefore, the objective of Big Beverage Inc. is to increase their resource availability, by identify if and how they are unnecessarily using tanks to produce final products. Their solution approach is to understand the frequency of shuffling between tanks to derive meaningful actions using evidence-based business processes discovered with PM. To achieve this, the existing sensor data needs to be aggregated to an event log.

2.2 State of the art

PM uses data to analyse processes [7]. Different techniques for this analysis exist. The first technique *process discovery* uses data to produce a process model, such as a petri net [6]. Different algorithms such as the alpha miner [18] or the inductive miner have been proposed for this [19]. The second type *conformance checking* compares data from as-is executions with (normative) process models, in order to identify deviations [6]. For this, tokens, rules or alignments are used [20]. The third type *process enhancement* adds additional information to process models, for example time information [6]. While these three are the traditional main techniques, recent years have added comparative, predictive and action-oriented PM [21]. The minimum data requirement for PM are a case ID, a timestamp and an activity name [22,7]. Additionally, a lifecycle information (e.g. start) helps to aggregate atomic events to a coherent activity [22].

Matching atomic events to higher hierarchy business processes is a general challenge in PM, not only limited to manufacturing sensor data. Van Zelst et al. [23] recently proposed a taxonomy for event abstraction techniques in PM. In their taxonomy, techniques are classified based on their supervision strategy, relation of case and activity, or used data. Only one of the 21 identified publications deals with continuous data (i.e. sensor data). The research of van Zelst et al. [23] focuses on very specific approaches, often on an algorithmic level. Consequently, the authors exclude higher-level procedures.

However, in practice, abstracting sensor data to higher level event logs is not necessarily an algorithmic challenge but also a procedural because data and domain might vary. Hence, we identify five higher-level approaches in the literature that explicitly deal with the aggregation of sensor data for PM [24,10,25,26,12]. We exclude approaches like [8,27], because PM is solely used to analyze machine behavior (i.e. no aggregation to superordinate business processes is performed) or the approach is too generic, respectively. By comparing and correlating the objectives of the authors' explicitly mentioned steps, we derive nine general phases that are described in literature. These nine general phases are shown on the left in Table 1. In *Collection*, necessary data is acquired. In the second phase *Identification*, the case ID needed to conduct PM is determined. *Segmentation* deals with the division of the sensor data following some logic. In *Characterization*, relevant features to distinguish possible activities are identified and calculated. Based on these features, the phase *Clustering* deals with the (automated) grouping of the sensor values. Afterwards, these clusters need some *Interpretation*, often using domain expert input. Once sensor data is clustered and interpreted, activities with human readable names can be derived in the *Generation* phase. In *Creation*, the final event log is generated, followed by the actual process *Mining*.

Van Eck et al. [12] propose a six step transformation approach to use sensor data from smart products in PM. Compared to the other approaches, the approach has a detailed description of activity generation. Koschmider et al. [10] develop a four step framework to derive process models from any kind of sensor data. Prathama et al. [26] derive a three step framework that utilizes sensor data from wearable devices in PM. The authors have a dedicated step for data acquisition. Brzyhczy and Trzcionkowska [24] report on their four step experience creating an event log from underground mining machinery logs. In contrast to the other authors, a detailed discussion on the challenges of case ID identification is reported. Lastly, de Leoni and Dündar [25] propose a four step abstraction technique based on clustering, that functions with little domain knowledge. Their approach is rather algorithmic and general. The two publications [25,12] also appear in the taxonomy in [23]. A general observation of Table 1 is that none of the procedures are applied to industrial manufacturing settings within a factory, albeit [24] describe a underground mining setting. Possibly therefore, they are the only ones discussing the challenge of identifying the case ID. The approaches [24,10,25,12] additionally have a strong focus on the computation of clusters by using distances measures or machine learning. De Leoni and Dündar [25] highlight this aspect as a key contribution.

Table 1 Overview of literature dealing with sensor data in the context of PM [24,10,25,26,12]

		Source				
		van Eck et al. [12]	Koschmider et al. [10]	Prathama et al. [26]	Brzyhczy and Trzcionkowska [24]	de Leoni and Dündar [25]
Phases	Collection			(1) Event data gathering		
	Identification				(1) Case ID Identification	
	Segmentation	(1) Segmentation of sensor data		(2.1) data pre-processing	(2) Data preprocessing	(1) Create sessions
	Characterization	(2) Feature selection and calculation to characterise segments		(2.2) data integration		
	Clustering	(3) Clustering of segments to identify time periods with similar behaviour	(1) Event correlation		(3) Data clustering	(2) Clustering of sessions
	Interpretation	(4) Interpretation of clustering results to label behaviour	(2) Activity Discovery		(4) Classification for labelling activity names in the raw data	(3) Visualize heat map
	Generation	(5) Activity creation by grouping labelled segments				
	Creation	(6) Process instance creation	(3) Event Abstraction	(2) Event log creation		(4) Creation of abstract event log
	Mining		(4) Discovery of process	(3) Multi-case perspective pm		

2.3 Comparison of Big Beverage Inc. needs and the state of the art

In summary, abstracting fine granular event data to higher level is a known challenge both in practice and research. Their overall goal is to create an event log with the columns case ID, timestamp, activity, and lifecycle information from raw sensor data. Even though Big Beverage Inc. has data from their machines at hand and goals in mind, the existing knowledge base about data abstraction does not prove to be applicable for them. This has to do with two aspects. First, the existing solutions rarely focus on manufacturing challenges, especially for BCP. These challenges include the difficulties of identifying activities and the lack of a case ID. This is complicated by the high parallelism and nesting of the manufacturing steps which leads to the challenge of associating activities and cases. Second, the algorithmic heavy approaches do not fit into the daily work of the company, because experts on clustering techniques from machine learning are sparse. As a result, we derive the following research question (RQ):

RQ: What is a general approach for manufacturers to utilize their machine sensor data in process mining?

Given the application scenario, the following prerequisites can be assumed. First, the needed data sources are known (i.e. if and where machine data exists). Second, the data has been extracted and is complete (e.g. queries for data bases are written and it is not a streaming PM use case). Third, the existing data is of adequate quality (e.g. no missing data). Various guiding publications can be found in literature concerning these issues [22,28,29,12], and are hence not explicitly detailed within this paper.

3. Research methodology to close the need for action

To answer our research question and achieve the goal of Big Beverage Inc., we followed the ADR approach proposed by [16]. The ADR team consists of the ADR researcher from academia, and various departments on the practitioner's side, such as the digital transformation, IT and production. Our research procedure, which took half a year in total, the design iterations, and the final generalization are shown in Table 2.

4. Framework for the domain driven utilization of manufacturing sensor data

The outcome of stage 4 of the research methodology is a framework that guides practitioners to utilize PM on their manufacturing sensor data. The framework consists of six phases with 17 sub-steps. Section 4.1

introduces the general procedure of the framework. Because phase (5) of the framework utilizes a grouping scheme and a dedicated case-inheritance algorithm, details about these two contributions will be given in a separate section 4.2. The framework is applied to Big Beverage Inc. in section 4.3.

Table 2 Summary of the ADR process and generated artefacts according to [16]

Stages and Principles		Artefact
Stage 1: Problem Formulation		
Principle 1: Practice-Inspired Research	The research was driven by the need for machine data to be analyzed with PM, and the challenges faced while generating an event log.	**Recognition:** While many approaches for event abstraction exist, they do not fit the needs of Big Beverage Inc. Many organizations have similar processes. A generalized framework is beneficial for many organizations.
Principle 2: Theory-Ingrained Artefact	We use the existing literature base depicted Table 1 and the event abstraction taxonomy by van Zelst et al. as a guiding principle.	
Stage 2: Building, Intervention, and Evaluation		
Principle 3: Reciprocal Shaping	The initial utilization was not as straight forward as the final framework may suggest. Instead, phases were constantly redone and generalized together with the domain experts. Especially the case definition proofed to be challenging, and multiple approaches were tried.	The **first analysis** approach resulted in an event log that only captured individual machine behavior but could not relate multiple machine to the manufacturing of the same product. A **second analysis** approach with a refinement of the machine data and a collaborative breakthrough in how cases are associated to machine behavior resulted in an event log that reflected all machine efforts necessary to produce a product. By the end of stage 2, we had the **technological capability** to transform the data to an event log.
Principle 4: Mutually Influential Roles	The ADR team included researchers, domain experts, and process analysts, both from academia and practice. The lead for the ADR project lays within the academia.	
Principle 5: Authentic and Concurrent Evaluation	A technical solution for the utilization was derived to work on the specific, real world machine data provided by Big Beverage Inc. A usable event log could be generated.	
Stage 3: Reflection and Learning		
Principle 6: Guided Emergence	The manufacturer realized that a standardization of the procedure was necessary to reproduce results in different machine areas. The ADR team conducted various brainstorming sessions to **analyze** the most relevant actions taken to achieve the project goal.	By the end of stage 3, a **schematic description of our technical solution** was derived.
Stage 4: Formalization of Learning		
Principle 7: Generalized Outcomes	We **synthesized** the schematic description of our actions by aggregating steps and cutting individual solutions.	The **artefact** of stage 3 is the **framework** for utilizing machine sensor data in process mining

4.1 Procedure model of the framework

The first phase **(1) Envision the desired outcome of the process mining analysis** has two sub-steps. In (1.1) the desired outcome needs to be determined. By outcome, we refer to the analysis-artifact that needs to be generated to achieve the higher hierarchy project goal. In (1.2) relevant stakeholders are listed. We differentiate between a shortlist team, i.e. the core project team, and a longlist team, i.e. experts who might be relevant for the process, IT or the sponsoring of the project.

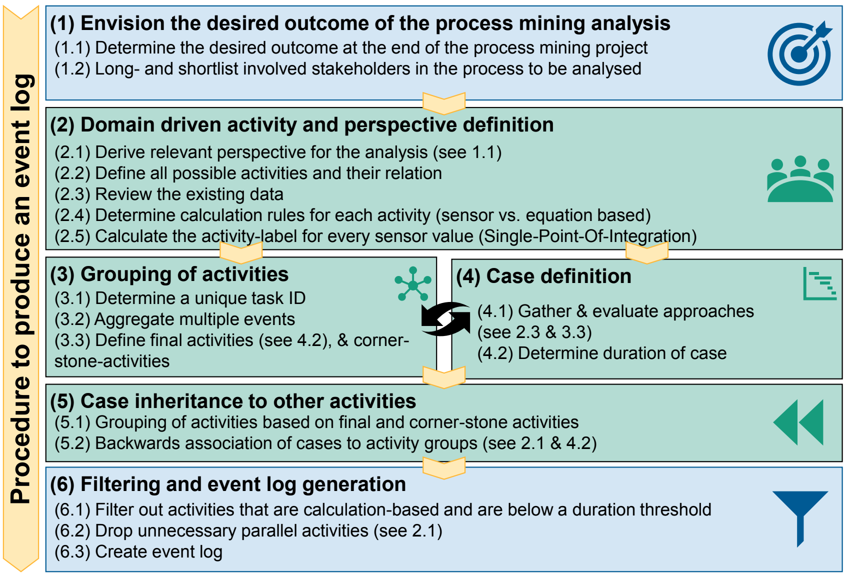


Figure 2 Framework for the utilization of manufacturing sensor data in PM projects

The second phase **(2) Domain driven activity and perspective** uses the initially defined outcome targets as an input. The outcome of this phase is a data frame, where every sensor value has an activity label. In **(2.1)** the relevant perspective for the analysis is chosen, based on the defined goals. This step has a crucial impact on the case definition in later steps. The perspective directly relates to the analysis goal. In **(2.2)** the core project team determines the possible activities and their relation. This can be done in a brainstorming session. Alternatively, a first sketch of the expected process or old process model can be made and discussed, e.g. by using process modeling techniques such as BPMN. The relation aspect refers to the possibility of activities having direct relation, e.g. when one tank fills, another one empties. In **(2.3)** initial data drops are reviewed, possibility leading to a first refinement of the needed data. In step **(2.4)** for each possible activity, calculation rules are determined. We differentiate between sensor- and equation-based rules. Sensor-based rules refer to calculations made using other sensor information, e.g. using machine coupling information. Equation-based rules are mathematical calculations performed to the existing data, e.g. a gradient. Lastly, in **(2.5)** the equations are applied to the sensor data. We advise to use one existing data file that fits the perspective the best, and then associate further sensor information to it. We call this the single-point-of-integration.

The third phase **(3) Grouping of activities** and the fourth phase (4) case definition are performed in parallel. In **(3.1),** every sensor response is given a unique task ID by finding the first and the last consecutive activity-label of the same kind. This task ID can be artificial, e.g. a combination of a consecutive number and the first letter of the activity-label. Then, in (3.2) the same events can be grouped to activity-label. Lastly, in **(3.3)** activities can be marked as a special activity based on the results from phase (4). Two kinds of activities are important: activities that can be the final activities in the process and activities which are corner-stone activities. Corner-stone activities are characteristic to the business process and are the primary activities in a process, which other sub-process activities work towards to.

In phase **(4) Case definition** the notion of a case is determined. In **(4.1)** possibilities for the case definition are gathered. This step is dependent on the initially defined perspective. While ideally, some business level information, e.g. a manufacturing order number, is available, our methodology is specifically designed for manufacturers who do not have these information on their machine data level (see section 1). Therefore, we propose a workaround that allows for the artificial generation of a case. We suggest looking for distinct characteristics in the machine data. This might be a certain machine status, sequences of machine states, or other characteristics that define the end of the case relevant to the analysis perspective. In **(4.2)** the start and end time of the case are determined as a preparation for the fifth phase.

In the fifth phase **(5) Case inheritance to other activities**, every activity is iteratively associated to a case, based on the backwards oriented business perspective of a final product. Because of this iterative passing down of case association, we call this inheritance. Like the previous phase, this phase is also tailored to organizations who have a more classical IT-architecture (see section 1). To achieve this, in **(5.1)** activities are grouped based on a special scheme utilizing the corner-stone activities. Afterwards, in **(5.2)** the final case ID can be iteratively associated to these groups. Remarkably, this allows to integrate BCP. The activity grouping scheme and the case inheritance algorithm are described in more detail in section 4.2.

Lastly, in **(6) Filtering and event log generation**, final preparations are conducted. In **(6.1)** activities below a certain duration threshold are dropped. In this way, the to-be discovered process model becomes clearer. For the same reason, we suggest dropping parallel, related activities in **(6.2)**. Parallelism is a complex driver in PM, especially when using out-of-the-box directly follows graphs, as used by most software vendors. Finally, in (6.3), the event log is generated in a CSV, XES, OCEL, etc. standard.

4.2 Activity grouping scheme and case inheritance algorithm

Phase (5) of the framework introduces the concept of activity grouping and iterative case inheritance. In (5.1), all activities are associated to the same group until a relevant corner-stone or final activity occurs. Then, a new group is build following the same scheme. This scheme is shown in Figure 3. The corner-stone and final activities are in bold letters. The group building scheme is displayed on the left side. Groups are necessary to cut down parallelism, and to associate a wide range of activities to a case. This association is done in (5.2), where activity-groups are now iteratively connected to the interval of the case using information about activity relations from step (2.1) of the framework. This association is performed on the three dimensions relation, time, and case-association-status. The association concept is shown in Figure 3 on the right side. We start by looking at the first defined case, which is case ID 1. We find an activity that has a relation to other activities ("Filled by Tank" is related to "Filling to Tank"). Based on the duration (dimension time) of that activity, we can search in the pool of all activity groups for a related activity (dimension relation) that has no case association yet (dimension case-association-status), for a closely overlapping activity. If we find one, like the activity in group 1, we associate all activities in that group to case ID 1. The same procedure is performed to the case ID 2, associating activity group 2 to the case.

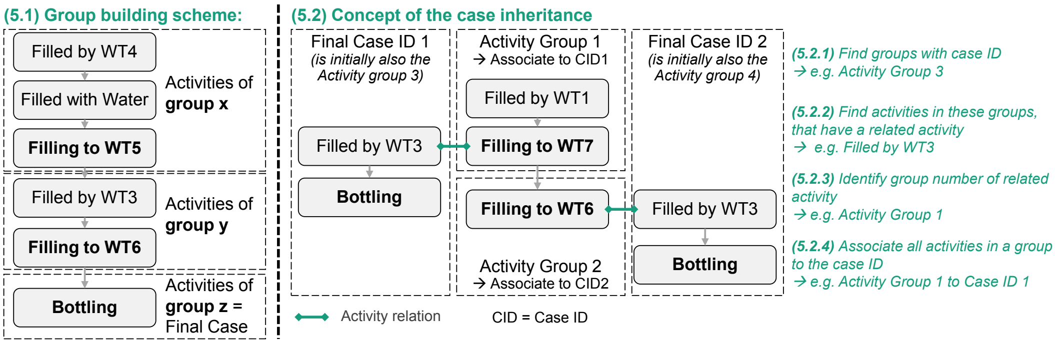


Figure 3 The schemes for the group building in step (5.1) and the (5.2) backwards association scheme

This algorithm is then performed again. While we will not find new activities for association in the activity groups 3 and 4, the activity group 1 is now associated to case ID 1, and has an activity "Filled by Tank 1" which possibly has a related activity, which is not associated to any case ID yet (not displayed in Figure 3). The iteration terminates, when no more associations can be made. This algorithmic approach is displayed in Figure 4, and can be executed in most programming languages.

```
Case-inheritance-algorithm
Input: dataframe, dictionary of activity relations
Output: dataframe

initialize previous_length with -1
while previous_length != length(activities with case_id):
    previous_length = length(activities with case_id)
    for every case_id:
        find activities that can have a relation
            get timestamps of activities
            search relating, undefined activities, where timestamps are close
                set every case_id in the activity_group to current case_id
```

Figure 4 Algorithm to iteratively associate case IDs

4.3 Application example at Big Beverage Inc.

As mentioned in section 3, our methodology involved multiple iterations to come up with the final solution. In this section, we briefly want to highlight the key application steps of the framework and the results achieved. In the beginning, the product batch was chosen as the analysis perspective to determine the needed interactions between tanks (2.1). Then, the activities were defined using a BPMN sketch of the process (2.2). In a workshop, each activity was related to one another (e.g. bottling and pipe flow need to be in parallel) and was given a calculation rule (2.4). While the interaction between the tanks could be determined using the connection data, other activities needed to be calculated using the gradient of filling level (e.g. filling by pipes). In the grouping of activities phase (3), we used the labelled sensor data to derive actual activities. The first and last sensor value of the same kind can easily be determined using a helper column that identifies changes to new labels. The data state after phase (3) is shown on the left side in Figure 5. The label "Fill" is reported from 2023-07-03 10:57 to 2023-07-03 12:13. These two timestamps can be taken and aggregated based on the task ID to the table structure on the right side. Depending on the analysis goal, the sensor data in between those two timestamps can be dropped or aggregated. For example, we kept the start and end payloads. The labels are now called activity because they have a start and end. It is now possible to mark final and primary activities, which can be used to form activity groups. In phase (4) a case ID needs to be determined. For example, we found that the final bottling machines saves data on the product change. This can be used to determine start and end timestamps for products. However, the bottling machine is not linked to other machines. But because these production times and the filling to the pipes are related activities, the case inheritance algorithm can be applied, iteratively associating more activity groups to a case ID. The data wrangling was conducted using the programming language Python.

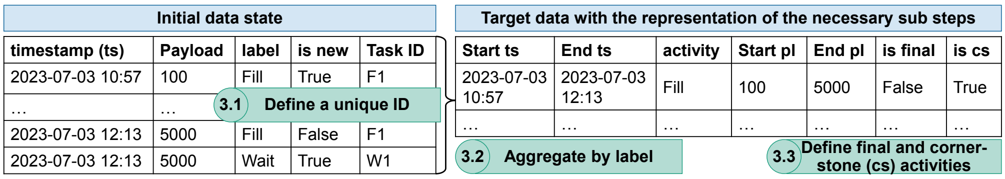


Figure 5 Schematic visualisation of the data transformation in phase (3)

5. Discussion

The application of the framework in section 4.3 shows that our framework produces viable event logs for PM, fulfilling the requirements given in section 2.3. From a managerial perspective, we contribute an applicable, easy to use framework for practitioners. With our framework, data scientists at Big Beverage Inc. were able to identify and quantify the frequency of tank utilization patters needed to produce a final beverage. In the future, the organization wants to incorporate the framework into a data pipeline, to reproduce the analysis more frequently. Practical limitations are twofold. First, the prerequisites discussed in section 2.3 need to be fulfilled. Second, the framework is designed with and for BCP. While this limits the contribution, the phenomenon of BCP is very frequent, e.g. in pharmaceutical processes [17]. In summary, our approach is applicable to manufacturing companies, especially with BCP, where data (sources) are known, extracted and of adequate quality. Additionally, no streaming PM use cases are possible. Therefore, our framework is relevant for practice and not only limited to beverage manufacturing scenarios. From a scientific perspective, we contribute a framework, the grouping scheme, and the case inheritance algorithm to the knowledge base. All three artefacts have been iteratively designed, generalized, and proven valid in a real-world setting. We briefly want to highlight the key differentiations to the existing state of the art. In contrast to [25], our framework is less algorithmic. Unlike [10,12] where sensor data is clustered, then labelled, we identify the activities domain-driven, and then determine them in the data. In that way, we are more applicable for practitioners. By particularly addressing BCP, we address shortcomings of [26,12], who focus on smart products. Lastly, both [24] and our framework address the problem of identifying a case ID. However, unlike [24] we do not have the possibility to identify the case IDs based on the workers positions. We therefore propose the case inheritance algorithm, whereby we address the high parallelism and nesting of typical BCP. In summary, we answer our initially defined research question, as well as the call for research in [13–15].

6. Conclusion and outlook

In this paper, we derive a framework for the utilization of manufacturing sensor data to be used in PM projects by conducting ADR. The framework consists of six phases that guide practitioners in transforming raw manufacturing sensor data to PM usable event logs. By using the framework, domain experts and process scientists can systematically solve challenges inherent in sensor data from batch and continuous manufacturing processes, such as a lack of case notion. We further contribute an activity grouping scheme and a case inheritance algorithm to the knowledge base. In contrast to other publications, we put a strong emphasis on involving domain expertise into the activity and case ID definition, because our ADR revealed this to be more practical in real world settings. Additionally, this allows for a wider range of application scenarios, such as pharmaceutical BCP. By collaborating with an organization from the beverage industry throughout the ADR, we demonstrate and validate the usability of our framework in real world scenarios. Limitations of our research are a possible over-specificity to the application scenario used in the ADR cycle. Further research should therefore identify, refine, and adjust our framework to more domains, process types and application scenarios.

Acknowledgements

This work is funded by the Ministry of Economic Affairs, Industry, Climate Action and Energy (MWIKE) of the State of North Rhine-Westphalia as part of the Leading-Edge Cluster, Intelligente Technische Systeme OstwestfalenLippe (it's OWL) and supervised by the project administration in Jülich (PtJ). The responsibility for the content of this publication lies with the authors.

References

[1] Joppen, R., Enzberg, S. von, Kühn, A., Dumitrescu, R., 2019. A practical Framework for the Optimization of Production Management Processes. Procedia Manufacturing 33, 406–413.

[2] Pirrone, L., Bernasconi, M., Friedli, T., 2023. Investigating The Role Of Digitalization In OPEX Programs – A Case Study From The Pharmaceutical Industry. Hannover : publish-Ing.

[3] Harmon, P., 2010. The Scope and Evolution of Business Process Management, in: , Handbook on Business Process Management 1. Springer, Berlin, Heidelberg, pp. 37–81.

[4] Boyes, H., Hallaq, B., Cunningham, J., Watson, T., 2018. The industrial internet of things (IIoT): An analysis framework. Computers in Industry 101, 1–12.

[5] Ismail, A., Truong, H.-L., Kastner, W., 2019. Manufacturing process data analysis pipelines: a requirements analysis and survey. J Big Data 6 (1).

[6] van der Aalst, W., 2016. Process Mining: Data science in action, 2. edtion ed. Springer, Berlin, Heidelberg, 467 pp.

[7] van der Aalst et al., 2012. Process Mining Manifesto, in: Daniel, Daniel, F., Dustdar, S., Barkaoui, K. (Eds.), Business Process Management Workshops, vol. 99. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 169–194.

[8] Bayomie, D., Revoredo, K., Bachhofner, S., Kurniawan, K., Kiesling, E., Mendling, J., 2022. Analyzing Manufacturing Process By Enabling Process Mining on Sensor Data.

[9] Martin, N., Fischer, D.A., Kerpedzhiev, G.D., Goel, K., Leemans, S.J.J., Röglinger, M., van der Aalst, W.M.P., Dumas, M., La Rosa, M., Wynn, M.T., 2021. Opportunities and Challenges for Process Mining in Organizations: Results of a Delphi Study. Bus Inf Syst Eng 63 (5), 511–527.

[10] Koschmider, A., Janssen, D., Mannhardt, F., 2020. Framework for process discovery from sensor data. International Workshop on Enterprise Modeling and Information Systems Architectures, EMISA 10, 32–38.

[11] Bano, D., Michael, J., Rumpe, B., Varga, S., Weske, M., 2022. Process-aware digital twin cockpit synthesis from event logs. Journal of Computer Languages 70, 101121.

[12] van Eck, M.L., Sidorova, N., van der Aalst, W.M.P., 2016. Enabling process mining on sensor data from smart products, in: 2016 IEEE Tenth International Conference on Research Challenges in Information Science (RCIS). 2016 IEEE Tenth International Conference on Research Challenges in Information Science (RCIS), Grenoble, France. 01.06.2016 - 03.06.2016. IEEE, pp. 1–12.

[13] Dreher, S., Reimann, P., Gröger, C., 2021. GI Edition Proceedings Band 307 "INFORMATIK 2020" Back to the Future: 28. September - 2. Oktober 2020 Karlsruhe, Deutschland. Köllen, Bonn, CD-ROM.

[14] Mayr, M., Luftensteiner, S., Chasparis, G.C., 2022. Abstracting Process Mining Event Logs From Process-State Data To Monitor Control-Flow Of Industrial Manufacturing Processes. Procedia Computer Science 200, 1442–1450.

[15] Thiede, M., Fuerstenau, D., Bezerra Barquet, A.P., 2018. How is process mining technology used by organizations? A systematic literature review of empirical studies. BPMJ 24 (4), 900–922.

[16] Sein, Henfridsson, Purao, Rossi, Lindgren, 2011. Action Design Research. MIS Quarterly 35 (1), 37.

[17] Lee, S.L., O'Connor, T.F., Yang, X., Cruz, C.N., Chatterjee, S., Madurawe, R.D., Moore, C.M.V., Yu, L.X., Woodcock, J., 2015. Modernizing Pharmaceutical Manufacturing: from Batch to Continuous Production. J Pharm Innov 10 (3), 191–199.

[18] van der Aalst, W., Weijters, T., Maruster, L., 2004. Workflow mining: discovering process models from event logs. IEEE Trans. Knowl. Data Eng. 16 (9), 1128–1142.

[19] Leemans, S.J.J., Fahland, D., van der Aalst, W.M.P., 2013. Discovering Block-Structured Process Models from Event Logs - A Constructive Approach, in: Hutchison, D., Kanade, T., Kittler, J., Kleinberg, J.M., Mattern, F., Mitchell, J.C., Naor, M., Nierstrasz, O., Pandu Rangan, C., Steffen, B., Sudan, M., Terzopoulos, D., Tygar, D., Vardi, M.Y., Weikum, G., Colom, J.-M., Desel, J. (Eds.), Application and Theory of Petri Nets and Concurrency, vol. 7927. Springer Nature, Berlin, Heidelberg, pp. 311–329.

[20] Carmona, J., van Dongen, B., Weidlich, M., 2022. Conformance Checking: Foundations, Milestones and Challenges, in: van der Aalst, W.M.P., Carmona, J. (Eds.), Process Mining Handbook, vol. 448. Springer International Publishing, Cham, pp. 155–190.

[21] van der Aalst, W.M.P., Carmona, J. (Eds.), 2022. Process Mining Handbook. Springer International Publishing, Cham.

[22] Bertrand, Y., van Belle, R., Weerdt, J. de, Serral, E., 2023. Defining Data Quality Issues in Process Mining with IoT Data, in: Montali, M., Senderovich, A., Weidlich, M. (Eds.), PROCESS MINING WORKSHOPS. Icpm 2022 international workshops, bozen-bolzano, vol. 468. SPRINGER INTERNATIONAL PU, [S.l.], pp. 422–434.

[23] van Zelst, S.J., Mannhardt, F., Leoni, M. de, Koschmider, A., 2021. Event abstraction in process mining: literature review and taxonomy. Granul. Comput. 6 (3), 719–736.

[24] Brzychczy, E., Trzcionkowska, A., 2018. Creation of an Event Log from a Low-Level Machinery Monitoring System for Process Mining Purposes, in: Yin, H., Camacho, D., Novais, P., Tallón-Ballesteros, A.J. (Eds.), Intelligent Data Engineering and Automated Learning – IDEAL 2018, vol. 11315. Springer International Publishing, Cham, pp. 54–63.

[25] Leoni, M. de, Dündar, S., 2020. Event-log abstraction using batch session identification and clustering, in: Proceedings of the 35th Annual ACM Symposium on Applied Computing, New York, NY, USA. ACM, New York, NY, USA.

[26] Prathama, F., Nugroho Yahya, B., Lee, S.-L., 2021. A Multi-case Perspective Analytical Framework for Discovering Human Daily Behavior from Sensors using Process Mining, in: 2021 IEEE 45th Annual Computers, Software, and Applications Conference (COMPSAC). 2021 IEEE 45th Annual Computers, Software, and Applications Conference (COMPSAC), Madrid, Spain. 12.07.2021 - 16.07.2021. IEEE, pp. 638–644.

[27] Iman, E., Laanaoui, M.D., Sbai, H., 2023. Applying Process Mining to Sensor Data in Smart Environment: A Comparative Study, in: Ben Ahmed, M., Boudhir, A.A., Santos, D., Dionisio, R., Benaya, N. (Eds.), Innovations in Smart Cities Applications Volume 6, vol. 629. Springer International Publishing, Cham, pp. 511–522.

[28] Bose, R.J.C., Mans, R.S., van der Aalst, W.M., 2013. Wanna improve process mining results?, in: 2013 IEEE Symposium on Computational Intelligence and Data Mining (CIDM). IEEE.

[29] Brock, J., Enzberg, D.-I.S. von, Kühn, D.-I.A., Dumitrescu, D.-I.R., 2023. Process Mining Data Canvas: A method to identify data and process knowledge for data collection and preparation in process mining projects. Procedia CIRP 119, 602–607.

Biography

Jonathan Brock (*1995) is a research associate at Fraunhofer Institute for Mechatronics Design IEM in Paderborn, Germany. His research focuses on using process mining in manufacturing settings. He studied industrial engineering in Bielefeld and Magdeburg, acquiring his M.Sc. in 2020.

Niclas Rempe (*1987) is a senior expert at Fraunhofer IEM. His research focuses on digital transformation and process optimization in manufacturing companies. He studied industrial engineering at the University of Paderborn and his doctoral thesis focused on the optimization of purchasing processes in SAP material management and KPI development including process mining in the railway industry.

Sebastian von Enzberg (*1984) leads the Industrial Data Analytics group at Fraunhofer IEM. His research focuses on the application of Data Analytics and Machine Learning in industrial companies. After studying electrical engineering at Otto-von-Guericke University Magdeburg, he completed his PhD on 3D data processing for metrology applications at the Chair of Neuro-Information Technology in December 2018.

Arno Kühn (*1985) is the head of strategic product & organization design at Fraunhofer IEM. With his team, he focuses on guiding medium-sized companies in digitalization and digital transformation. The topics range from digital strategies for product and business to digital platforms and Industry 4.0. Arno Kühn is also part of the management team of the technology network it's OWL - Intelligent Technical Systems OstWestfalenLippe.

Roman Dumitrescu (*1981) is director at the Fraunhofer IEM and head of the department »Advanced Systems Engineering« at the University of Paderborn. His research focuses on the product development of intelligent technical systems. Prof. Dumitrescu is also one of the managing director of it’s OWL. Among others, he is a member of acatech, the expert group Innovation Dialogue of the German Federal Government and the steering committee of the NRW state government’s Initiative Wirtschaft & Arbeit 4.0.

CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
CPSL 2023-2

5th Conference on Production Systems and Logistics

Adaptive Multi-Priority Rule Approach To Control Agile Disassembly Systems In Remanufacturing

Marco Wurster[1], Finn Bail[1], Sebastian Behrendt[1], Gisela Lanza[1]
[1]*wbk Institute of Production Science, Karlsruhe Institute of Technology, Germany*

Abstract

End-of-Life (EOL) products in remanufacturing are prone to a high degree of uncertainty in terms of product quantity and quality. Therefore, the industrial shift towards a circular economy emphasizes the need for agile and hybrid disassembly systems. These systems feature a dynamic material flow. Besides that, they combine the endurance of robots with the dexterity of human operators for an effective and economically reasonable EOL-product treatment. Moreover, being reconfigurable, agile disassembly systems allow an alignment of their functional and quantitative capacity to volatile production programs. However, changes in both the system configuration and the production program to be processed call for adaptive approaches to production control. This paper proposes a multi-priority rule heuristic combined with an optimization tool for adaptive re-parameterization. First, domain-specific priority rules are introduced and incorporated into a weighted priority function for disassembly task allocation. Besides that, a novel metaheuristic parameter optimizer is devised to facilitate the adaption of weights in response to evolving requirements in a reasonable timeframe. Different metaheuristics such as simulated annealing or particle swarm optimization are incorporated as black-box optimizers. Subsequently, the performance of these metaheuristics is meticulously evaluated across six distinct test cases, employing discrete event simulation for evaluation, with a primary focus on measuring both speed and solution quality. To gauge the efficacy of the approach, a robust set of weights is employed as a benchmark. Encouragingly, the results of the experimentation reveal that the metaheuristics exhibit a notable proficiency in rapidly identifying high-quality solutions. The results are promising in that the metaheuristics can quickly find reasonable solutions, thus illustrating the compelling potential in enhancing the efficiency of agile disassembly systems.

Keywords

Adaptive Production Control; Metaheuristics; Disassembly; Agile System; Priority Rules

1. Introduction

Remanufacturing is a vital method to close the loop in circular supply chains by increasing material efficiency and optimizing resource consumption [1]. In this process, End-Of-Life (EOL) products undergo disassembly into individual components, which are subsequently recovered and reassembled to create a product with restored quality and functionality, resembling a "like-new" state [2]. However, the implementation of efficient remanufacturing systems comes with many domain-specific challenges that make the planning and operation of such systems more complex than in most conventional production systems [3] [4]. Especially the disassembly processes are of complex matter [5], as there is a high degree of uncertainty regarding the type, quantity and quality of incoming EOL products [6]. Therefore, disassembly processes are merely conducted manually in remanufacturing, which limits its economic feasibility, especially in high-wage countries [7].

DOI: https://doi.org/10.15488/15278
ISSN: 2701-6277

The distinctive features of product disassembly impose specific requirements on the design of efficient disassembly systems. Especially the synergetic integration of manual and automated workstations is of essence for an economical disassembly [7]. High flexibility in all components of the system is required including a modular structure, hybrid workstations, flexible material flow and flexible tools [7]. Agile disassembly systems realize these attributes by focussing on the integration of flexibly automated resources in a hybrid factory to deal with varying product specifications [8]. The concept is based on the idea of combining learning robots with human operators to increase productivity and reduce operative costs while maintaining enough flexibility to deal with inherent uncertainties. Robots with cognitive abilities and problem-solving competencies take over suitable disassembly tasks from human operators but are backed up manually in case of operational failures. A modular system structure with loosely linked disassembly stations allows for a flexible material flow to realize product instance-specific routings. Besides that, the system can adjust its capacity to volatile production programs by adding, removing or substituting stations. This enables the system to reconfigure and adapt to changing events throughout multiple production periods [8]. While the hybrid system architecture poses a prerequisite for efficient disassembly, a suitable planning and control system is vital to exploit the additional degrees of freedom.

To overcome the challenges in agile disassembly systems, a control system must aim to resolve the following requirements: The control system must (A) manage a highly flexible and dynamic material flow, as the redundancies in the system allow many routing alternatives while coping with complex system and order states. Besides that, the control system must (B) adapt to different system configurations and loads to ensure good allocation decisions in a continuously changing system environment due to frequent system reconfigurations. As the high degree of uncertainty in remanufacturing leads to ineffective production plans [9], this paper neglects predictive schedules and focuses on reactive order allocation.

2. Related Work

Disassembly planning and control is a broad research field with a rising interest in the last decades [10]. Nevertheless, there is limited research available on appropriate methods that address the specific challenges in agile disassembly systems. Available approaches are either too rigid for reactive control tasks, neglect hybrid systems or do not focus the organizational level and don't scale for disassembly systems with multiple stations. Tang et al. propose a promising solution to simultaneously control the disassembly sequence and the allocation of operations and stations [11]. The approach is dynamic in a way that it doesn't rely on an initial disassembly plan. However, tasks are not distributed among different stations, as all stations have the functional capacity to fully disassemble a discarded product. Concerning the allocation of operations to specific disassembly stations, Kim et al. state as well that predefined disassembly plans are rarely effective as actual system states mostly diverge from the planned system states [12,13]. Therefore, they propose an approach where the initial disassembly plan is rerouted in case of occupied stations or machine failures. In contrast, Hrdina and Zülch state that merely rescheduling a predefined disassembly schedule isn't sufficient to cope with the high degree of uncertainty in a disassembly system, as often systematic changes have to be implemented for further scheduling. Instead, decisions should be made dynamically and individually for each operation [14]. They introduce a dynamic control system for a manual disassembly line which enables a simulation-based optimization of operations. Stations can adjust disassembly operations or methods and operations can be shifted to subsequent stations. Paschko et al. identify that static measures for material release control such as ConWIP result in efficiency losses when applied in highly uncertain environments of disassembly systems [15]. Instead, they propose an adaptive control logic based-on reinforcement learning, which takes system information into account. In [16] a dynamic control logic is proposed for agile hybrid disassembly systems. It balances the allocation of disassembly tasks between a flexible robot and a human operator considering different quality conditions of discarded products. The approach is based on Deep Q-Learning which shows promising results in reducing operational failures and reducing operational costs and system makespan when compared with a priority rule heuristic. The investigated system and the control problem are close to the setting at hand. However, the deployed reinforcement learning agent requires retraining and tuning after the disassembly system is reconfigured, limiting its adaptivity and applicability in practice.

Heuristic priority rules (PR) are often used as a simple means to control the material flow in conventional production systems [17]. Using priority rules to make individual, self-organized and robust routing decisions (see [18]) can be suitable for agile disassembly systems. However, no singular priority rule optimizes the material flow over all possible system configurations [17]. Hence, multiple rules can be combined through a parametrization to depict a more diverse control mechanism and allow adjustments of the control via reparameterization. Typically, priority rules are applied to sequencing problems, with only a few relevant approaches explicitly exploring them for order-to-station allocation problems in flexible job shops. In [19] and [20] stations are enabled to select the next order they process from a set of pending orders. The selection is based on priority rules. Stecke et al. conclude that the effectiveness of priority rules is highly dependent on the system configuration while Xanthoplous et al. emphasize that a combination of rules yields favourable results [19,20]. In [21] and [18] an operation selects the next station it is being processed on. In these cases, the usage of priority rules leads to an increased system performance compared to a random station allocation. In the scope of product disassembly, Guide et al. present an approach, that uses priority rules for disassembly sequence planning to determine the processing order in the input buffer of a disassembly station [22]. In general, however, the usage of priority rules is very limited.

Even though disassembly control is a vibrant research topic, to the best of the authors' knowledge, only a few existing approaches are suitable to control agile disassembly systems. Priority rules on the other hand are a well-established means in flexible job shops, but, despite their promising potential, they haven't been applied to flexible disassembly shops yet. Following this research deficit, a novel adaptive control logic for agile disassembly systems based on heuristic priority rules is proposed in this work. First, domain-specific priority rules are presented, which are fused in a weighted sum to result in a joint priority score. Weights are optimized according to the target criteria, urging for near-optimal foresighted order allocation decisions in a complex disassembly environment (A). To account for adaptivity, the logic is furthermore extended by a metaheuristic optimization module to re-parameterize the control system after changes in system configuration (B).

The remainder of this paper is structured as follows: Section 3 presents the agile control approach, comprising the system architecture, the rule-based control module and the module for system re-parameterization with five different optimization algorithms. In section 4, the different algorithms are validated and compared by efficiency and solution quality. Eventually, section 5 concludes the paper with a summary and outlook on future work.

3. Approach

The proposed approach builds on the system architecture depicted in Figure 1. It encompasses a model of the agile disassembly system including an executable discrete-event simulation. Combined with the control system module determining the material flow, the *Operation* perspective is marked. Additionally, to accommodate reconfiguration capabilities, a *Reconfiguration* perspective is introduced, featuring a system configurator and a control optimizer for the control system. Unlike the control system, both modules strategically adjust the system at designated time points without direct interference during system operations. Given a production program comprising multiple subsequent production periods, the system is typically adapted between these periods in two steps. First, a new system configuration is generated by a system configurator with functionalities like capacity and layout planning, enabling structural adaption. Second, the control optimizer adapts the control system for a logical adaption using an image of the new system configuration. In the following, the focus is on the system model, the control system and the control optimizer, which will be described in detail. Due to limited scope, the system configurator will not be extensively covered in this paper. However, a compatible approach can be found in [23].

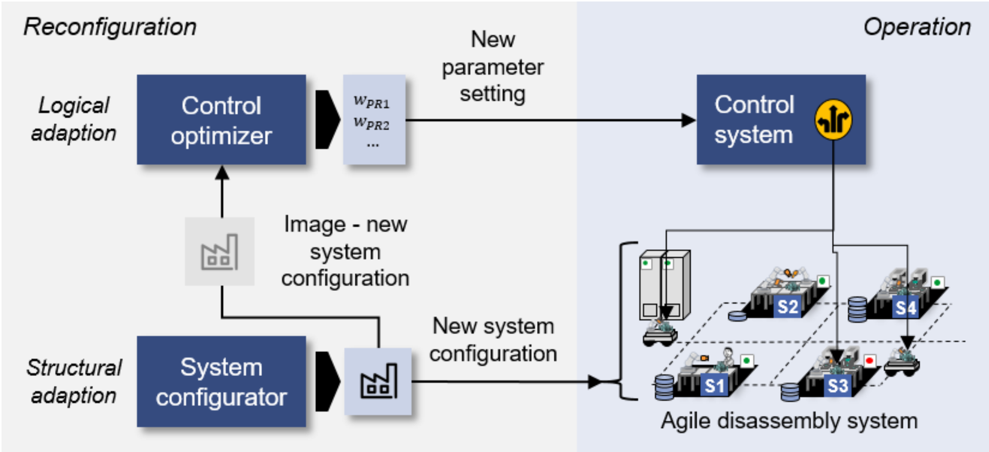


Figure 1: Overview of the system architecture

3.1 System Model

In its basic features, the agile disassembly system is based on the model established in [16]. However, the model is slightly extended, hence, modifications will be specifically highlighted in the following.

The agile disassembly system pursues to disassemble a set of orders $O = (o_1, o_2, \ldots)$, predefined by a given production program and released to the system. The overall aim of the disassembly system is to maximize the number of fully disassembled orders given a defined amount of resources. To fully disassemble an order, product-specific disassembly tasks must be processed. The set $Tsks_i = (tsk_{i,1}, tsk_{i,2}, \ldots)$ denotes the sum of all possible disassembly tasks throughout the entire disassembly process of order o_i. However, it is not always necessary to process all tasks in $Tsks_i$, as alternative disassembly sequences are possible. Let $Tsks_{i,possible} = (tsk_{i,1}, tsk_{i,2}, \ldots)$ be the set of all disassembly tasks of order o_i that can be processed at the current time. The orders are processed by a set of stations $S = (s_1, s_2, \ldots)$ which can be adjusted between production periods. Each station has a different set of capabilities so that the disassembly system can adjust its functional and operational capacities to new requirements by reconfiguring itself. The capabilities of station s_j can be denoted as $Cap_j = (tsk_1, tsk_2, \ldots)$. Meanwhile, the set of stations that are capable of processing task tsk_i is noted as $Enab_i = (s_1, s_2, \ldots)$. A specific instance of a task, when executed on a station, marks an operation op_i.

The simulation includes order-specific processing times and failure rates. The product structures and corresponding disassembly tasks are modelled and organized by disassembly Petri nets, similar as proposed in [11,24]. As the state of EOL products can strongly differ when entering a disassembly system, quality classes are introduced to better depict reality. The quality class influences the processing times, operation failure rates and the capability of a station to perform a task.

To account for the hybrid nature of the disassembly system, three distinct station types with varying capabilities and attributes are introduced. The first type are Manual Stations (MS), which rely on human operators and possess the ability to perform all disassembly operations. Although they offer the highest level of flexibility, operating these stations can be costly. The second type, Automatic Stations (AS), stand out due to their rapid and nearly deterministic operation times. However, their capabilities are limited to routine tasks and disassembling products that are in good condition. Conversely, Robotic (Learning) Stations (RS) gradually extend the scope of automatic resources. Equipped with flexible tools and cognitive abilities, RS are capable of assuming a broader variety of tasks. Moreover, they can effectively solve minor problems and autonomously deal with anomalies which is prerequisite for many disassembly tasks. In addition to the individual station instances, an integral part of the system is the employment of automated guided vehicles (AGV), which facilitate the transportation of orders between the stations [25].

Overall, the introduction of these three station types, namely MS, AS and RS, along with the use of AGV, enables an effective and efficient operation of the disassembly system.

3.2 Control Logic

Released disassembly orders are initially vacant and require an allocation decision including both the next disassembly task and the next station for the next disassembly operation. In most cases, multiple disassembly tasks $\forall tsk_i \in Tsks_{i,possible}$ can be processed by several stations $\forall s_j \in Enab_i$, making the decision very complex. Each allocation option can be described as a tuple (tsk_i, s_j) corresponding to a specific operation denoted $Op_{i,j}$. To select the optimal operation, multiple priority rules Π are used to calculate individual rule-specific scores $v_k \in \mathbb{R}, v_k \in [0,1]$. Thereby, each $\pi \in \Pi = [\pi_1, \pi_2, \dots, \pi_K]$ is given a weight w_k for scaling and to foster the rule-specific importance, while $\sum w_k = 1$ needs to be respected for a convex combination of the individual weights. Eventually, for each operation, a total score $v_{\text{Total}}(Op_{i,j})$ can be facilitated by a weighted sum to identify the most suitable operation:

$$v_{Total}(Op_{i,j}) = \sum_{k=1}^{K} w_k v_k \tag{1}$$

The main goal of the agile disassembly system is to unburden human operators and effectively integrate automated resources while increasing the productivity of the system. Therefore, the main performance indicators for the agile disassembly system are throughput - if time is limited - or makespan - if the order backlog is limited. Appropriate priority criteria need to balance operational and tactical preferences to improve said performance indicators. Thus, the following three rules are presented:

Lowest Buffer Utilization (LBU) scores stations by the number of orders that are in the input- and output buffer of a station. This is done by calculating the relative proportion of buffer spaces occupied. Hereby cap_j denotes the maximal buffer capacity of station s_j and $ocup_{j,in/out}$ the occupied input and output buffer.

$$v_{LBU}(Op_{i,j}) = \frac{cap_j - (ocup_{j,in} + ocup_{j,out})}{cap_j} \tag{2}$$

Lowest Station Cost (LSC) prioritises stations based on their costs. These can be hourly costs or simply relative cost rates. The station costs of station s_j are denoted as c_j. For scaling, it is set into relation with the highest station costs c^{max} and the lowest station cost stations c^{min} of all deployed stations (min-max normalization).

$$v_{SCR}(Op_{i,j}) = \frac{c^{max} - c_j}{c^{max} - c_{min}} \tag{3}$$

Finally, *Shortest Processing Time (SPT)* calculates the mean processing times of certain disassembly tasks on specific stations. Stations with shorter processing times are preferred. Unlike the previous two, SPT is a common priority rule, well-known in the scheduling literature [26]. However, while conventional approaches usually consider deterministic processing times, this approach builds on historic data to account for uncertainty. Thus, a rolling window of the last operations is used to calculate $t_{i,j}^{avg}$, the mean and expected processing time of tsk_i processed on stations of the same type as s_j. For a normalized score v_{SPT}, $t_{i,j}^{mean}$ is compared with the maximum $t_{i,\max}^{mean}$ and minimum $t_{i,\min}^{mean}$ mean processing times for tsk_i of all capable stations:

$$v_{SPT}(Op_{i,j}) = \frac{t_{i,j}^{mean}}{t_{i,max}^{mean} - t_{i,min}^{mean}} \quad (4)$$

The given priority rules have broad applicability, suitable not only for remanufacturing but also for agile production systems. However, the control system is not limited to them but can also incorporate other rules that are common in linear production. The given ones are chosen as examples due to their ability to balance system utilization and cost-effectiveness-to-throughput ratio under uncertainty, an emerging challenge closely associated with the proliferation of hybrid disassembly systems.

Through changes in the system configuration and the production program, a shift in the optimal parametrization is observable. Figures 1-3 depict the changes in the system efficiency of individual parametrizations that result from changes in the production system. All figures show the exhaustive convex solution space for all possible weight combinations, based on an individual system configuration. Each point in a figure represents a parametrization w which was simulated 20 times to account for stochastic behaviour. The colour indicates the number of orders which were disassembled during an eight-hour shift. Additionally, the red circle marks parametrizations that yield results within 2.5% of the found optima. Figure 2a corresponds to systems with a high proportion of MS in the system configuration. Figure 2b is generated from a system with many orders from low-quality classes which must be disassembled. Figure 2c depicts the influence of the order release. A ConWIP logic is used in all cases, while in case of Figure 2c, the fixed WIP-limit is reduced by half.

This paper aims to enable the control system to adapt its parametrization and thereby optimize the material flow individually for every time period. This way the flexibility of the agile disassembly system can be leveraged more optimally.

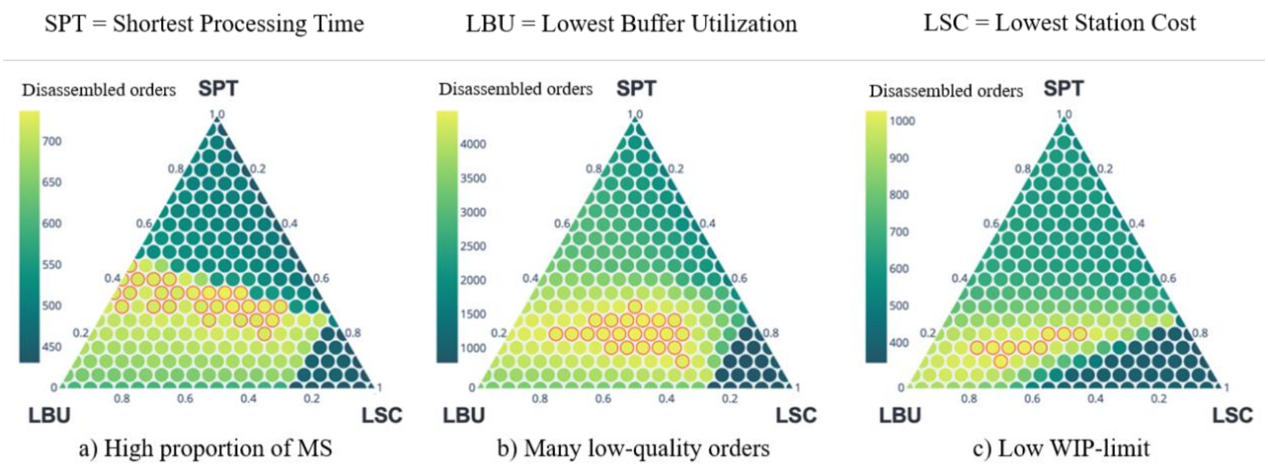


Figure 2: Amount of fully disassembled orders for different system configurations (a) High proportion of MS, b) Many low-quality orders, c) Low WIP-limit) depending on parametrization – Red border indicates parametrizations that are within 2.5% of the best solution

To re-optimize the parametric control, four different metaheuristics are implemented and compared against a robust parameter set. The metaheuristics can be classified as population-based and local search methods [27]. A grid search was applied to all metaheuristics to determine the optimal parameter configuration.

Simulated Annealing (SA) is a local Search Metaheuristic that is based on the cooling behaviour of metals [28]. It distinguishes itself from other local search methods by accepting worse solutions with a defined probability influenced by an iteratively changing temperature. By gradually decreasing the temperature, the algorithm transitions from exploration to exploitation. Contrarily Particle Swarm Optimization (PSO), Evolutionary Algorithms (EA) and Artificial Bee Colony (ABC) are population-based metaheuristics, however, all of them utilize different search strategies. PSO mimics the movement of animal groups by moving the population throughout the search space [29]. Hereby the movement is influenced by the best solution for each entity and the best solution for the population. EA is based on the principle of natural selection [30]. Through three basic operations; selection, crossover and mutation, the fitness of the population is incrementally increased. Lastly, ABC additionally combines aspects from local search and random search as the neighbourhoods of the best solutions are predominantly searched and non-improving solutions are periodically reinitialized randomly [31].

4. Validation

To evaluate the effectiveness of a dynamic reparameterization of the production control, six use cases were defined each simulating an eight-hour shift. The use cases differ in their production program, machine setup and release mechanism. Due to the high complexity of fully depicting all modifications and the limited scope of the paper, only a qualitative description of the modifications is given in Table A1. All simulations consider six different products for disassembly, each with a different number of quality classes (ranging between 3 and 5), which additionally influence processing times and the capabilities of machines. As mentioned above the costs to operate MS (10 cost units) are costlier than RS (7 cost units) and AS (5 cost units). The products are also distinguishable through different degrees of complexity as the number of components and alternative disassembly sequences can change. To benchmark the effectiveness of the optimizers, the results are compared with a robust, however static parametrization. This parametrization corresponds to $w = \left(\frac{1}{3}, \frac{1}{3}, \frac{1}{3}\right)$ and was determined by selecting the best static parametrization throughout the six use cases. The hyperparameters for each metaheuristic were optimized through a grid search in an area guided by related literature and preliminary experiments. Each optimizer is evaluated through the mean number of fully disassembled orders which is calculated by a sample of five simulation replications per use case with varying seeds to account for stochasticity. The overall increase in system efficiency is presented in Table 1.

Table 1: Mean number of orders fully disassembled by metaheuristic after optimization – Percentual efficiency increases compared to robust parameters indicated in brackets

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Mean
Robust Parameters	732.2	1016.8	1474.4	578.6	4243.2	741.4	**0.00%**
Simulated Annealing	718.4 (-1.88%)	1053.8 (3.64%)	1550.2 (5.14%)	670.2 (15.83%)	4490.0 (5.82%)	1029.6 (38.87%)	**11.24%**
Particle Swarm Optimization	739.8 (1.04%)	1063.6 (4.60%)	1512.4 (2.58%)	660.6 (14.17%)	4523.4 (6.60%)	1013.4 (36.69%)	**10.95%**
Artificial Bee Colony Optimization	729.2 (-0.41%)	1087.0 (6.90%)	1550.2 (5.14%)	664.8 (14.90%)	4514.4 (6.39%)	1031.6 (39.14%)	**12.01%**
Evolutionary Algorithm	705.4 (-3.66%)	998.8 (-1.77%)	1543.6 (4.69%)	624.4 (7.92%)	4365.2 (2.88%)	984.6 (32.80%)	**7.14%**

Firstly, all optimizers outperform static parametrization, which indicates that adaptive control is beneficial. The degree of improvement strongly depends on the considered use case. This can be explained by the fact that in some cases the robust parameters are close to the optimum and further improvement is simply not possible (e.g., use case 1). However, in other cases a change in parametrization results in large improvements (e.g., use case 6). Especially in cases where the RS and AS can only execute a small proportion of the overall tasks, it is vital to utilize these stations as much as possible. This often requires case specific adjustments to the parametrization, hence creating possibilities of improvement through optimization. Focussing on the mean improvement, the ABC provides the best results and the EA the smallest amount of improvement. Nevertheless, except for the EA, all optimizers are within a span of 2%. This motivates to additionally take the convergence speed of each algorithm into account.

Figure 3 exemplary illustrates the development of the current best-found solution throughout the algorithm. The fitness value is plotted against the number of performed simulation runs. As each evaluation of a parametrization requires one simulation run, this unit of measurement allows comparing the different metaheuristics. An analysis based on the number of iterations isn't possible since population-based approaches require multiple function evaluations per iteration compared to local search methods.

The fitness values of Figure 3 do not strictly mandate the results that are seen in Table 1. As the simulation is stochastic, a high fitness during optimization does not inevitably ensure a good outcome in the actual production period. The convergence speed is also quantitively analysed in Table A2 by taking the mean number of simulation runs required to overcome the threshold of within 2% of the best-found fitness value. It can be said that the EA yields the slowest improvement of the optimizers, which confirms the prior findings from Table 1. The results of SA, ABC and PSO are comparable. SA seems to converge faster than the population-based approaches throughout the use cases 1-5, but the discrepancy in use case 6 is significant. This could be interpreted as a statistical outlier or a possible edge case described in use case 6. Nevertheless, SA and PSO demonstrate a high convergence speed on average.

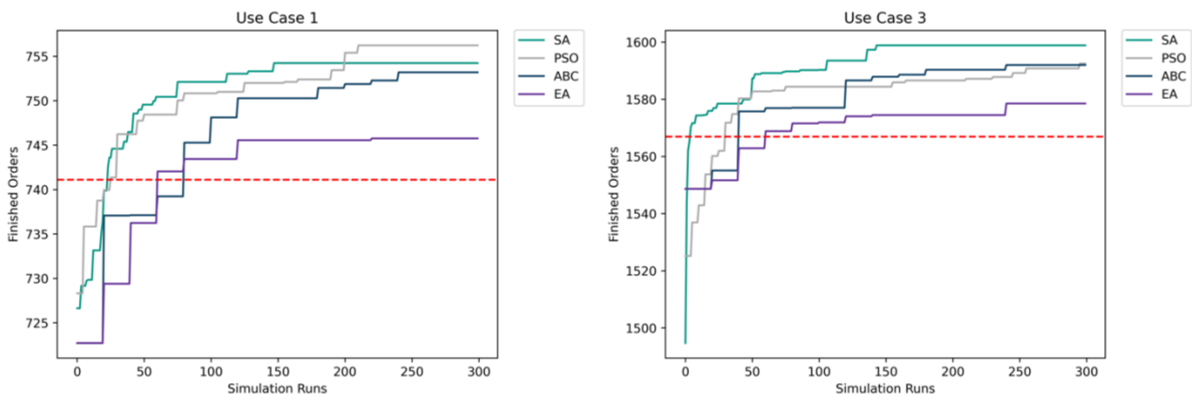


Figure 3: Mean fitness value of the best-found solution - Red line indicates the threshold within 2% of the global best-found solution

5. Conclusion

This paper comprises a model and control system for agile hybrid disassembly systems in remanufacturing. In order to boost the system efficiency, a combined priority rule approach that reactively allocates disassembly orders to suitable stations has been proposed. The approach shows promising results while posing a suitable method for industrial practitioners due to its intelligible nature and domain-specific expandability. Besides that, the combination of multiple priority rules is to be highlighted at this point, as it yields better results than conventional uni-criterial approaches in complex environments such as the disassembly domain. Besides that, it is shown that logical adaptions must follow structural adaptions in case of a system reconfiguration, for which reason, the approach was extended by a simulation-based metaheuristic parameter optimizer. While all reparameterizations outperform the robust parameters, ABC produces the best results. However, PSO and SA require less time to achieve a reasonable outcome.

While preliminary experiments indicated that the selected priority rules (LSC, LBU, SPT) yield good results, further rules should be incorporated to potentially enhance effectiveness. In particular, a multi-priority rule heuristic based on more than three rules should be investigated. Besides that, a comparison with more sophisticated generalized control approaches such as RL-based allocation agents could reveal interesting findings. Eventually, the approach should be validated on a real scenario to bridge the gap to industrialization.

Acknowledgements

This work is part of the AgiProbot project funded by the Carl Zeiss Foundation.

Appendix

Additional Tables

Table A1: Overview of the modifications that distinguish the considered use cases

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Modification	Increased frequency of products in bad condition	Increased frequency of products with high complexity	Increased frequency of products with low complexity	Only products in bad condition	High proportion of MS in system configuration	Lower CONWIP level

Table A2: Mean number of simulation runs required to overcome the threshold of 2% within the best found solution for each metaheuristic

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Mean
Simulated Annealing	23	44	4	17	3	201	**48.67**
Particle Swarm Optimization	25	50	30	25	15	85	**38.33**
Artificial Bee Colony	80	140	40	80	20	140	**83.33**
Evolutionary Algorithm	60	320	60	180	60	100	**130**

References

[1] Potting, J., Hekkert, M., Worrel, E., Hanemaaijer, A., 2017. Circular Economy: measuing innovation in the product chain. Planbureau voor de leefomgevig (2544).

[2] Giutini, R., Gaudette, K., 2003. Remanufacturing: The next great opportunity for boosting US productivity. Business Horizons 46 (6), 41–48.

[3] Zhang, R., Ong, S.K., Nee, A.Y.C., 2015. A simulation-based genetic algorithm approach for remanufacturing process planning and scheduling. Applied Soft Computing 37 (6), 521–532.

[4] Cui, Y., Guan, Z., He, C., Yue, L., 2017. Research on remanufacturing scheduling problem based on critical chain management. IOP Conf. Ser.: Mater. Sci. Eng. 215, 12005.

[5] Guide, V.D.R., 2000. Production planning and control for remanufacturing: industry practice and research needs. Journal of Operations Management 18 (4), 467–483.

[6] Lundmark, P., Sundin, E., Björmark, M., 2009. Industrial Challenges within the Remanufacturing System. Proceedings of The International 3rd Swedish Production Symposium, SPS'09, Göteborg, Sweden, 2-3 December 2009, 132–138.

[7] Kim, H.-J., Harms, R., Seliger, G., 2007. Automatic Control Sequence Generation for a Hybrid Disassembly System. IEEE Trans. Automat. Sci. Eng. 4 (2), 194–205.

[8] 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.

[9] Kurilova-Palisaitiene, J., Sundin, E., 2014. Challenges and Opportunities of Lean Remanufacturing. IJAT 8 (5), 644–652.

[10] Priyono, A., Ijomah, W., Bititci, U., 2016. Disassembly for remanufacturing: A systematic literature review, new model development and future research needs. JIEM 9 (4), 899.

[11] Tang, Y., Zhou, M., Caudill, R.J., 2001. An integrated approach to disassembly planning and demanufacturing operation. IEEE Trans. Robot. Automat. 17 (6), 773–784.

[12] Kim, H.-J., Chiotellis, S., Seliger, G., 2009. Dynamic process planning control of hybrid disassembly systems. Int J Adv Manuf Technol 40 (9-10), 1016–1023.

[13] Kim, H.-J., Ciupek, M., Buchholz, A., Seliger, G., 2006. Adaptive disassembly sequence control by using product and system information. Robotics and Computer-Integrated Manufacturing 22 (3), 267–278.

[14] Hrdina, J., Zülch, G., 2017. Simulationsunterstützende Entwicklung von Methoden zur reaktiven Steuerung von Demontagelinien. Simulation in produktion und Logistik, 325–334.

[15] Paschko, F., Knorn, S., Krini, A., Kemke, M., 2023. Material flow control in Remanufacturing Systems with random failures and variable processing times. Jnl Remanufactur 13 (2), 161–185.

[16] Wurster, M., Michel, M., May, M.C., Kuhnle, A., Stricker, N., Lanza, G., 2022. Modelling and condition-based control of a flexible and hybrid disassembly system with manual and autonomous workstations using reinforcement learning. J Intell Manuf 33 (2), 575–591.

[17] Geiger, C.D., Uzsoy, R., Aytuğ, H., 2006. Rapid Modeling and Discovery of Priority Dispatching Rules: An Autonomous Learning Approach. J Sched 9 (1), 7–34.

[18] Scholz-Reiter, B., Peters, K., Beer, C. de, 2004. Autonomous control of shop floor logistics. Proc. IFAC-MIM, in print.

[19] Stecke, K.E., Solberg, J.J., 1981. Loading and control policies for a flexible manufacturing system. International Journal of Production Research 19 (5), 481–490.

[20] Xanthopoulos, A.S., Koulouriotis, D.E., Gasteratos, A., Ioannidis, S., 2016. Efficient priority rules for dynamic sequencing with sequence-dependent setups. 10.5267/j.ijiec, 367–384.

[21] Subramaniam, V., Lee, G.K., Ramesh, T., Hong, G.S., Wong, Y.S., 2000. Machine Selection Rules in a Dynamic Job Shop. Int J Adv Manuf Technol 16 (12), 902–908.

[22] Guide, V.D.R., Kraus, M.E., Srivastava, R., 1997. Scheduling policies for remanufacturing. International Journal of Production Economics 48 (2), 187–204.

[23] Behrendt, S., Wurster, M., May, M.C., Lanza, G., 2023. Extended Production Planning of Reconfigurable Manufacturing Systems by Means of Simulation-based Optimization. Hannover : publish-Ing.

[24] Zussman, E., Zhou, M., 1999. A methodology for modeling and adaptive planning of disassembly processes. IEEE Transactions on Robotics and Automation 15 (1), 190–194.

[25] Klein, J.-F., Wurster, M., Stricker, N., Lanza, G., Furmans, K., 2021 - 2021. Towards Ontology-based Autonomous Intralogistics for Agile Remanufacturing Production Systems, in: 2021 26th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA). 2021 IEEE 26th International Conference on Emerging Technologies and Factory Automation (ETFA), Vasteras, Sweden. 07.09.2021 - 10.09.2021. IEEE, pp. 1–7.

[26] Haupt, R., 1989. A survey of priority rule-based scheduling. OR Spectrum 11 (1), 3–16.

[27] Sörensen, K., Glover, F.W., 2013. Metaheuristics, in: Fu, M.C., Gass, S.I. (Eds.), Encyclopedia of Operations Research and Management Science. Springer, Boston, MA, pp. 960–970.

[28] Kirkpatrick, S., Gelatt, C.D., Vecchi, M.P., 1983. Optimization by simulated annealing. Science (New York, N.Y.) 220 (4598), 671–680.

[29] Kennedy, J., Eberhart, R., 1995. Particle swarm optimization, in: Proceedings of ICNN'95 - International Conference on Neural Networks. ICNN'95 - International Conference on Neural Networks, Perth, WA, Australia. 27 Nov.-1 Dec. 1995. IEEE, pp. 1942–1948.

[30] Jones, G., 2002. Genetic and Evolutionary Algorithms, in: Ragu Schleyer, P. von, Allinger, N.L., Clark, T., Gasteiger, J., Kollman, P.A., Schaefer, H.F., Schreiner, P.R. (Eds.), Encyclopedia of Computational Chemistry, vol. 1. John Wiley & Sons, Ltd, Chichester, UK, p. 1.

[31] Karaboga, D., 2005. An idea based on honey bee swarm for numerical optimization TR06. Erciyes university engineering Faculty, Kayseri, Turkey.

Biography

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.

Finn Bail (*1998) 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. He studied industrial engineering and management at the Karlsruhe Institute of Technology (KIT).

Sebastian Behrendt (*1997) 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. He studied mechanical engineering with a specialization in production systems, data analysis and machine learning at the Karlsruhe Institute of Technology (KIT).

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.

CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
CPSL 2023-2

5th Conference on Production Systems and Logistics

Towards A Modular IT-Landscape For Manufacturing Companies: Framework For Holistic Software Modularization

Sebastian Junglas[1], Martin Perau[1], Dino Hardjosuwito[1], Tobias Schröer[1], Wolfgang Boos[1], Günther Schuh[1]

[1] *FIR (Institute for Industrial Management) at the RWTH Aachen University, Aachen, Germany*

Abstract

Companies in the manufacturing sector are confronted with an increasingly dynamic environment. Thus, corporate processes and, consequently, the supporting IT landscape must change. This need is not yet fully met in the development of information systems. While best-of-breed approaches are available, monolithic systems that no longer meet the manufacturing industry's requirements are still prevalent in practical use. A modular structure of IT landscapes could combine the advantages of individual and standard information systems and meet the need for adaptability. At present, however, there is no established standard for the modular design of IT landscapes in the field of manufacturing companies' information systems. This paper presents different ways of the modular design of IT landscapes and information systems and analyzes their objects of modularization. For this purpose, a systematic literature research is carried out in the subject area of software and modularization. Starting from the V-model as a reference model, a framework for different levels of modularization was developed by identifying that most scientific approaches carry out modularization at the data structure-based and source code-based levels. Only a few sources address the consideration of modularization at the level of the software environment-based and software function-based level. In particular, no domain-specific application of these levels of modularization, e.g., for manufacturing, was identified.

Keywords: Information System; Modularization; IT Landscape; Manufacturing; Literature Review

1. Introduction

Dynamic production environments lead to a need for adaptable processes in manufacturing companies [1]. Adaptable processes require changeable IT systems and the resulting IT landscapes to enable and support such processes [2]. In this context, an IT landscape is to be understood as the sum of the individual information systems used [3]. Today's major information systems in manufacturing companies are mainly monolithic, rigid, and unsuitable for such a requirement [4]. A typical life cycle of such a monolithic information system lasts 7-10 years, and the information systems' configuration and design are based on the initial requirements from the beginning of the respective life cycle [5]. The needed incremental adaptation of these changing requirements over time only happens individually and is not structured, and thus the information system cannot adapt to the dynamic environment.

Studies show that future-proof information systems and the resulting IT landscapes must be flexible, functional, and consistent [6]. This can be achieved through a modular approach. A modular approach offers the added value that individual modules can be developed independently, used selectively, and configured according to demand [7]. Furthermore, due to the above-mentioned requirement for flexibility, a quick implementation can be carried out in the event of changing requirements [7]. Modularization of information systems is a promising path to a holistic best-of-breed approach [8,9]. A best-of-breed approach requires that the best solution for the specific use case is selected and implemented (cherry-picking) [10]. Modularizing

DOI: https://doi.org/10.15488/15302
ISSN: 2701-6277

information systems can enable the suitable composition of modules for the needed functionality fit within a modular IT landscape. The functionality is tailored to the respective use case, as just the fitting modules (in the sense of the best-of-breed approach) can be used. This suitable functionality can be achieved in modules, if modules consist of business-related functions that fit together and are only loosely connected to their environment. Hereby a module is defined as loosely coupled with other modules and having a high cohesion of its components within the module [12]. This definition of a module also has an advantage for consistency - interfaces will only exist where they are needed. This is in direct contrast to IT landscapes as they exist today. In today's IT landscapes, monolithic information systems prevail. Their size and complexity makes them slow to change and hinder the capacity of companies to adapt to a changing environment [11]. A monolithic system always means compromises. Thus, it is crucial to focus on the modularization of information systems to enable modular IT landscapes and adaptable processes.

This paper analyzes and presents existing approaches to modularizing information systems within IT landscapes. Particularly relevant is the classification in a domain-specific reference. The aim is to present distinct types, respectively levels, of software modularization and to analyze whether any types of software modularization are underrepresented in the scientific consideration to date. This will test the hypothesis that domain-specific modularization of information systems in manufacturing companies does not exist in the necessary form seen in the market. This goal is pursued with systematic literature research. The research question to be answered is: What types of software modularization exist, and are any particular types of software modularization underrepresented in science?

This paper is divided into five chapters. After the introduction, the conducted method is discussed and presented in detail. Chapter 3 presents the results of the research. Chapter 4 deals with the discussion of the results obtained before a critical appraisal and an outlook is given in Chapter 5.

2. Applied methodology

The overarching method is based on the systematic literature review framework according to vom Brocke et al. and consists of five steps [13]:

1. Definition of review scope
2. Conceptualization of topic
3. Literature search
4. Literature analysis and synthesis
5. Research agenda

Defining the scope of the literature review ensures that the objectives of the given research question are systematically implemented throughout the literature review process. The taxonomy of the literature review, according to Cooper, supports this [14]. The figure below shows our definition of the review scope for our research question.

Characteristic	Categories			
goal	integration	criticism	central issues	
perspective	neutral representation	espousal of position		
organisation	historical	conceptual	methodological	
audience	specialised scholars	general scholars	practitioners / politicians	general public
focus	research outcomes	research methods	theories	applications
coverage	exhaustive	exhaustive and selective	representative	central/pivotal

Scope of this paper — None scope of this paper

Figure 1: Definition of the review scope of this paper (Following Cooper [14])

The goal of the paper is the integration or, more specifically, the synthesis of existing approaches to software modularization and the derivation of existing central issues of these approaches for the application context of the design of the modular IT landscape of manufacturing companies. It follows that the literature review is classified as an espousal of position, as we want to synthesize the literature accordingly to consider whether the consideration of the application of software modularization approaches has already been studied scientifically. A view from an espousal perspective does not contradict the necessary scientific neutrality as long as the conclusions are logical and transparent, which we ensure through the detailed description of our methodology [14]. The organization of the relevant sources to generate the knowledge to answer the research question is accomplished through the development of a framework. The literature review is conceptual in character and aims at combining similar approaches [14], in our case, software modularization approaches. The framework is aimed at scientists from different fields, as the paper's topic is located at the interface between computer science and production management. The focus of the material of the literature review cannot be classified precisely, as existing research methods, research outcomes, applications, and theories can contribute to the development of the framework. According to Cooper, exhaustive and selective coverage is suitable for an integrative literature review [14], as it allows for the necessary comprehensive investigation with the simultaneous synthesis of the literature. Accordingly, we have chosen the exhaustive and selective coverage category for our literature review. The definition of the review scope serves as a guideline for the entire literature review and as input for the next steps.

The second step is the rough conception of the topic field, which enables the derivation of the search strings for the literature review steps [13]. The rough conception of the topic field is based on the research questions. The overall theme of the paper are modular IT landscapes, and the research questions focus on the formation of modules within information systems (and thus IT landscapes) under the application of a method. Modules in this paper's context are formed from IT landscape information systems. To achieve this, it is necessary to design information systems modularly. Thus, in the literature search, modules of information systems are focused. In the context of this paper, modules are understood as system components that should have a loose coupling between each other and a high cohesion of their respective internal elements [12,15,16]. Furthermore, the term “software” is synonymous with “information system” in the literature research. For the procedure of module formation, different terms are used. The term “modularization” describes the division of an information system into modules [15]. Other terms used by authors instead of modularization in this context are “structuring” and “decomposing”[15,16], which are used as synonyms for “modularization” in the literature review. The keywords for the systematic literature research are derived from the formation of modules within information systems under the application of a method.

For the search strings of the systematic literature research, the term “module” is used as keyword 1. Furthermore, to ensure that the modules considered in the literature search, are modules of information systems, the term “information system” is used as keyword 2, as well as its synonym “software”. Since the research questions are about forming modules and not just examining modules themselves, the method of forming modules is focused on in the literature review. Thus, the term “modularization” as well as its synonyms “structuring” and “decomposing” are used as keyword 3. Based on this conception of the thematic field, the following search strings were developed (see Table 1).

Table 1: Search strings for the literature review

Nr.	Key Word 1	Boolean	Key Word 2	Boolean	Key Word 3
1	Module	AND	Software	AND	Structuring
2				AND	Modularization
3				AND	Decomposing
4		AND	Information system	AND	Structuring
5				AND	Modularization
6				AND	Decomposing

In the third step, a literature search was conducted. Based on a search string search in electronic databases, a multi-stage filtering and screening process was carried out following vom Brocke et al. and Moher et al. to reduce the number of publications to be considered systematically [13,17]. The framework of this process was documented using the STARLITE method (see Table 2).

Table 2: Documented literature search according to STARLITE [18]

Element	Description
Sampling strategy	Consideration of all literature within defined boundaries
Type of studies	Scientific articles, books, and PhD-Thesis
Approaches	Search strings search in electronic databases
Rang of years	2014 until 06/2023
Limits	No duplicates; only English or German publications; publicly available publications
Inclusion and exclusion	Including: software modularization or information system modularization; Excluding: Product modularization; Ontology modularization; service modularization
Terms used	See Table 1.
Electronic sources	Scopus

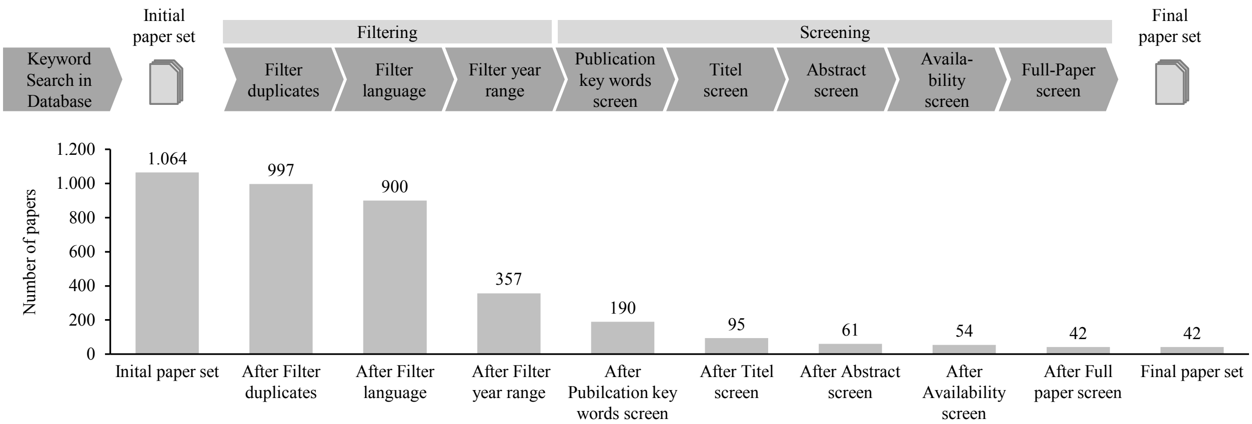


Figure 2: Filtering and Screening process of the literature search

The resulting publications, including the documentation of the filtering and screening process, can be found in the following document: https://epub.fir.de/frontdoor/index/index/docId/2704.

The literature review and synthesis are to be conducted to identify the approaches used for software modularization and, using these approaches, to derive which levels of software modularization. For this purpose, the objects of modularization used per paper are to be first analyzed and, based on these objects, a framework of the different levels of software modularization is to be developed by assigning thematically related objects to a level of software modularization. Objects of modularization describe those objects that are combined into modules by the respective modularization process. The derivation of the research agenda is done in section 4 based on the findings of section 3.

3. Results of the literature review

This chapter presents the results of the literature review. The research papers were examined according to different approaches to modularization – concrete the objects of modularization. Objects of modularization refer to those aspects that are combined and thus result in a module. Overall, the following objects of modularization were identified during the described literature review: requirements, organizational units, conceptual model use case, GUI-based functions, artifacts, classes, subset of program functions, features, domain entities, aspects, packages, and source code. The identification of the mentioned objects of modularization within the examined papers shows that different kinds of objects are considered. This becomes clear for example since requirements determine the needs for a software application, classes describe the software-technical structuring of methods and source code the executable syntax of the software application.

Since the paper's goal is to synthesize existing approaches to software modularization and derivate existing central research gaps in the application context of the design of the modular IT landscape of manufacturing companies, an initial, generally valid approach for the synthesis is necessary. The V-Model is used as the basis of the synthesis, enabling a generic and holistic view of the software development process. The V-Modell is an established standard in software development and enables the decomposition of software development processes into different levels of consideration (see Figure 3) [19–21].

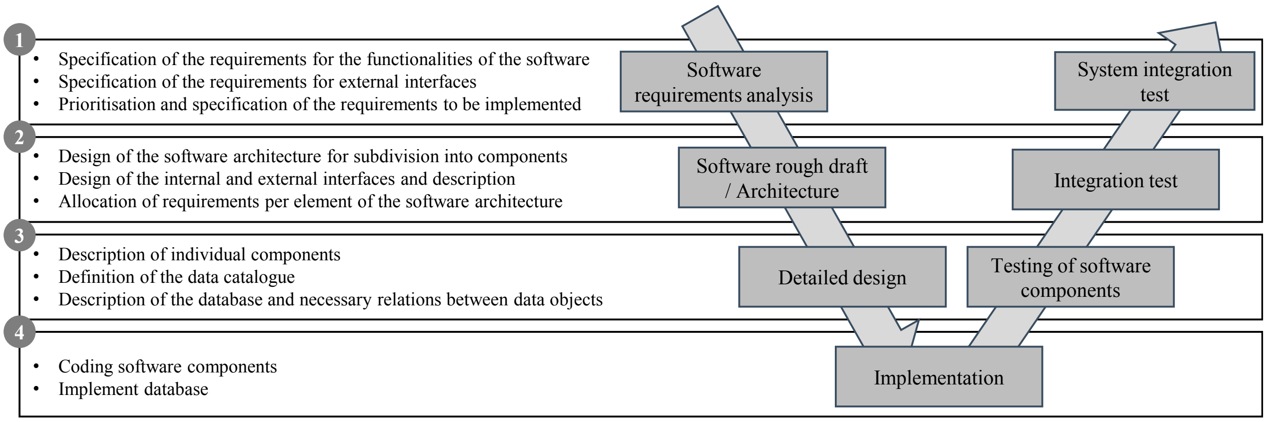


Figure 3 V-Modell for Software Engineering following Dröschel et al. [19]

A strongly business-driven approach characterizes the first step of the V-Modell. The software requirement analysis specifies requirements for software functionalities and external interfaces. Then, in the second step, the software is divided into individual components, and the interfaces between the individual components are defined. A critical component is also the assignment of requirements to the respective components. In the third step of the V-Modell, the data-related description of individual software components takes place through component descriptions, data catalogues, and the necessary data relationships. The fourth step of the V-Modell considers the implementation of the data-related description of the individual components through the implementation of the components through source code. [19] The subsequent consideration of the different test steps is not relevant in the context of this paper and will thus not be discussed.

A framework for holistic software modularization was developed based on the V-Modell. Four levels of software modularization exist: software environment-based, software function-based, data structure-based, and source code-based (see Figure 4). The levels differ in their weighting regarding the focus on business-specific aspects towards a focus on technical aspects with the given order. This differentiation results from the associated objects of software modularization. In addition, the mentioned levels of software modularization are hierarchically structured. This means that a formed module in a level of software modularization can be further modularized on a lower level. The modularization on the lower level uses different objects than within the higher modularization level.

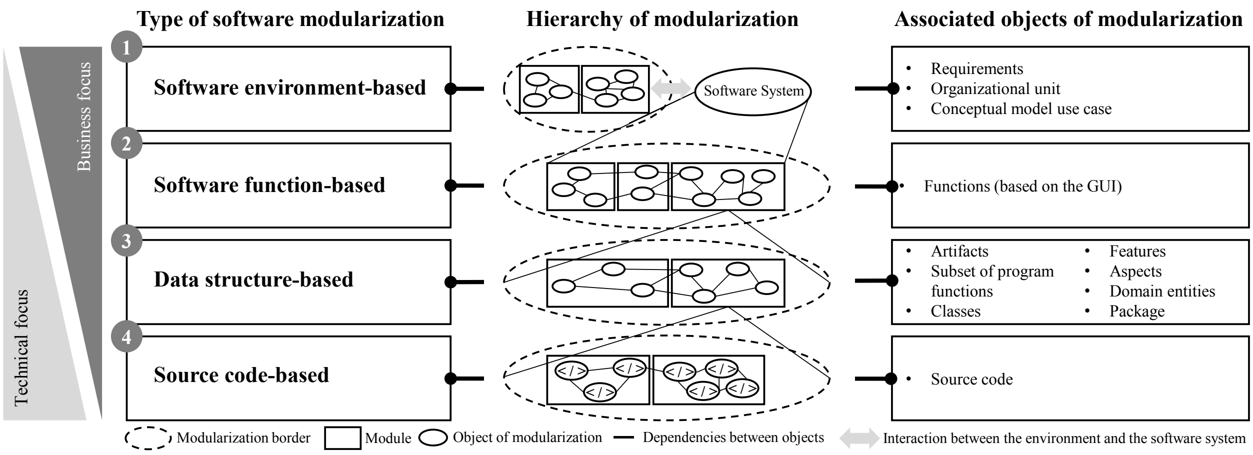


Figure 4 Framework for holistic software modularization

The most business-focused view of software modularization is the software environment-based modularization, in which primarily external objects are considered as the modularization objects, e.g. business units. The level of software function-based modularization considers the decomposition of the software system into individual components, considering the functions of the entire system. The level of data structure-based modularization has a strong technical focus. Here, the primary goal is to optimize the data structure of a single software component by modularizing various objects, e.g., classes. The fourth level of software modularization, source code-based modularization, has an exclusively technical focus. In the following, the respective levels of modularization are described.

Software environment-based modularization (Level 1)

At this level, the software environment is included in the modularization process. The software system is influenced by various actors and activities in the environment. These factors can be used for modularization approaches. The strongest business focus can be seen at this level of modularization. No technical factors are included in the modularization efforts. The modularization objects used at this level are requirements, organizational units, and conceptual models (Use Case).

Requirements (e.g. in [22]) refer to the functional needs of software [12]. Requirements are combined in logical groups and modules are developed from them [22]. Another object of modularization are organizational units (e.g. in [23]). Here, modules are formed that can be designed based on the organizational unit in which they are used (e.g. production planning, sales, or procurement). Organizational units are structures in a company, that can be complemented by the responsibilities of the unit and size means the number of involved people [24]. The object of modularization is therefore directly dependent on the company's structure. Use cases refer to fields of application that are mapped in software. The Use Case describes the interaction between a product and the actor [25]. Based on the definition of use cases, various specific situations can be mapped, which can then be combined in software as a module.

Software function-based modularization (Level 2)

At the level of software function-based modularization, the individual necessary components are used at the function level to define and design suitable modules. This is the first time that a technological design of business components has taken place. The analysis of the available research papers just shows one approach where functions based on the GUI elements (e.g. main window, menu bar) are used as an object of modularization [26].

Data structure-based modularization (Level 3)

At the level of data structure-based modularization, mainly technical components are used to form modules. There is a strong data-related focus that structures the individual data points and makes them available as objects for modularization. The research conducted here shows a large number of objects that are used to form modules. These are artifacts, subsets of program functions, classes, features, aspects, domain entities, and packages.

Artifacts (e.g. in [27]) are software elements produced during the software development process. In this context, an artefact can be defined as the structure, routines, or values of software [28]. Subset of program functions (e.g. in [29]) means those functions that are necessary for the operation of the software. This can mean, for example, memory capacities. The object of modularization here therefore refers to the higher-level technical functions and not to the procedural implementation of tasks. Domain Entities (e.g. in [30]) are objects in software always related to a data point. This means that a recurring data point classifies as an entity and thus works like a variable in software. The reverse conclusion is that the object of modularization tends to lead to very finely granular modules. A package combines various individual classes of software. This shows the connection to the classes that are also analyzed as objects of modularization (e.g. in [31]). Classes unite features of the software. Features are, for example, attributes or methods. These classes then have the same features. [12] Here a hierarchical arrangement of the objects of modularization can be seen, which results in a different granularity of the modules depending on the application. Aspects of software (e.g. in [23]), on the other hand, refer to software functionalities that do not contribute to the business logic, such as the logging of input data. In summary, modularization is carried out at all levels of a software hierarchy. The objects of modularization are usually sub-objects of a higher hierarchy level.

Source code-based modularization (Level 4)

On the fourth level of modularization, only technical objects are used to form modules. The reference to the business logic is no longer present and a purely technical implementation is carried out or used for modularization. Only one modularization object can be assigned to this level - the source code.

Source code (e.g. in [22]) can be defined as a human-readable form of a program in a programming language. Modularizations at the code level mean the sensible combination of areas of the source code. Here, modularization means that lines of code are clustered which can be expected to facilitate the implementation or execution of the software [32]. This makes the developer's work easier, as no things must be implemented twice, which also improves the performance of the software.

4. Discussion of the results

The results of the systematic literature research clearly show that there is a focus area in software development in which modularization activities are already taking place today. In the big picture, modularization as a driver for making software more flexible and improving its functionality aims to break down software boundaries and thus design entire IT system landscapes through modules. The papers analyzed here clearly show that the efforts toward modularization are only considered in a detached IT system. The reference to the structure of an IT system landscape is completely missing. Furthermore, in the division of the classification of the papers in the developed framework, it becomes clear that only a few objects of modularization could be identified on the level of software environmental-based and software function-based modularization (level 1 and 2) (see Figure 6).

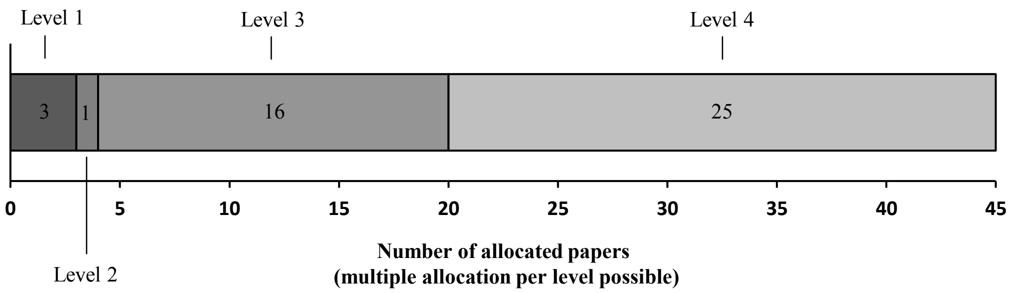


Figure 5 Distribution of the papers in the levels of the developed framework

Modularization takes place on the data structure-based and software code-based modularization level (levels 3 and 4), but the reference to the actual business logic is mostly missing. On the first two levels, it is about requirements and the realization in the respective business logic - there are hardly any objects of modularization in use in science. Especially in this context, the domain reference is absent, and the initial established hypothesis established can be verified. Domain reference and the consideration of requirements or functions of business logic are not considered. However, this domain-specific perspective is necessary to form modules considering the business logic. Thus, the research questions can be answered. Predominant modularization approaches take place, for the most part, on the technical-focused levels of software modularization. This means that mainly software development components are considered that have no connection to business logic. The reference to the application domain could not be identified. This shows the research gap in business-focused modularization.

5. Conclusion and Outlook

In theory, modular IT landscapes and the modular information systems they require have many advantages, such as rapid adaptability and transparent interfaces, while at the same time ensuring comparatively low costs. However, implementing holistic, modular IT landscapes has not yet been implemented in practice. Our literature analysis shows that there is a lack of scientific foundations for software modularization within the higher level of software development or the development of IT landscapes. Based on systematic literature research, objects of software modularization were examined in existing scientific approaches, and a framework for holistic software modularization was derived from this. Types of software modularization can be differentiated according to their weighting between business focus and technical focus. The main business focus is the modularization type of software environmental-based modularization followed by software functional-based modularization. The types of data structured-based and source code-based modularization have a technical focus. Modularization on the levels of software environmental-based or functional-based modularization is only considered by a minority of authors. This lack of modularization approaches at these levels shows the need for future research. For a holistic modularization of software and the implementation of modular IT landscapes, modularization approaches are needed at these levels of software development. Due to the high relevance of business logic within these levels, a generic view of modularization is insufficient. It requires the consideration of business for the respective domain-specific application areas. The resulting modularization approaches on the levels of software environmental-based and software functional-based modularization are building blocks for future-proof IT landscapes.

Acknowledgments

The underlying research project Serial Production of Electrolyzers in the Gigawatt Range (SEGIWA) is funded by the German Federal Ministry of Education and Research (BMBF) as part of the joint project H2Giga – funding code: 03HY121K.; Funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany´s Excellence Strategy – EXC-2023 Internet of Production – 390621612

References

[1] Bischoff, J., Taphorn, C., Wolter, D., Braun, N., Fellbaum, M., Goloverov, A., Ludwig, S., Hegmanns, T., Prasse, C., Henke, M., Hompel, M. ten, Döbbeler, F., Fuss, E., Kirsch, C., Mättig, B., Braun, S., Guth, M., Kaspers, M., Scheffler, D., 2015. Erschließen der Potenziale der Anwendung von ‚Industrie 4.0‘ im Mittelstand: Studie im Auftrag des Bundesministeriums für Wirtschaft und Energie (BMWi), 401 pp.

[2] 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.

[3] Hanschke, I., 2010. Strategic IT Management. Springer Berlin Heidelberg, Berlin, Heidelberg.

[4] Ditsche, J., Rohrhirsch, D., Grunow, S., Fritze, R., 2022. The digital dilemma: Why companies struggle to master digital transformation, 16 pp.

[5] Schneider, S., Wollersheim, J., Krcmar, H., Sunyaev, A., 2018. How do Requirements Evolve over Time? A Case Study Investigating the Role of Context and Experiences in the Evolution of Enterprise Software Requirements. Journal of Information Technology 33 (2), 151–170.

[6] Gronau N., 2019. Trend im ERP-Markt 2019: ERP Technologie. https://erp-management.de/themen/erp-technologie/artikel/trends-im-erp-markt-2019/. Accessed 4 August 2023.

[7] Böhmann, T., 2004. Modularisierung von IT-Dienstleistungen: Eine Methode für das Service Engineering. Deutscher Universitätsverlag, Wiesbaden, 317 pp.

[8] Kletti, J. (Ed.), 2015. MES - Manufacturing Execution System: Moderne Informationstechnologie unterstützt die Wertschöpfung, 2. Auflage ed. Springer Vieweg, Berlin, Heidelberg, 288 pp.

[9] Rizni, M.I., Poravi, G., 2018. Best of Breed ERP: A Dashboard for Strategic Decision Makers. International Conference of Intelligent Systems, Modelling and Simulation 8, 58–61.

[10] Hanschke, I., 2010. Strategic IT Management. Springer Berlin Heidelberg, Berlin, Heidelberg, 348 pp.

[11] Newman, S., 2015. Building Microservices: Designing Fine-Grained Systems. O'Reilly Media, Inc.

[12] Balzert, H., 2009. Lehrbuch der Softwaretechnik: Basiskonzepte und Requirements Engineering, 3. Auflage ed. Spektrum Akademischer Verlag, Heidelberg, 624 pp.

[13] Brocke, J. Vom, Cleven, A., Niehaves, B., Plattfaut, R., Riemer, K., Simons, A., 2009. Reconstructing the Giant: On the Importance of Rigour in Documenting the Literature Search Process, in: Information systems in a globalising world. Challenges, ethics and practices. 17th European Conference on Information Systems (ECIS) 2009, Verona. 08.-10.06.2009, pp. 2206–2217.

[14] Cooper, H.M., 1988. Organizing Knowledge Syntheses: A Taxonomy of Literature Reviews. Knowledge in Society 1 (104), 104–126.

[15] Parnas, D.L., 1972. On the criteria to be used in decomposing systems into modules. Communications of the ACM 15 (12), 1053–1058.

[16] Yourdon, E., Constantine, L.L., 1979. Structured Design: Fundamentals of a Discipline of Computer Program and Systems Design. Prentice-Hall, River, NJ, United States, 473 pp.

[17] 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), 332-336.

[18] Booth, A., 2006. ‘‘Brimful of STARLITE’’: toward standards for reporting literature searches. Journal of the Medical Library Association JMLA 4 (94), 421–430.

[19] Dröschel, W., Wiemers, M., 1999. Das V-Modell 97: Der Standard für die Entwicklung von IT-Systemen mit Anleitung für den Praxiseinsatz. De Gruyter Oldenbourg, München, 696 pp.

[20] Gräßler, I., Oleff, C., 2022. Systems engineering: Verstehen und industriell umsetzen. Springer Vieweg, Berlin, Heidelberg, 235 pp.

[21] Rausch, A., Broy, M., 2008. Die V-Modell XT Grundlagen, in: Höhn, R., Höppner, S. (Eds.), Das V-Modell XT. Anwendungen, Werkzeuge, Standards. Springer, Berlin, Heidelberg, New York, pp. 1–28.

[22] Naseem, R., Deris, M.B.M., Maqbool, O., 2014. Software modularization using Combination of Multiple Clustering, in: 17th IEEE International Multi Topic Conference 2014, Karachi, Pakistan. 08.12.2014 - 10.12.2014. IEEE, pp. 277–281.

[23] Berta, P., Vranic, V., 2019. Synergy of Organizational Patterns and Aspect-Oriented Programming, in: 15th International Scientific Conference on Informatics, Poprad, Slovakia. 20-22 November 2019. IEEE, pp. 439–444.

[24] Petersen, K., Wohlin, C., 2009. Context in industrial software engineering research, in: 3rd International Symposium on Empirical Software Engineering and Measurement (ESEM), Lake Buena Vista, FL, USA. 15.10.2009 - 16.10.2009. IEEE, pp. 401–404.

[25] Schach, S.R., 2011. Object-oriented and classical software engineering, 8th ed. ed. McGraw-Hill, New York, 667 pp.

[26] Seo, Y.-S., Huh, J.-H., 2022. GUI-based software modularization through module clustering in edge computing based IoT environments. J Ambient Intell Human Comput 13 (3), 1625–1639.

[27] Tabrizi, A.H.F., Izadkhah, H., 2019. Software Modularization by Combining Genetic and Hierarchical Algorithms, in: 5th Conference on Knowledge Based Engineering and Innovation (KBEI), Tehran, Iran. 28.02.19 - 01.03.19. IEEE, pp. 454–459.

[28] Benbasat, I., Zmud, R.W., 2003. The Identity Crisis within the Is Discipline: Defining and Communicating the Discipline's Core Properties. MIS Quarterly 27 (2), 183–194.

[29] Riesco, A., Zhang, M. (Eds.), 2022. Formal Methods and Software Engineering, 1st ed. 2022 ed. Springer International Publishing; Imprint Springer, Cham, 440 pp.

[30] Gonçalves, N., Faustino, D., Silva, A.R., Portela, M., 2021. Monolith Modularization Towards Microservices: Refactoring and Performance Trade-Offs, in: 18th International Conference on Software Architecture Compansion (ICSA-C), Stuttgart, Germany. 22-26 March 2021. IEEE, pp. 54–61.

[31] Paixao, M., Harman, M., Zhang, Y., 2015. Multi-objective Module Clustering for Kate, in: Search-Based Software Engineering. 7th International Symposium, SSBSE, Bergamo, Italy. 5-7 September, 2015. Springer International Publishing, Cham, pp. 282–288.

[32] Jiaze, S., Xu, Y., Wang, S., 2018. PSO with Reverse Edge for Multi-Objective Software Module Clustering. International Journal of Performability Engineering 14 (10), 2423–2431.

Biography

Sebastian Junglas (*1991) has been working at the Institute for Industrial Management (FIR) at the RWTH Aachen University since 2020, first as a project manager and since 2022 as group lead production control. He studied mechanical engineering and management at the RWTH Aachen University and Production Management at the Technical University Wroclaw, Poland. In his research, he focuses on the modularization of IT landscapes, especially in the area of Production-IT.

Martin Perau (*1996) studied production engineering and management, business, and economics at the RWTH Aachen University and in Finland at the Aalto University in Helsinki. He is a research assistant at the Institute for Industrial Management (FIR) at RWTH Aachen University in the Department of Production Management since 2022. His research focuses on IT landscapes and information systems and their potential to support sustainable and circular production processes.

Dino Hardjosuwito (*1988) has been working at the Institute for Industrial Management (FIR) at the RWTH Aachen University since 2020, first as a project manager and since 2021 as a group lead production planning. He studied mechanical engineering as well as production engineering at the RWTH Aachen University and also studied at Carnegie Mellon University in Pittsburgh, USA, and ETH Zurich in Switzerland. In his research, he focuses on the modularization of IT-landscapes especially in the area of business process management.

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.

Prof. Dr.-Ing. Wolfgang Boos, MBA (*1975) studied mechanical engineering at RWTH Aachen University after training as a tool mechanic in the field of stamping and forming technology. Following his studies, he completed his doctorate at the Machine Tool Laboratory (WZL) with distinction and became the managing senior engineer of the Chair of Production Systems at the WZL. Since 2023 he is the managing director of the Institute for Industrial Management (FIR) at the RWTH Aachen University.

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.

5th Conference on Production Systems and Logistics

Development Of An Adaptive Augmented Reality Qualification System For Manual Assembly And Maintenance

M. König[1], L. Merkel[2], B. Arndt[1], C. Berger[1], M. Heller[3], M. Eisenbarth[4], J. Schilp[5]

[1]Fraunhofer Research Institution for Casting, Composite and Processing Technology IGCV, Augsburg, Germany
[2]INOYAD GmbH, Augsburg, Germany
[3]ZF Airbag Germany, Aschau am Inn, Germany
[4]ZF Group, Alfdorf, Germany
[5]University of Augsburg UNA, Augsburg, Germany

Abstract

The manufacturing industry is facing various challenges today - globalization, fast-moving sales markets, short product life cycles, individualization, mass production and diversity of variants are trends that will continue or even increase in the future. Speed and flexibility in production are thus becoming important success factors for companies. To meet the demands of the market, there is a growing necessity to deploy employees flexibly within the production process. This increases the need for additional qualification of workers. By overlaying reality with virtual cues, Head-mounted displays (HMD) can present information in a situation-specific and location-linked manner. Data glasses also offer a high and convertible degree of support through the possibility of providing different media forms while both hands are available at the same time. Augmented Reality (AR) guidance systems are already available on the market and are suitable as permanent assistance systems, but only to a limited extent for qualification aspects. An industrially applicable qualification software that collects expert knowledge from skilled workers and then makes it available to new or inexperienced employees in an adaptive way that promotes learning is currently not available. This paper therefore presents the development of the software AQUA, which taps internal expertise with low effort and creates training courses that convey learning content to learners without over- or under-challenging them.

Keywords

Augmented reality; Adaptive manufacturing; Knowledge management; Assembly; Maintenance

1. Introduction

While automatic and semi-automatic production are particularly suitable for the manufacturing of only a few variants and high quantities [1], manual assembly offers the flexibility for producing smaller quantities with a high diversity [2]. Currently, the qualification for assembly or maintenance tasks often takes place by means of the "on the job" measure "demonstrate - imitate", in which already experienced employees train new workers directly in line. Since the learning process takes place during series production, this can lead to overstressing due to time pressure [3]. In order to meet cycle times, there are frequent interruptions during the learning processes. The qualification can therefore have gaps [4] and furthermore the quality and duration of the learning processes can vary greatly between employees [3]. In addition to demonstration and imitation, classic media such as paper instructions support qualification processes. However, these make it difficult to transfer theory into practice [2]. Augmented reality-based qualification systems are promising as cognitive transfer between instruction and execution can be minimized [5]. HMD are becoming more common in

DOI: https://doi.org/10.15488/15312
ISSN: 2701-6277

industry, as well as in fields such as medicine, military, and sports, as both hands remain free [2]. Various studies have already demonstrated that the execution of assembly processes is faster with the help of AR guidance systems and lead to a lower error rate [6] [7] [8] [9]. These guidance systems are already available on the market and are suitable as permanent assistance systems, but only to a limited extent for qualification as they guide with the same support through assembly and workers thus remain dependent on the system. For this reason, the distinction between cognitive guidance/assistance and training/qualification systems is important [10]. In particular, given the different display capabilities of HMD, there is a lack of scientific guidelines on how a universal user interface should look like. Furthermore, existing training systems for HMD lack scalability making economical use impossible so far [2]. The goal of the project "Adaptive Augmented Reality based qualification – AQUA" is to develop and evaluate an adaptive AR qualification system for HMD to train employees in manual assembly and for maintenance tasks. The software should optimally support learners taking into account their learning progress and thus differentiate itself from AR guidance systems. In addition, the system adapts to diverse assembly processes by integrating new work instructions and learning content with as little effort as possible. In this way, the initial creation effort for AR trainings reduces in particular to ensure acceptance. In addition, the training creation should/must be possible for practical authors (e.g. supervisors, technicians) without programming knowledge. The AQUA software taps expert knowledge from experienced practitioners, bundles this knowledge and then prepares it for inexperienced employees in order to support them in learning in the best possible way.

2. Augmented Reality based qualification systems

The contemporary technological landscape at the intersection of Augmented Reality (AR) and qualification within the realm of production represents a dynamic field marked by substantial advancements [11]. Koteleva et al. [12] provided an exploration of AR's utility in skill acquisition and training by showing an example of combining AR with the maintenance of oil pumps. Their work highlighted AR's ability to create training environments that improve knowledge retention and hands-on experience. Werrlich et al. [13] developed an AR training system for HMD in which the number of AR functions reduces as learning progresses. The authors investigated the advantages and disadvantages of HMD-based training compared to training conducted using trainers. They showed ten percent fewer picking errors and five percent fewer assembly sequence errors for the HMD group compared to the human trained group. However, the HMD group required 60 percent more time for training. The authors suggested that the HMD subjects first had to familiarize themselves with the interaction modalities and functions of the new system. In 2020, Werrlich confirmed his assumption [14]. These works collectively spotlight AR's transformative potential in the context of AR-based qualification systems. However, they do not highlight the challenges of seamlessly integrating AR into production workflows and the crucial factor of user acceptance. While AR technology holds promise for industrial training, solving practical issues also becomes essential for its successful adoption.A recent trend is the fusion of AR with Artificial Intelligence (AI) and Machine Learning (ML) techniques [15]. AI-driven AR might personalize training experiences, adapt content dynamically based on individual performance, and even predict skill gaps proactively. This fusion promises to revolutionize workforce qualification by tailoring training regimens precisely to the needs and capabilities of each worker. However, the literature does not yet show any existing prototypes in this area, but only talks about the possibilities of this fusion. The AQUA project aims to change this. Another aspect that has received limited attention in existing literature is the incorporation of experiential knowledge from subject-matter experts. The infusion of ML into AR systems may optimize content delivery in the future, but it often falls short in capturing the nuanced insights and practical wisdom that experienced trainers and experts bring to the training process. The expertise of human trainers, who understand the contextual intricacies of production processes, is crucial in not only conveying information but also in imparting tacit knowledge that goes beyond what can be explicitly programmed into AI algorithms. This human element, where trainers impart their wisdom and adapt training on the fly based on the unique challenges of each learner, remains an area that warrants further exploration.

3. Methodology

The implementation of expert knowledge in adaptive learning environments play an overriding role for AQUA. Paramythis & Loidl-Reisinger [16] provide an appropriate statement here. "A learning environment is considered adaptive if it is able to observe/monitor the activities of its users, interpret them based on specific knowledge models, derive user preferences and needs from the interpreted activities, map them appropriately in associated models, and finally, based on the existing knowledge and the subject matter at hand, dynamically facilitate the learning process". The research questions arise from this definition:

- How can industrial companies implement an adaptive expert knowledge and AR-based qualification system into their structure?
- What does an AR-based qualification system look like and what data needs to be collected during the learning process to ensure adaptivity?
- How can the system interpret/learn from the collected data (ML) to improve the individual's learning?
- Does the system improve learning over traditional qualification methods and is it monetarily profitable?

The initial phase involved conducting a requirement analysis between application partners and researchers to establish shared objectives and fundamental principles for AQUA. Table 1 shows the results:

Table 1: AQUA requirement analysis

common goals	**core principles**	**in scope**	**out of scope**
▪ Increasing flexibility of the workforce ▪ Relief for trainers ▪ Enable independent maintenance of skills ▪ Up-to-date training documentation ▪ Standardization of training content ▪ Overcoming language barriers ▪ Avoidance of over- and under-challenging	▪ Simplicity and usability of software are more important than functional scope ▪ Implementation of expert knowledge ▪ Fun in learning and creating trainings	▪ Viewing AR-trainings ▪ Creation and modification of training instructions on HMD ▪ Exclusive use for offline training ▪ Preventive and reactive training ▪ Training of defined linear manual processes	▪ Hardware development ▪ Training on moving objects ▪ Simultaneous training of several persons ▪ Connection to production IT ▪ Quality inspection through data glasses

3.1 Implementation of AQUA into companies structure

A method to use especially at the beginning of software projects is the sketching of case diagrams – they are suitable for modelling the system structure. Use case diagrams show relations between actuators, main use cases and system boundaries [17]. Figure 1 shows the developed structure for AQUA and answers the first research question.

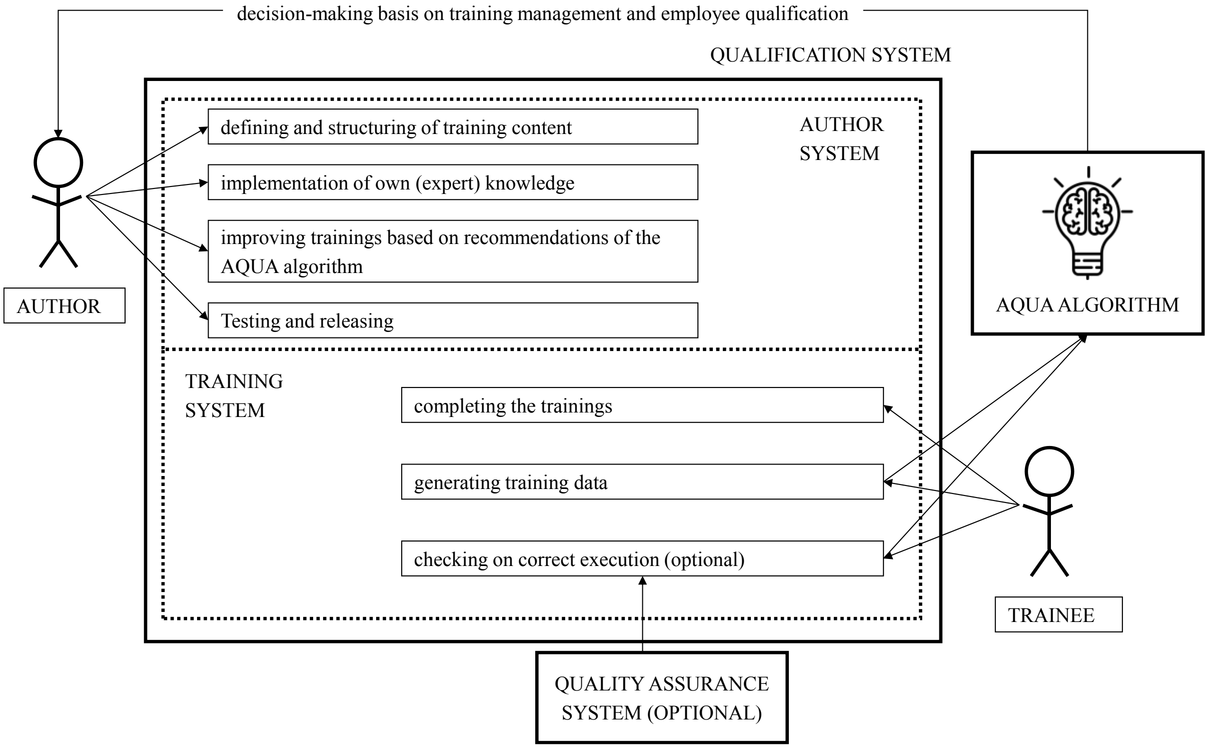


Figure 1: AQUA qualification method

Authors and trainees are actors. The use cases for authors are defining and structuring of training content, implementation of own knowledge, improving trainings based on the AQUA algorithm and testing/releasing. The use cases for trainees correspond to the execution of the training. The training system has an optional input for external quality assurance systems. Since the system must ensure general applicability, we refrain from permanently integrating a special testing system for one specific case. After knowing how to implement an adaptive AR-based qualification system into a manufacturing companies structure (Figure 1), the next research question is what an AR-based qualification system should look like (Figure 2). Therefore now follows the development of the AQUA User interface.

3.2 User Interface

The Cognitive Load Theory describes a branch of learning theory that investigates the functioning of the human memory system and thus derives guidelines for the design of teaching materials in order to effectively use and expand the information in the long-term memory. In the learning of new facts, however, the short-term memory plays an essential role, as it enables and influences the absorption of information into the long-term memory [18]. Hattie & Yates [19] describe, that especially the use of different media is conducive to efficient learning. Mayer [20] also supports this hypothesis. The authors further advocate active learning. According to their findings, passive observation is particularly ineffective when the learning content includes movement sequences. Furthermore, passivity carries the risk of distraction as well as purely superficial learning. For AQUA, the User Centered Design method according to DIN EN ISO 9241-210 forms the basis for designing the training and authoring area. The method goes through several iterations and creates various designs. The application partners evaluate the designs with the researchers by means of qualitative and semi structured interviews. Figure 2 shows exemplarily the result for the AQUA training area. The media forms provided are text, safety instructions, additional (textual) information, images, videos and position markers. The trainee can freely choose between these media forms in his training and combine them as desired for his particular work task. In addition, the trainer/author is also free to choose which media forms he or she makes available to the learner for the respective work tasks.

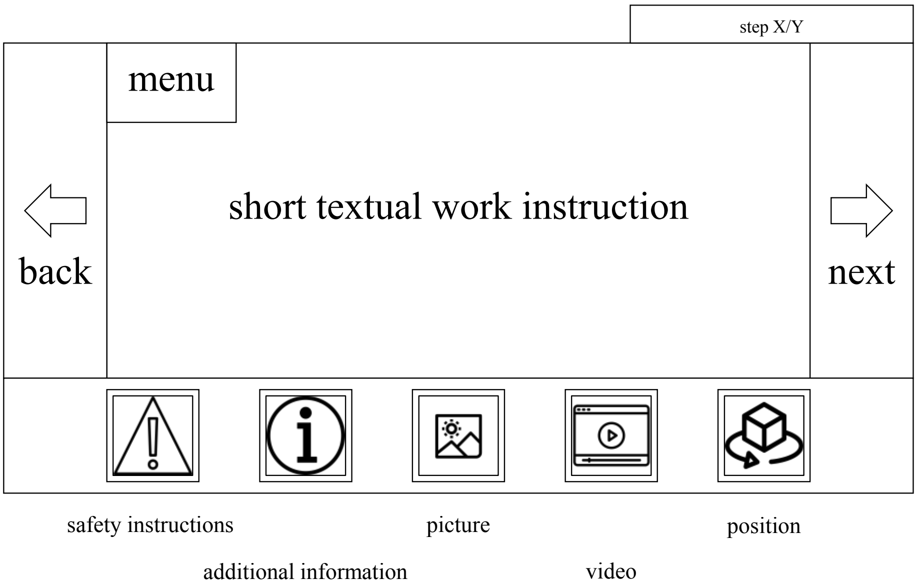


Figure 2: AQUA user interface

A central finding in the AQUA project is that authors only disclose their own experiential knowledge if they accept the system and enjoy using it. Therefore, the author area is deliberately very simple and accessible. Authors work exclusively with HMD - they can record images and videos directly, set the position markers and implement texts, for example, by voice input. In addition, the author creates and saves trainings on the data glasses directly at the assembly/maintenance object and edits/improves them if necessary without additional software or computer. The entire AQUA software can be controlled using hand gestures and speech. AQUA provides ten basic rules for authors to create adaptive AR-training instructions. The rules are, among others, taken from guidelines for effective communication from the military [19] [21]:

- Use the 1st and 2nd person (I/you)
- Use active instead of passive
- Put important content in front
- Use dynamic verbs instead of nominal
- Avoid adjectives if possible
- Be concise, but not too concise - do not use superfluous words
- Do not use foreign words or abbreviations if possible
- Record short videos (max. 20 sec) and short trainings (max. 15 min)
- Point out possible dangers and always share your tips and tricks
- Make every single media form as self-explanatory as possible

The HMD for AQUA is Microsoft HoloLens 2 (HL2). Fraunhofer IGCV chose HL2 after a market research as a suitable. It offers many different interaction options and can provide the necessary media forms. Hand tracking, which is possible on HL2, makes interactions feel very real, ensuring a high level of user-friendliness. The 3D development platform is Unity3D. The programming language used is C#. In order to make the various positioning objects appear in the right places, the software module Vuforia Image Targets supports the project. Using this library, a QR code acts as coordinate origin for positioning the individual elements. The Mixed Reality Toolkit provides various functions for AQUA to interact with 3D elements in a virtual space. Figure 4 shows a developer at the company LUDO FACT with digitally inserted user interface of the AQUA software. One of the Use Cases for LUDO FACT in the project is the debugging of their robotic system. The robot places and sorts game boxes on various conveyor belts. Employees then place the game pieces, instructions, dice, etc. on the belts. The robot unit can be in various states of malfunction. LUDO FACT implemented a wide variety of suppression measures for the respective fault scenarios in AQUA. The person responsible for the plant recorded the AQUA app as an expert author. Since then, inexperienced employees have been able to get the system up and running again independently with AQUA in the event of a malfunction.

Figure 3 AQUA practical example at the company LUDO FACT

3.3 Training data collection

While an employee is training, he generates training data. This data includes individual assembly times, data on the media forms used and, if applicable, data from the optional quality assurance system. The required support levels derive from the selected media forms. In order to draw conclusions from qualitative media form data to quantitative support level data, 41 employees of the applying companies in the AQUA project rated the support level of the available media forms with regard to assembly and maintenance from 1 (very low support) to 5 (very high support). Table 1 shows the result of the survey.

Table 2: AQUA derivation degree of support

	short instruction	long text	image (photo)	video	AR position
respondent 1	1	2	3	4	1
…	…	…	…	…	…
respondent 40	2	3	1	4	3
respondent 41	2	2	2	5	3
total	82	97	77	180	113
average	**2,00**	**2,37**	**1,88**	**4,39**	**2,76**

The average values of the individual media forms form the basis for calculating the level of support per work step in the further course of the project. If a trainee uses several forms of media in one assembly step, the values add up accordingly. The performed trainings generate the following data for the AQUA algorithm (Figure 4):

- assembly function [22], complexity [23] and competence according to REFA [24]
- execution durations
- media form usage
- applied degree of support
- quality (optional)
- additional human help (e.g. by trainer) necessary

Figure 4 illustrates the recording of the training data graphically:

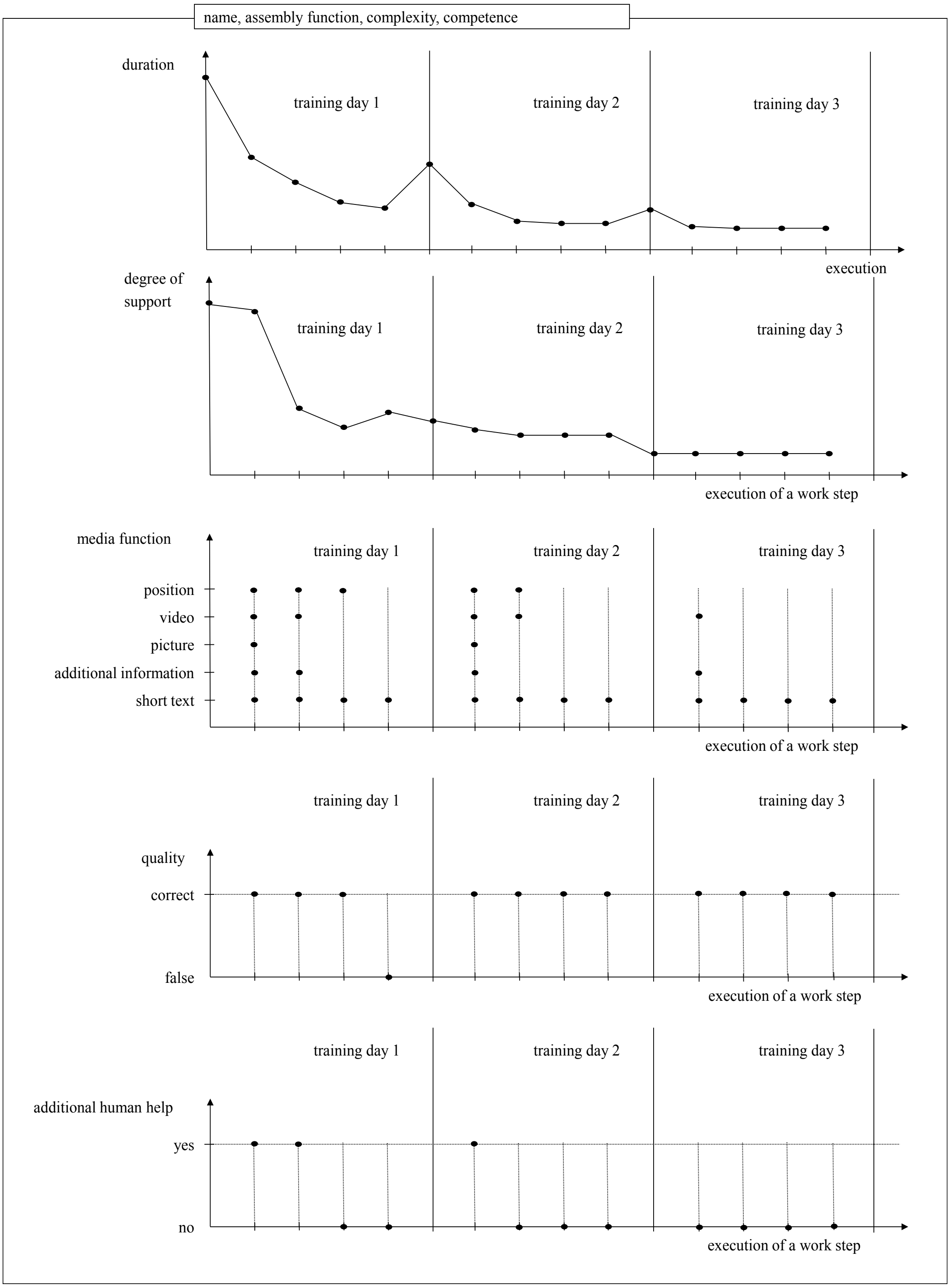


Figure 4: AQUA training data

4. Conclusion

In conclusion, this paper presents AQUA, a software designed to bridge the gap between experienced production workers and less-experienced beginners through the innovative use of augmented reality. AQUA not only captures the valuable expertise of seasoned employees but also delivers it to novices without overwhelming or underutilizing them. This approach has the potential to revolutionize workforce training and knowledge transfer in manufacturing settings. The development of AQUA marks a significant milestone, with implementation and testing at three partnering companies. Initial feedback from these trials has been promising. The complexity of the systems integration, for example, is very low. Installing the AQUA app on the data glasses takes about five minutes. Authors can create trainings offline and, if required, download them from the HMD to company computers via Microsoft Device Portal. The training of an expert author by the developers takes about 30 minutes. Once an author has created and edited a few training sessions with the help of a researcher, he or she can use both the data glasses and the app independently and generate new training sessions very quickly.The AQUA project is currently conducting a long-term study of the companies using the system. The continuously emerging data train the AQUA algorithm so that it can draw conclusions about the quality of the created trainings as well as the learning success of the test persons. In addition, after collecting enough training data, AQUA draws conclusions between assembly functions and media forms and can make recommendations based on it when creating future instructions. The further course of the project includes a comparison of learning success between the AQUA system and comparable training methods (video or oral explanations). Furthermore, the project aims to evaluate the economic viability of AQUA by conducting a comprehensive cost-benefit analysis. This assessment will not only consider the initial investment required for implementation but also the long-term advantages in terms of reduced training time, increased productivity, and enhanced knowledge retention.

Acknowledgements

This publication is part of the research project AQUA (Augmented Reality based qualification AZ-1406-19) funded by the Bavarian Research Foundation BFS. The project consortium consists of the technology partners Fraunhofer IGCV and INOYAD as well as the applying companies AUDI, LUDO FACT and ZF.

References

[1] Lotter, B.; Wiendahl, H.-P., 2012. Montage in der industriellen Produktion, p. 1-8.

[2] Werrlich, S., 2020. Gestaltungskonzept für Augmented Reality unterstütztes Training an manuellen Montagearbeitsplätzen, p. 1-17.

[3] Buck, H.; Witzgall, E., 2012. Mitarbeiterqualifizierung in der Montage, in: Lotter, B.; Wiendahl, H.-P., 2013 Montage in der industriellen Produktion, p. 397–417.

[4] Gerst, D.; Kranz, A.; Möhwald, H.; Weig, A., 2003. Qualifizierung von Produktionspersonal in flexiblen Montagesystemen. Ergebnisse des Verbundprojekts „Hochflexible Produktionsendstufen PEflex". in: wt Werkstattstechnik online 93 (5), p. 404–412.

[5] Eder, M.; Hulla, M.; Mast, F.; Ramsauer, C., 2020. On the application of Augmented Reality in a learning factory working environment. in: Procedia Manufacturing 45, p. 7–12.

[6] Hořejší, P., 2015. Augmented Reality System for Virtual Training of Parts Assembly, p. 699 706.

[7] Rios, H.; Hincapié, M.; Caponio, A.; Mercado, E.; Mendívil, E. G., 2011. Augmented Reality: An Advantageous Option for Complex Training and Maintenance Operations in Aeronautic Related Processes, in: Shumaker, R., 2011. Virtual and mixed reality - new trends, p. 87-96.

[8] Loch, F.; Quint, F.; Brishtel, J., 2016. Comparing Video and Augmented Reality Assistance in Manual Assembly, in: 2016 12th International Conference on Intelligent Environments IEEE, p. 147–150.

[9] König, M.; Stadlmaier, M.; Rusch, T., 2019. MA2RA - Manual Assembly Augmented Reality Assistant. in: 2019 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM Macao), p. 501-505.

[10] Webel, S.; Bockholt, U.; Engelke, T.; Peveri, M.; Olbrich, M.; Preusche, C., 2011. Augmented Reality Training for Assembly and Maintenance Skills. in: BIO Web of Conferences, p. 97.

[11] Eleonora B.; Vignali, G., 2019 Augmented reality technology in the manufacturing industry: A review of the last decade, IISE Transactions, p 284-310.

[12] Koteleva, N.; Buslaevb, G.; Valneva, V.; Kunshin, A., 2020. Augmented Reality System and Maintenance of Oil Pumps. in: IJE Transactions B: Applications Vol. 33, No. 8, p 1620-1628.

[13] Werrlich, S.; Lorber, C.; Nguyen, P.; Yanez, C.; Notni, G., 2018. Assembly Training: Comparing the Effects of Head-Mounted Displays and Face-to-Face Training. In: Jessie Y.C. Chen und Gino Fragomeni (Hg.): Virtual, Augmented and Mixed Reality: Interaction, Navigation, Visualization, Embodiment, and Simulation, Bd. 10909. Cham: Springer International Publishing (Lecture Notes in Computer Science), p. 462–476.

[14] Werrlich, S., 2020: Gestaltungskonzept für Augmented Reality unterstütztes Training an manuellen Montagearbeitsplätzen (Dissertation). Hg. v. TU Ilmenau. Ilmenau.

[15] Sahija, D.,2021.: Critical review of machine learning integration with augmented reality for discrete manufacturing, in: International Journal For Innovative Research In Multidisciplinary Field Issn: 2455-0620.

[16] Paramythis, A.; Loidl-Reisinger, S., 2004. Adaptive Learning Environments and e-Learning Standards, p. 1-4.

[17] Kleuker, S., 2018. Grundkurs Software-Engineering mit UML, p. 64.

[18] Sweller, J., 2010. Cognitive Load Theory: Recent Theoretical Advances. in: Plass, J., Cognitive load theory. p. 29-47.

[19] Hattie, J.; Yates, G. C., 2014. Visible learning and the science of how we learn, p. 113-118.

[20] Mayer, R. E., 2009. Multimedia learning.

[21] Bolin, R., 1964. Effective Army Writing, p. 14-25.

[22] Lotter, B., 2006. Montage in der industriellen Produktion. Ein Handbuch für die Praxis, p. 1-9.

[23] Samy, S.N., ElMaraghy, H., 2010. A model for measuring products assembly complexity, in: International Journal of Computer Integrated Manufacturing 23, p. 1015–1027.

[24] REFA, 1989. Arbeitspädagogik. REFA - Verband für Arbeitsstudien und Betriebsorganisation, p.133-149.

Biography

Maximilian König (*1990) studied industrial engineering at the University of Augsburg. Since 2018, he has been working as a research associate in the field of cognitive assistance systems at Fraunhofer IGCV. He leads various research projects and is doing a doctorate at the University of Augsburg.

Dr.-Ing. Lukas Merkel (*1990) received his doctorate from the Technical University of Munich in the field of cognitive assistance systems. He worked for Fraunhofer IGCV as research associate from 2016 to 2020. Since 2020, he is managing partner of INOYAD GmbH in Augsburg.

Benedikt Arndt (*1999) is currently studying business informatics at the University of Augsburg. He works at Fraunhofer IGCV as an auxiliary scientist.

Christoph Berger (*1982) is head of a department for production processes and automation at Fraunhofer IGCV. He was managing director of the Mittelstand 4.0 Competence Center in Augsburg from 2016 to 2019.

Maik Heller (*1975) has been Production Manager at ZF's plant in Aschau am Inn since 2017. He is responsible for the production of inflators, injection mouldings, igniters and spare parts. Before that, he was 30 years in leading positions at Boge, NXP, Phillips and VW.

Dr.-Ing. Michael Eisenbarth (*1970), Senior Vice President Operations, is responsible for global production and supply chain management withing the Passive Safety Division at ZF Group since 2020. The division is developing and producing airbags, inflators, seatbelts and steering wheels in more than 30 plants globally. Before that, he held various leading management positions at Delphi, Continental and Vitesco Technologies for over 20 years in the automotive business. In addition to other honorary positions, he is also member of the advisory board of the German Assembly Congress.

Prof. Dr.-Ing. Johannes Schilp (*1976) has held the Chair of Production Informatics at the University of Augsburg since 2015. He is also head of a main department at Fraunhofer IGCV, head of the Innovation Advisory Board of the Swabian Chamber of Industry and Commerce, and, among other honorary activities, an advisory board member of the German Assembly Congress.

5th Conference on Production Systems and Logistics

Modelling The Influence Of Production Planning And Production Scheduling On Business Performance In The Manufacturing Industry Of South Africa

Elizabeth Chinomona[1], Mamonare Minky Kgaogelo Mogano [2]

[1] *Department Of Logisticsand Supply Chain. Vaal Univetsity Of Technology, P Bag X021, Vanderbijlpark 1900, South Africa*

[2] *Department Of Logisticsand Supply Chain. Vaal Univetsity Of Technology, P Bag X021, Vanderbijlpark 1900, South Africa*

Abstract

It is apparent that for manufacturing companies to succeed, it is crucial to consider the factors that will contribute positively to the performance of the business. The issues related to production planning and production scheduling on business performance have been neglected. Product planning and production scheduling be adopted as factors manufacturing companies could consider improving their business performance. There has been little research done to prove that production planning and production scheduling can lead to improving the overall business performance of the manufacturing industry. Therefore, this study seeks to fill this lacuna by investigating the influence of production planning and production scheduling on business performance in manufacturing industries. A quantitative approach was adopted for this study, and a questionnaire was distributed physically and electronically. Three hundred and six (306) respondents participated in the study. Data obtained were analysed using SPSS 28.0 and AMOS 28.0. The results of the study proved that production planning and production scheduling have a positive impact on business performance. Production planning and scheduling have proved to deliver a competitive advantage and improved customer satisfaction in the manufacturing industry.

Keywords

Production planning; Production scheduling; Business performance; Manufacturing industry

1. Introduction

The issues related to production planning have been neglected. Production planning is equally important as it is the core function in the manufacturing environment. Product scheduling and first to market can be adopted as factors manufacturing companies could consider to improve their business performance [1]. Arguably, although little research has been done to prove that production scheduling, and first to market influence the performance of a business, little has been done to demonstrate that production planning, scheduling and first to market can be adopted by a manufacturing company as strategic risk management techniques to oversee operations and the advantages that come with it. There has been little research done to prove the benefits of production planning, production scheduling and first to market for the organisation, as well as how to improve the overall business performance. Therefore, this study seeks to fill this lacuna by investigating the influence of production planning, production scheduling and first to market on business performance in manufacturing industries. It has been observed that problems with some manufacturing industries in the country seem to be a lack of skills set to carry out activities such as production planning. There seems to be a lack of understanding of what production planning is with regards to how to use it to the advantage of the organisation and how to use this strategy to counter future production issues which may occur, such as late deliveries and poor-quality products.

Conceptual framework and hypotheses development

This model consists of two predictor variables which are production planning, production scheduling and business performance as the outcome variable.

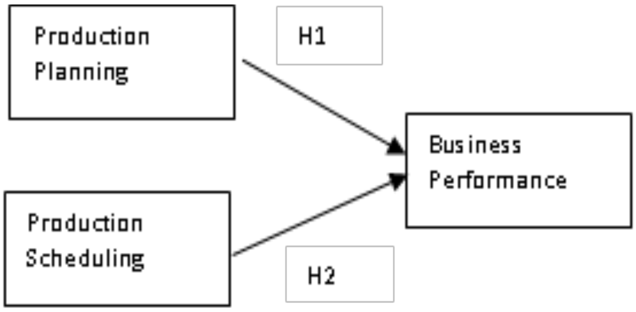


Figure 1: Conceptual framework

H1: Production planning positively influences business performance within the manufacturing industry.

H2: There is a positive relationship between production scheduling and business performance.

2. Literature review

The theory applies to this study, and the explanation of constructs is done under the literature review.

2.1 Production theory

Production theory was introduced by [2]. Production theory is the study of production or the economic process of converting inputs into outputs. The progressive refinement during the years in the measurement of the volume of physical production in manufacturing companies suggests the possibility of the following: firstly, to measure the changes in the amount of labour and capital, which have been used to turn out this volume of goods and secondly, to determine what relationships exist between the three factors of labour, capital and product. It is important to understand that the production theory is at the heart of business operations and discussions regarding economic organisations in manufacturing processes [3]. In 1928, Cob and Douglas developed a neoclassic production function which they referred to as the C-D production. The function was tested empirically by various authors and showed positive results [3]. [4] and [5] argued that, based on the research they had done, the relationship between production planning and business performance is either positive or negative. Production uses resources to create a product or service that is suitable for use, gift-giving in a gift economy or exchange in a market economy [6]. This can include manufacturing, construction, storing, shipping and packaging. The theory of production acts as an economic method used by manufacturing organisations to determine how much of the products should be produced as well as how much of each of the raw materials will be acquired to meet the production requirements.

2.2 Production planning

Production planning correlates with complexities in production. It has subsets that consist of process planning and machinery capacity, delivery lead time and layout [7]. Production planning is a process that links together the performance of functions, such as job size, machine load and requested delivery as one process [8].The main concerns of production planning are to produce default free products and to satisfy customers by delivering jobs on time. The production planning process uses a material requisition plan, along with job size, safety stock and planned lead time [9]. The principles of productive relations that correlate between production factors and products or goods can positively assist with the vital task of production planning if these factors are cleared up from the grounds of production considerations. The main objective of production planning is to draw the gross requirement of the manufacturing facility and transform this into production orders and material purchases through the use of methods such as Economic Order Quantity (EOQ) and Material Requirement Plan (MRP). These methods can determine the expected lead time [10]. The process of production planning identifies activities that need to be performed for the manufacturing plant to efficiently execute the production plan, namely identifying the production programme, selecting the production procedure and identifying the potential productivity of the manufacturing plant, as well as understanding process planning [11].

A manufacturing plant usually produces a variety of products to satisfy a certain demand, depending on the target market. This encourages organisations to determine which product to produce by putting together the production factors at hand. The organisation must decide on the product type as well as the required quantities to make good profits for the established planning period [3]. Poor production planning consequently results in poor business performance within the manufacturing industry [12]. Firm and production strategies must conform to one another and reflect the performance and environment of the firm [13]. Theoretically, manufacturing firms are expected to adopt best practices directly related to production planning. These often include production planning and production scheduling in the environment of demand uncertainty.

2.3 Production scheduling

Production scheduling looks at aligning the allocated job sequence problems, job production size, machine capacity and order size requested. It pertains to establishing the timing of the use of specific resources in a firm [14]. The main difference between production planning and production scheduling is that planning takes the material requisition plan, customer orders and material production into consideration to draw up a production plan that will ensure customers' orders will be ready on time. Production scheduling focuses on implementing the production plan and converting work orders once they have an execution tie period allocated to them [15]. This relates to the overall production scheduling plan for the production process within some given period to give an idea to management as to what quantity of materials and other resources are to be procured and when, so that the total cost of operations of the organisation is kept to the minimum over the period [16]. Scheduling is an important aspect of operations control in both manufacturing and service firms with increased emphasis on output levels and lead time in meeting demand and in satisfying the customer [17]. Production scheduling has been found to influence business performance in manufacturing firms [18]. Production scheduling focuses on executing the production plan and converting work orders once they have an execution tie period allocated to them. Its function is to boost production planning and control for improved performance [19]. Scheduling can be identified as the process of allocating jobs to various machinery while adhering to specific time frames and ensuring control over the movement of products and material components throughout the manufacturing plant. Labour must be coordinated as well at all assembly points for production to take place.

Production scheduling looks at aligning the allocated job sequence problems, job production size, machine capacity and order size requested. It also pertains to establishing the timing of the use of specific resources in a firm [20]. This relates to the overall production scheduling plan for the production process within some given period to give an idea to management as to what quantity of materials and other resources are to be procured and when, so that the total cost of operations of the organisation is kept to the minimum over the period [21]. Scheduling is an important aspect of operations control in both manufacturing and service firms with increased emphasis on output levels, lead time in meeting demand and satisfying the customer [22]. Production scheduling has been found to positively influence business performance in manufacturing firms, which, in turn, means production scheduling is a dimension of production planning and an antecedent of business performance.

2.4 The notion of business performance

If businesses can consistently provide their customers with the desired quality and quantity of the products demanded at an acceptable price, this may assist them in gaining a competitive advantage over their competitors [23]. For a business to be successful over a long period, the business must have an internal foundation and management over its operations for inbound and outbound movement to run smoothly [24]. One of the manager's toughest and most important responsibilities is to evaluate the performance of their business, and this is done through performance appraisal [25]. The selection of a suitable strategy cannot bring the desired results by itself [13]. In particular, the enhancement of the manufactured product quality, a direct response to market demands, the minimal delay on the firm's behalf and, of course, the minimal production cost, have been emphasised [13]. Businesses that want to grow have to adapt to the rapidly changing environment through continuous innovation to develop new products to reach new customers [23]. Customer perceived value is a function of quality and price. It enhances repurchase intention and discourages switching behaviour. Some customers equate value with price, and this is usually the case when goods are perceived to have uniform or homogenous levels of output, the cheapest goods are seen as the most valuable [26]. The role played by the perceived value on business performance directly results in an assessment of whether a seller's price can be reasonably justified and a price paid higher than other customers is likely to be perceived as less fair [27], [28]. Thus, customer perceived value is a dimension of business performance.

It is important to fully understand the competencies of each unit and their strengths, weaknesses, expectations and values to build productive and positive relationships amongst organisations, making relationship building an antecedent of business performance [14]. Collaboration takes place when people from different units work together in cross unit teams on a common task to provide significant help to each other for a better output. This factor also serves as an antecedent of business performance. Collaboration within business units leads to better innovation which happens because people from different areas, business units, divisions, technology centres and sales offices come together to create new ideas through these interactions and go on to develop exciting products.

If businesses can consistently provide their customers with the desired quality and quantity of the products demanded at an acceptable price, this may assist the business in gaining competitive advantage over their competitors [23], [29], [30]. [12] state that one of a manager's toughest and most important responsibilities is to evaluate the performance of their business, and this is done through performance appraisal. The selection of a suitable strategy cannot bring the desired results by itself [31]. Firm and production strategies must conform to one another and reflect the performance and environment of the firm. In the past few years, a vast number of approaches-theories have been developed regarding the improvement of the firm's operational performance. In particular, the enhancement of the manufactured product quality, a direct response to market demands, minimal delay on the firm's behalf and, of course, minimal production cost has been emphasised [32].

3. Methodology

Convenience sampling was used as a sampling technique in this study. Reliability and validity of a measurement is the degree to which the measurement instrument employed has no error, and the approach to assessing reliability includes using Cronbach's alpha coefficient and alternative forms.

Table 1: Accuracy analysis statistics

Research Constructs		Descriptive Statistics		Cronbach's Test		CR	AVE	Factor Loading
		Mean	SD	Item-total	α Value			
Production Planning	PP1	4.662	0.636	0.479	0.767	0.881	0.650	0.761
	PP2			0.702				0.919
	PP3			0.607				0.796
	PP4			0.520				0.738
Production Scheduling	PS1	4.570	0.593	0.459	0.704	0.803	0.513	0.519
	PS2			0.494				0.661
	PS3			0.446				0.770
	PS4			0.570				0.866
Business Performance	BM1	4.492	0.654	0.608	0.846	0.887	0.663	0.802
	BM2			0.757				0.873
	BM3			0.731				0.875
	BM4			0.677				0.824

Significant Level <0.05 *; significant level <0.01 ***; significant level <0.001 **, BP= Business Performance; PP = Production Planning; PS = Production Scheduling

Cronbach's alpha was used in this study to measure the reliability of all constructs; the reliability of the constructs is determined by a higher level of Cronbach's coefficient alpha. Reliability of a construct must be above 0.7 to enhance the internal consistency of the construct. Based on table 1, PP, PS, and BM Cronbach alpha are above the threshold of 0.7 and therefore reliable. The item to the total value observed from table 1 ranges from 0.479 to 0.757 specifically between PP, PS, and BM, which showed valid results and are above the required cut off point of 0.3. A composite reliability index value that is higher than 0.7 proves the adequacy of the internal consistency of the research construct. An analysis of data from table 1 illustrates that all research constructs are above 0.7, which affirms the existence of internal validity of all constructs measured is reliable. The average value extracted (AVE) should be greater than 0.5. Based on data in table 1, all average values extracted range between 0.5 and 0.6 adhere to the required acceptability value, thus all constructs met the required degree of acceptability.

3.1 Discriminant validity

This refers to the extent to which scores from a measure are distinct and do not correlate to other measures. Discriminate validity was measured in this study by observing the correlation matrix as well as the average variance extracted result.

Table 2: Correlation matrix

Research Variable	BP	PP	PS

	BP	**1.000**		
	PP	.681***	**1.000**	
	PS	.429***	.675***	**1.000**

Significant Level <0.05 *; significant level <0.01 ***; significant level <0.001 **, BP= Business Performance; PP = Production Planning; PS = Production Scheduling

As indicated in table 2, there is a positive correlation across all constructs, and they are all below the required level l of 1.0, which proves there is discriminant validity in the measurement scale.

3.2 Hypothesis testing results

Once the reliability and validity of the research constructs and measurement instruments have been proved and confirmed, the researchers tested the hypothesis of the study. Smart PLS software was used to test and verify the relation of the hypothesis.

Table 3: Results of hypothesis testing

Path Coefficients	Hypothesis	Path Coefficient	P value	T-Statistics	Decision
Production Planning -> Business Performance	H1	0.628	***	8.006	Significant and supported
Production Scheduling -> Business Performance	H2	0.989	***	19.910	Significant and supported
Significant Level <0.05 *; significant level <0.01 ***; significant level <0.001 **, BP= Business Performance; PP = Production Planning; PS = Production Scheduling					

Table 3 above focuses on the P value and T-statistics. T-statistics should be above 1.96, and all the above values are above the recommended threshold, which shows a strong and significant relationship between the variables.

4. Discussion of results

The results acquired from testing hypothesis one confirms the correlation between production planning and business performance. The hypothesis proves that there is a significant relationship between production planning and business performance, and the relationship is supported. The results obtained from this study are supported by [6], [9], [34] who regards production planning as a strategic function in the manufacturing process and that it is closely related to business performance. [10] and [35] affirm that production scheduling cannot be successfully executed without the function of production planning. Based on the results obtained, it can be concluded that when organisations align planning and scheduling strategically, it becomes highly likely that they can effectively execute lean manufacturing and boost production.

The results of this study prove that the relationship between production scheduling and business performance is significant and supported (H2). The $p<0.001$ and the path coefficient is $\beta = 0.989$. Furthermore, the t-statistic value is observed at 19.910. This illustrates that production scheduling in the manufacturing organisation influences business performance in a very significant way than production planning. The literature has supported the significance of the scheduling function on business performance. This is supported by [29] and [36] who state that production scheduling is a vital function in manufacturing as this heightens control in the factory, ensures continuous flow and prevents bottlenecks, thus improving overall business performance. It can be concluded that production scheduling is critical to the success and overall performance of the business. This function plays an important role in gaining business market share and potentially being the market leader. This function requires more focus from manufacturing companies to reap the full rewards.

5. Limitations and implications for future research

The electronically sent questionnaires had very few respondents and so many errors when returned. The sample size was only limited to Gauteng thus results could be more meaningful and robust if more provinces were included or rather do a comparison of two provinces to get different results. Also, the researchers could have received more participants if this study was across more than one province. The results and findings in this study proved to be very insightful into the organisations in the manufacturing industry, specifically general managers, and production/operations practitioners. This study used a quantitative method for data collection thus future researchers can consider using a mixed method approach. This can allow the researcher(s) to get further constructive details from the respondents. This study drew three hypotheses' statements though there was potential to use more, thus, future studies can expand the field of research by looking into other contributing variables.

6. Conclusion

This study has presented vital information relating to best operational practices that should be implemented in manufacturing industries. It has proved that variables such as production planning, production scheduling and first to market can positively improve the performance of manufacturing industries. This study has also briefly highlighted other factors, which can be considered by management to drive efficiencies throughout the production plan. The findings confirm that production planning can be used as a risk avoidance technique by ensuring production is carried out efficiently by minimising waste and costs related to production job changeovers. This study can contribute to increasing literature on lean manufacturing and production excellence. These recommendations are of value to production planners, production managers, general managers, and supply chain practitioners in the manufacturing space. This study also enlightens managers in this industry in identifying areas for improvement in their production process, scheduling process and first to market techniques and applying beneficial strategies for production improvement.

Acknowledgements

I would like to say thank you to our Vaal University librarian Rebecca Fani for assisting in looking for articles for literature review and language editor Dr Kufakunesu Zano.

References

[1] Feng, H., Jiang, Z., Li, M., Feng, N., 2018. First- Or Second-Mover Advantage? The Case of It-Enabled Platform Market, 1–71.

[2] Cobb, C.W., Douglas, P.H., 1928. A theory of production. The American Economic Review 18 (1), 139–165.

[3] Fandel, G., 1985. The theory of production and cost department of production management. S. Springer-Verlag Berlin Heidelberg: Germany.

[4] Krugman, P.R., 1995. Growing world trade: Cause and Consequences. Brookings Papers in Economic Activity, 327–362.

[5] Lawrance, R.Z., Slaughter, M.J., 1993. International trade and American wages in the 1980s: giant sucking sound or small hiccup? Brookings Papers in Economic Activity Microeconomics, 161–210.

[6] Hietala, A., 2017. First-Mover advantages and -disadvantages: Case study on prospectum Oy. Helsinki Metropolia University of Applied Sciences, 1–32.

[7] Takahashin, K., Onosato, M., Tanaka, F., 2015. A comprehensive approach for managing feasible solutions in production planning by an interacting network of zero-suppressed binary decision diagrams. Journal of Computational Design and Engineering 2, 105–112.

[8] Sharma, V., Balodiya, R., 2013. Analysis of production planning and control of typical process (leather) industry. International Journal of Advanced Electrical and Electronics Engineering 2, 41–44.

[9] Samaranayake, P., 2013. Improving manufacturing lead time using holistic approach to planning and executing with intergraded data structure: numeric simulation and comparison. Interactions Journal of Production Research 51, 4484–4501.

[10] Tseng, C., Tseng, C., 2019. Corporate entrepreneurship as a strategic approach for internal innovation performance. Asia Pacific Journal of Innovation and Entrepreneurship 13, 108–120.

[11] Dantzig, G.B., 1951. Maximisation of the linear function of variables subject to the linear inequalities. Wiley, London.

[12] Gomez, J., Lanzolla, G., Maicas, J.P., 2016. The role of industry dynamics in the persistence of first mover advantages. Long Range Planning, 265–281.

[13] Vranakis, S., Chatzoglou, P., 2014. Business factors relating to manufacturing firms performance. Journal of Industrial Engineering and Management 1, 336–359.

[14] Nguyen, T.T., Nguyen, T.H., Pham, H.T., 2020. The effect of corporate entrepreneurship, organizational culture on supply chain management and business performance in chemical industry. Uncertain Supply Chain Management 8, 67–76.

[15] Jayaslaw, S., Jewkes, E.M., 2016. Price and lead time differentiation, capacity strategy and market competition. International Journal of Production Research 54, 2791–2806.

[16] Mwalim, A.O., Egessa, R., Evans, K., 2019. Effect of setting of performance contract objectives on organizational performance in the state owned sugar companies. International Journal of Multidisciplinary and Current Research, 1–8.

[17] Maccarthy, B., L., Brabazon, P.G., 2020. Order Fulfillment in High Variety Production Environments . Journal Operations Management Division, 1–19.

[18] Kloock, J., 1969. Betriebswirtschaftliche input-output-model. Germany, Wiesbaden.

[19] Hulse, E.O., Silva, T.L., Camponogara, E., Rosa, V.R., Viera, B.F., Teixeira, A.F., 2020. Introducing approximate well dynamics into production optimization for operations scheduling. Department of Automation and Systems Engineering, Federal University of Santa, 1–34.

[20] Cheah, J.H., Memon, M.A., Chuah, F., Ting, H., Ramayah, T., 2018. Assessing reflective models in marketing research: A Comparison Between Pls and Plsc Estimates.

[21] Madankumar, S., Rajendran, C.A., 2018. A mixed integer linear programming model for the vehicle routing problem with simultaneous delivery and pickup by heterogeneous vehicles, and constrained by time, Windows, 1-14.

[22] Wang, C., Jiang, P., 2017. Deep neural networks based order completion time prediction by using Real-Time Job Shop RFID Data. Journal of International Manufacturing, 1–17.

[23] Pham, H.D., 2020. Impact of human resource management practices on enterprises' competitive advantages and business performance: evidence from telecommunication industry. Management Science Letters, 721–732.

[24] Williams, P., AshillL, N.J., Naumann, E., Jackson, E., 2015. Relationship quality and satisfaction: customer perceived success factors for on time projects. International Journal of Project Management, 1–15.

[25] Tokola, H., Groger, C., Jarvenpaac, E., Niemi, E., 2016. Designing manufacturing dashboards based on a key performance indicator survey. Conference on Manufacturing Systems, 619–624.

[26] Muturi, F.M., Madawi, J.K., Owino, E.O., 2014. Antecedents of customer perceived value. International Journal of Business and Social Science 5 (4), 319–326.

[27] Nanda, T., Khamba, J.S., Singh, D., 2015. Role of technology innovation in improving manufacturing performance. International Journal of Social, Behavioral, Educational, Economic, Business and Industrial Engineering 1, 389–402.

[28] Chinomona, E., 2023. The Influence of market orientation, risk taking and innovative performance on new product performance: a case of Gauteng province in South Africa. African Journal of Business and Economic Research (AJBER) 18 (2), 203–229.

[29] Song, M., Zhao, L., Benedetto, C.A., 2013. Do perceived pioneering advantages lead to first-mover decisions. Journal of Business Research 66, 1143–1152.

[30] Tripathi, V., Stanton, C., Strobino, D., Bartlett, L., 2019. Measuring the quality of maternal and care processes at the time of delivery in sub-Saharan Africa: development and validation of a short index, 1–12.

[31] Barzanji, R., Naderi, B., Begen, M.A., 2019. Decomposition algorithms for the integrated process planning and scheduling problem. Department of Industrial Engineering, 1–28.

[32] Brunaud, B., Laínez-Aguirre, J.M., Grossmann, I.E., 2019. Inventory policies and safety stock optimization for supply chain planning. American Institute of Chemical Engineers Journal 65, 99–112.

[33] Poelmans, E., Raisanen, S., Taylor, J.E., 2019. The long-run effect of geographically-staggered legalizations: was there a first-adopter advantage for states that legalized beer more quickly in 1933. History Society. The Journal of the Economic and Business, 1–15.

[34] Pielmeier., Theumer, P., Schutter, C.L., Sonyman, S., Bessdo, O. Braunreuther, S., Reinhard, G., 2019. Methods of event based production. conference on intelligent computation in manufacturing engineering, 373–378.

[35] Yang, J.Q., Zhang, X, M, Fu, H, Y, Lui, C., 2017. Inventory competition in a dual-channel supply chain with delivery lead time consideration. Applied Mathematical Modelling 42, 675–692.

[36] Mofokeng, S.A., Chinomona, E., Mafini, C., 2023. Internal drivers of innovation and sustainability in south african manufacturing small and medium enterprise. African Journal of Inter/Multidisciplinary Studies 5 (1), 1–14.

Biography

Professor Elizabeth Chinomona is a 50-year-old black female senior lecturer at Vaal University of Technology in South Africa. She has been an assistant and part time lecturer in Zimbabwe and Taiwan. She has successfully supervised and graduated more than 5000 Bachelor of Technology (Honours) students, 20 Masters students, and 8 PhD students. To date, she has published more than 100 papers in peer-reviewed accredited journals. She sits on numerous Academic Journals Editorial Boards.

Mamonare Minky Kgaogelo Mogano is a 29-year-old black female who has soared to exceptional heights in the logistics and supply chain industry. With her fervent passion for supply chain, she has achieved significant milestones in her academic and professional journey. She earned her Master's degree in Supply Chain Management from the Vaal University of Technology in 2022, this has been a testament to her dedication.

CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
CPSL 2023-2

5th Conference on Production Systems and Logistics

Design Guidelines For Digital Kanban Systems With High Service Level

Roman Ungern-Sternberg[1], Christoph Kilian Merz[1]

[1]*Fraunhofer Institute for Manufacturing Engineering and Automation IPA, 70569 Stuttgart, Germany*

Abstract

One success factor of Kanban is its elegant simplicity for physical inventory control. However, especially in multi-variant productions inventory levels are digitally tracked. To maintain the high service levels of the Kanban systems, the digital representation in the ERP must reliably reflect the physical inventory levels and deviations should be detectable. The design of such a digitally tracked Kanban systems requires a booking logic and a method for deviation detection. Especially in multi-stage systems with several inventory levels, the design of a simple and robust Kanban logic is challenging.

Thus, the paper first gives an overview of existing inventory booking strategies. Based on the strategies the effects of inventory deviations on logistical performance in classic Kanban and digitally controlled Kanban systems are discussed. Design guidelines summarize the analysis. Subsequently, three different design alternatives of a classical, digital and high resolution Kanban system are developed. These guidelines and design alternatives should enable practitioners to setup reliable Kanban systems including their digital representation.

Keywords: Kanban; Inventory Management; Production Planning; Deviations; ERP

1. Introduction

A factor for the widespread use of Kanban as a production control system is its simplicity: An empty bin triggers the release of a new batch. A well-defined Kanban system support two main logistical goals:

- **Controlled inventory levels:** The fixed number of Kanban cards keeps the inventory levels in control. Overstock is not possible.
- **High service level:** Service level is the ability to instantly and completely fulfill a customer demand without waiting time. The constant availability of one or more filled Kanban bins supports high service levels without complex planning mechanisms. [1–3]

However, in multi-stage high-variety production the level of transparency in a classical Kanban is not sufficient as it lacks three critical functions for digital operations:

1. **Digital process triggers:** To start automated processes such as order creation, digital triggers are necessary. However, a physical Kanban system relies only on the transportation of the Kanban itself. To automate the processes, clear guidelines for triggers are necessary. [2,3]
2. **Digital inventory tracking:** The majority of quantitative approaches for inventory dimensioning and demand forecasting rely on time series data. A physical Kanban system does not support the tracking of inventory levels over time, as consumption data are not stored. Thus, a systematic way for inventory tracking of a Kanban system is needed. [1,3]
3. **Automated deviation detection:** Inventory deviations are often a high cost factor in production [4]. To detect regular (e.g. BOM-issues) or irregular (e.g. scrap) inventory deviations, a comparison

DOI: https://doi.org/10.15488/15264
ISSN: 2701-6277

between actual and planned quantities is necessary. As a physical Kanban is solely relying on actual inventory levels such an analysis is not possible in a classical Kanban.

The challenge is to keep the digital representation of the Kanban in the ERP-systems synchronized with the physical reality on the shop floor while maintaining the system's simplicity. To setup a digital Kanban system, several conceptual design questions (such as trigger points) must be answered to fulfill the above-mentioned requirements. Existing approaches focus on single elements of a digital Kanban system such as digital identification of booking. However, a systematic design approach is missing, leading to the following research question:

How can a simple digital Kanban system be systematically designed to enable digital inventory tracking and deviation transparency while keeping high logistical service levels?

Core of the paper are design decision to be made while setting up such a Kanban system. For the design, the system engineering's problem solving cycle is followed. [5] The first chapter describes situation and objective of the system. The second chapter searches for solutions while analyzing potential design decisions and summarizing the preferred options in design guidelines. [6] Chapter three analysis existing design approaches of Kanban systems and summarizes their limitations emphasizing the need for a new solution. Based on the preceding chapters, Chapter 4 develops the configuration options for Kanban systems and thus focuses on the synthesis of solutions as well as the selection of an appropriate solution. Chapter 5 shows the article's limitations and an outlook.

2. Kanban Systems

The chapter first describes the key elements of a Kanban system with a digital representation and discusses the challenges regarding high service levels. Based on the system description, the effects of inventory deviations are highlighted. For the three main design decisions booking verification, time and quantity design guidelines are synthesized.

2.1 Elements of Kanban Systems

Figure 1 shows the elements and functionality of a Kanban system in two layers: The actual physical flow of Kanbans as well as a possible digital representation of the inventory levels. The Kanban material flows from a warehouse (supply) to the work centers where the materials are consumed to produce finished goods. The production quantities are determined by production orders (demand). [1] When using a digital representation, two types of Kanban inventory have to be differentiated:

- **Shop Floor Inventory**: Quantity that is physically stored in a defined storage location (e.g. number of parts in Kanban bins).
- **ERP Inventory**: Quantity that is booked to a clearly defined storage location in the ERP system (e.g. number of parts in the locations labeled "shop floor").

In the Kanban system there is a distinct signal (trigger) that starts the Kanban cycle, i.e. releasing the delivery of a new batch of Kanban material. With two types of inventory, there are two feasible triggers [7,8]:

- **Shop Floor Trigger:** In classic TPS Kanban systems, a shop floor trigger initiates the Kanban cycle. Usually an empty Kanban box or a Kanban card represents the trigger. (Fig. 1a)
- **ERP Trigger:** In an ERP System, the trigger is raised when falling below a threshold inventory level (reorder point). (Fig. 1b)

Processes can be automatically initiated by using ERP triggers. However, this requires an accurate and timely representation of the shop floor inventory within the ERP system. The article discusses the deviations between shop floor and ERP inventory based on the following three questions:

- **Deviation effects:** How do deviations affect the on-time delivery of material supply (Fig. 1c) and production order release (Fig. 1d)?
- **Time**: How are changes in inventory levels recorded digitally for inventory tracking? (Fig. 1e)
- **Quantity:** What are causes for deviations between the shop floor and ERP inventory levels, and how can they be detected? (Fig. 1f)

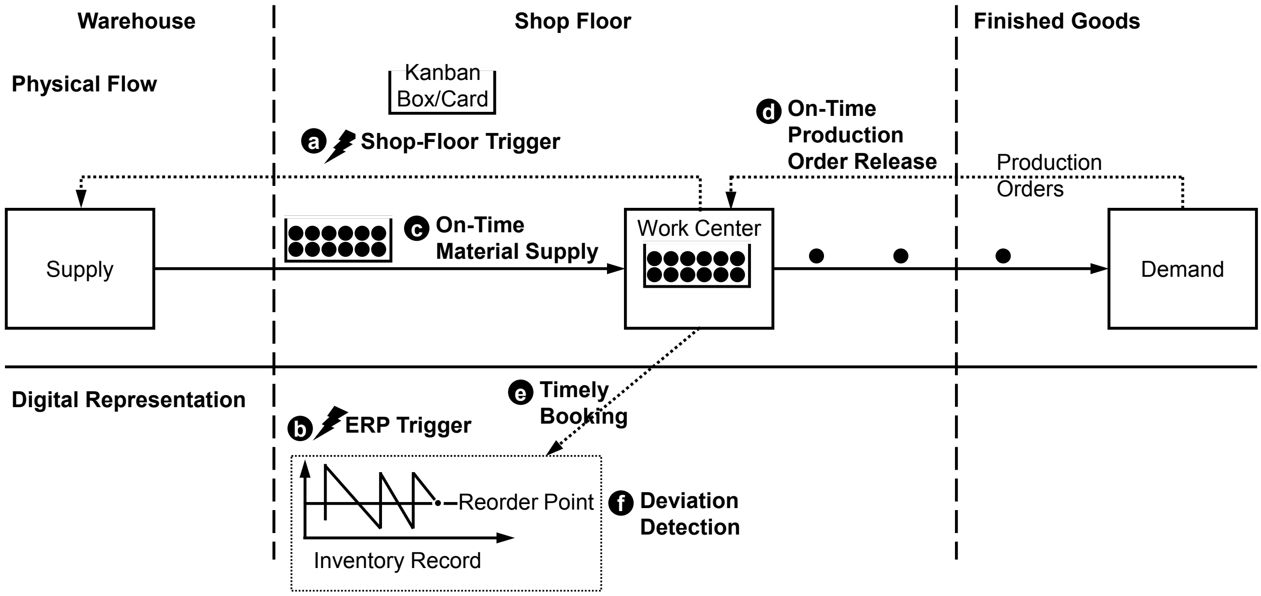


Figure 1: Elements of a digital Kanban system

2.2 Effects of Inventory Deviations on Logistical Performance

Depending on the selected type of trigger, the effects of deviations on material supply (service level) and production order release vary. Having always sufficient material is critical for the work center. If a material availability check is performed, having enough material is critical for a timely order release. Figure 2 summarizes the deviations effects (excessive inventory or inventory shortage) for the two trigger types.

	Shop-Floor Trigger		ERP Trigger	
ERP Inventory	Excess Inventory (ERP > Shop Floor)	Inventory Shortage (ERP < Shop Floor)	Excess Inventory (ERP > Shop Floor)	Inventory Shortage (ERP < Shop Floor)
Material Supply	Material supply on time	Material supply on time	Delayed material supply	To early material supply
Production Order Release	Order release no problem	Order release no problem	Release orders when parts are missing	Order approval is blocked, (thus inventory might be ok.)

Figure 2: Effects of inventory deviations on logistical performance depending on the trigger

Shop Floor trigger. The Kanban system solely relies on the physical inventory levels. Thus neither excessive inventory nor inventory shortage affect the on time trigger of material reordering. The availability check does not consider the physical Kanban. Therefore, any discrepancies in stock do not affect the order release. [2]

ERP trigger. If ERP triggers are used, inventory discrepancies generally have critical impacts. Excess inventory leads to delayed material delivery. These can cause material shortage at the workstation. Inventory shortage can lead to excessive material at the work center. Excess inventory in the ERP can lead to order release though material is not available at the work center. If the ERP inventory is less than the actual shop floor inventory level this could lead to holding back of production orders, even though material is available.

In summary, Kanban systems with shop floor triggers are resistant to inventory deviations leading to high service levels and on time order release. Kanban systems with digital triggers are sensitive to inventory deviations. However, a digital representation it necessary to analyze the causes of inventory deviations.

2.3 Timely Inventory Booking

To generate a digital representation in the ERP, it is essential to book inventory changes to timely reflect the actual inventory on the shop floor in the ERP system. There are two ways to book changes in quantity:

Verified booking: For a verified quantity, the physical measurement is accurately recorded using methods such as counting or weighing and entered into the ERP system. This can be achieved by either confirming or correcting the actual quantity and using the actual measured quantity as the nominal value.

Not Verified booking: For a not verified quantity, the specified or planned quantity is transferred to the ERP system without verification and becomes the nominal quantity. The specified quantity could be derived from a production order, a Kanban label or the bill-of-material, etc.

Clearly, verified quantities have benefits for the accuracy of the ERP system. However, any type of quantity verification and booking in the ERP system is associated with effort. Therefore, verification should be done at points where few bookings are required. This is usually at the entry to the workstation as full boxes are delivered making visual checks easier.

► **Guideline 1: Verified quantities:** Quantities should be verified, ideally at a point with higher quantities and a lower amount of transactions to reduce effort.

Figure 3 shows the four methods for inventory booking depend on the relative position to the actual date of consumption.

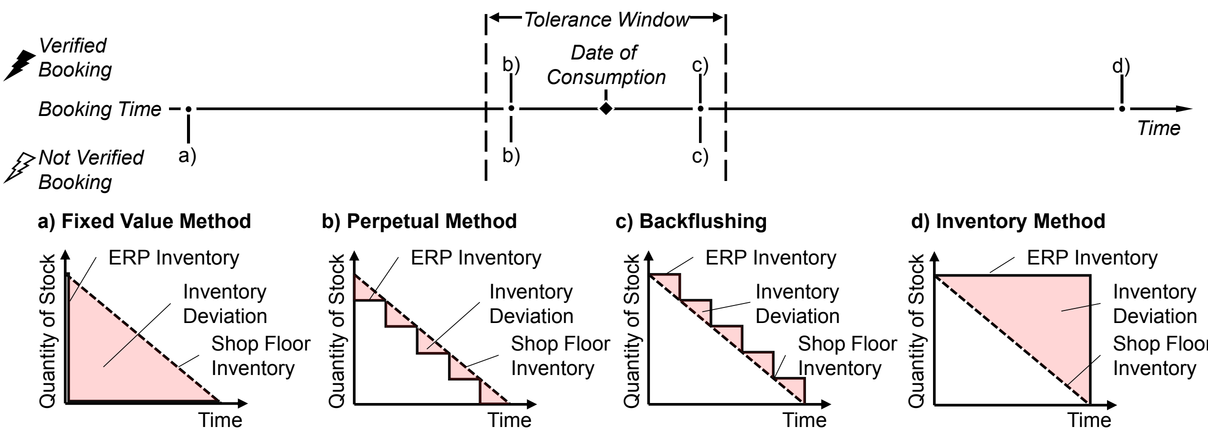


Figure 3: Classification of booking methods relative to date of consumption

Ex-ante bookings: With these methods, consumption is booked before the material is withdrawn. This type of booking often results in a shortage of inventory in the ERP system upon withdrawal, as booking occurs before material is withdrawn.

Using the **fixed value method** the material consumption in terms of quantity is immediately booked out as consumption. The method is usually not suitable for inventory management as the time delay and thus the inventory deviation is too big. Goods that are procured infrequently and for a specific purpose are possible exceptions. [9,10]

By using the **perpetual method**, material consumption is recorded via inventory accounts and material withdrawal slips, so the material consumption quantity is equal to the sum of all documented material withdrawals. The booking and the material consumption take place at the same time. [9,10] As the time delay is short and within a tolerance window, this method is suitable to record changes in Kanban quantities.

Ex-post booking: The other category covers delayed booking methods. Material consumption is booked after occurrence. This type of booking tends to result in excess inventory in the ERP system.

Backflushing determines the planned material consumption retrospectively based on produced quantities of finished products, by using bills-of-material. With this method, the planned consumption is booked after the actual consumption has been withdrawn. [9,10] As the time delay is short and usually within a tolerance window, this method is suitable to record changes in Kanban quantities.

The **inventory method** involves the withdrawal of material before it is booked, summarizing the quantity of material consumed for a period, e.g. monthly consumption of screws. [9,10] The inventory method is usually not suitable to record Kanban quantities as the time delay and thus the inventory delay is too big.

A small tolerance window not only enhances system stability but also improves data reliability, facilitating accurate conclusions. Additionally, adherence to the tolerance window enhances data reliability and enables the drawing of accurate conclusions. Systematically recording stock movements requires additional effort. Nonetheless, this additional effort is crucial to maintain synchronization between the shop floor and ERP.

► **Guideline 2: Timely Bookings:** Bookings of shop floor changes should occur within a narrow time window in the ERP system. The proverb "every movement results in a booking and every booking results in a movement" is a good shop floor facilitator for the guideline.

2.4 Deviation Detection

As shown above, deviation are especially critical when using ERP triggers. There are numerous reasons for quantity deviations. Knowing the total Kanban quantity (sum of all items in the Kanban bins) and using a physical trigger, two main reasons for deviation can be detected by analyzing the inventory trend (Figure 4):

a. **Decreasing ERP Inventory:** A decrease in ERP inventory occurs when the planned material consumption is higher than the actual consumption. This can be caused by over reported scrap or too high quantities in the bill-of-materials.
b. **Increasing ERP Inventory:** An increase in ERP inventory happens when the reported material consumption by ERP is less than the actual consumption. Causes are unreported scraps or consumption of parts missing in the bill-of-material.

The smaller the Kanban quantities, the smaller is the window for deviations and a fast deviation detection.

► **Guideline 3: Small Quantities:** The Kanban quantities should be as small as possible. This allows for a timely automated detection of deviations.

3. Existing Approaches on Deviations in Digital Kanban Systems

The literature review carried out used the bibliographic database Scopus to identify existing design approaches for Kanban systems allowing deviation detection. The search was conducted in November 2022 using the keywords "inventory", "deviation", "kanban", "method", "difference", "count", "cycle", "posting", "ERP", "MES", "control", "dimensioning" and "design" within title and abstract.

None of the papers found, focuses on the effects of inventory deviations and detection of deviations in digital Kanban systems. However, several papers are touching the research question. Thus the relevant papers are newly clustered as following:

- How does the **Kanban design** affect inventory deviations?
- How do electronic Kanban systems (**e-Kanban**) handle quantity deviations?
- How do **RFID** Kanban systems handle the time lag between bookings?
- How do systems derived from **accounting** deal with deviations and their logistical effects?

Kanban Design/Concepts. The enormous popularity of Kanban has led to a myriad of Kanban systems being used in today's industrial environment. These Kanban systems are adapted to the individual circumstances of production and logistics systems. [11,12] According to Kumar et al. [13] two general movements can be distinguished from literature. These two streams are Kanban empirical theory and modelling approach. Kanban empirical theory can be further divided into flow stope, assembly line and batch production system. The modelling approach can be divided into mathematical, queuing, markovian, simulation and cost minimization. [13] From their review of the literature, Akturk et al. [14], Kumar et al. [13] and Junior et al. [12] show that a large number of authors have worked on design and optimizing the parameters associated with improving the performance of Kanban. Dimensioning of the most appropriate trigger point in different systems is undertaken. However, there is a lack of investigation in the literature on what triggers the Kanban cycle and how deviations can be detected. [15–19] Even Li, who designs a robust Kanban system, neglects the aspect of inventory deviations. [20]

In summary, the literature on Kanban design is concerned with optimizing the parameters of a Kanban system. In addition to classical Kanban, special cases such as the ramp-up process, no constant flow rate are also considered. Trigger points for optimizing the quantities in the system are discussed in particular. What is missing, however, is the consideration of different triggers and, in particular, the recognition of deviations in the quantity. Furthermore, all of these systems have been designed for the use of physical triggers.

e-Kanban. E-Kanban is a form of modification from classical Kanban. Some authors are concerned about the dimensioning and optimization for the e-Kanban. [21,22] Considered from some authors is the technical implementation of e-Kanban in enterprises. [23] Several authors also deal with the integration of suppliers into e-Kanban. [24]

However, no author deals with the detection of deviations in the context of e-Kanban. Marikova [25] points out as a considerable problem in the introduction of e-Kanban the bad data quality and discrepancies in the data basis.

One approach to digitizing Kanban is called e-Kanban. Solutions for technical implementation and integrating external suppliers are considered. Inventory deviations are also not considered in these approaches.

RFID. Several approaches can be found in literature where RFID triggers the ERP system. [26,27] Some authors propose RFID Kanban systems. The focus of this approaches is the optimization of the information flow to reduce the inventory in the kanban cycle. [28–31] These approaches share the fact that the material movement is technically tagged and thus enables traceability through the processes. Due to the automatic action-based booking, there is no time delay in booking. However, these approaches do not deal with inventory deviations between ERP and shop floor.

There are many technical proposals for the use of RFID to track the movements of the inventory. How to optimize Kanban using RFID is also covered. Recording inventory movements without time delay is the advantage of RFID. The issue of discrepancies between the inventory in the ERP and the actual inventory is not taken into account.

Accounting. Inventory transactions and recording of inventory changes are clearly regulated by standards. Performing inventory at the end of the year is well described in literature. However, it is not considered how deviations between physical inventory and account inventory can be performed without delay. Haryono [32] deals with the deviation between physical inventory transactions and computing in accounting information systems only from the perspective of financial evaluation. Nonetheless, none of the authors have taken into account the impact on logistics. [33]

There is a good description of inventory taking. There are also approaches that deal with recording discrepancies. However, these do not consider the logistical implications.

Deficits of exiting approaches. Approaches to the design of Kanban systems are varied. There are different directions: Adapting Kanban to the given conditions, optimizing the approaches in terms of quantities and performance. However, no approach addresses deviations in general and between ERP and shop floor in particular. Neither do they consider the issue of different triggers. There is evidence that the literature partially answers the three research questions presented in this article. Nevertheless, no single approach addresses all of the research questions.

4. Designing robust, multi-stage Kanban systems

Based on the deficits of the existing Kanban system (Figure 1) and the derived guidelines the section develops three Kanban setups with increasing inventory transparency and digital functionality. The development is based on the classical Kanban system and incrementally increases the systems complexity. The three approaches are based on several analysis-synthesis discussions with industrial partners and production planners. This allows for a step-by-step transition of existing Kanban systems:

- The **classical Kanban** system implements an ERP trigger for material replenishment in the warehouse without deviation detection on the shop floor.
- The **robust digital Kanban** adds deviation detection on the shop floor to the system.
- The **high-resolution Kanban** additionally supports deviation detection for each work center.

4.1 Physical shop floor Kanban (Classical Setup) with digital reordering

The system consist of three logistical zones: Warehouse, Shop Floor and Finished Goods. Only within the warehouse, a digital inventory tracking is established (Figure 5).

A physically empty Kanban box (or card) triggers the material replenishment from the warehouse. When the refilled Kanban is transferred from warehouse to shop floor the Kanban quantity is booked out from the warehouse. Reordering from the warehouse is digitally triggered by the ERP inventory level.

As the shop floor inventory levels are not recorded, deviations cannot be detected automatically. As the system relies on physical triggers only, on time material supply and production order release due to wrong digital data is impossible.

The system is suitable for cheap items where deviations in consumption are uncritical (e.g. C-Parts, consumables) and product specific cost allocation is not necessary (e.g. same quantities for each product).

4.2 Robust and Simple Digital Kanban with Physical Triggers

The second solution extends the first solution by a digital representation of the shop floor inventory level. Materials consumed by production are deducted from the shop floor inventory via backflush (e.g. piece-by-piece based on bill-of-materials). (Figure 6)

The reorder of material from warehouse to the shop floor is still based on physical triggers (empty Kanban). When transferring the refilled Kanban from warehouse to shop floor the Kanban quantity is rebooked via transfer order from warehouse to shop floor.

As quantities are digitally represented on the shop floor, deviations can be detected on the shop floor according to section 2.4. However a precise identification of the exact work center causing the deviations is not possible, as all Kanban are represented by a single inventory level on shop floor level. Due to physical triggers, deviations do not affect the service level of the materials on the shop floor.

The system is suitable for expensive parts where deviations must be tracked. However, the identification of deviations (e.g. wrong BOMs) still requires manual effort. The identification might be delayed especially if the total Kanban quantity on the shop floor is high (e.g. an item is used in multiple work centers).

4.3 High-Resolution Digital Kanban with Inventory Trigger

The third solution extends the digital Kanban by a digital representation of each work center's inventory level and a bin-level tracking in the warehouse. This setup allows a precise tracking of the inventory levels and batches available at each location for each point in time. (Figure 7)

An empty Kanban triggers the physical replenishment from a FIFO controlled supermarket to the respective work center. A transfer booking from the supermarket to the work center reflects the consumption. From the supermarket, reorder bookings can be done with a digital trigger.

Inventory deviations can be detected timely and precisely due to the relatively small quantities. However the system requires additional bookings from the supermarket to the respective work centers.

The system is suitable for expensive Kanban parts where precise tracking is mandatory. Furthermore, the setup additionally support batch traceability, which is mandatory in industries like pharmaceutics.

4.4 Comparison and Validation

The three solutions built upon each other and thus allow a step-by-step refinement of the Kanban system. This approach supports the gradual refinement of an existing analog Kanban system to a high precision Kanban system.

All three systems maintain **controlled stock levels**. In case of classical Kanban, it is limited to the physical stocks. Having a digital representation the stock levels can also be controlled via ERP system. All systems have a high shop floor **service level** as the shop floor trigger is always physical.

The degree of digital inventory tracking and the support of digital triggers increase from the first to the third solution. The digital inventory tracking combined with BOM backflushing is basis for the automated deviation detection, which is possible in the second and third solution.

In an industrial use case (machine assembly with 50+ Kanban loops), the transition from a classical to a robust digital Kanban has been validated. Production planners highlighted the simple implementation as no additional inventory locations or changes in SAP R/3 were necessary. Operators confirmed the high service level as a simple physical trigger is used. The practitioners emphasized the importance of continuous inventory control as suggested in Fig. 4.

5. Discussion and Outlook

A digital representation of Kanban inventory is necessary to benefit from digitalization (e.g. automated triggers and processes). However, it is essential to manage deviations between digital and physical Kanban in order to avoid subpar service levels. This paper systematically describes the critical elements of Kanban systems and derives design guidelines for implementation.

Based on the design guidelines and existing approaches, three practical solutions are derived. The solutions are based on standard ERP functionality and the industrial applicability is validated in a motor production. Further research is needed in detailing the exact ERP requirements and the integration with other Industry 4.0 tracing and tracking methods.

This paper presents a systematic approach to solving a tangible material supply problem by digitizing existing Kanban systems, while maintaining service levels and simplicity with standard ERP functionality.

The high resolution Kanban enables complete traceability of single batches. Further research is needed to design robust procedures for batch traceability in Kanban systems. Batch traceability is mandatory in many high quality industries such as medical technology and cannot be reached with existing Kanban systems.

Appendix

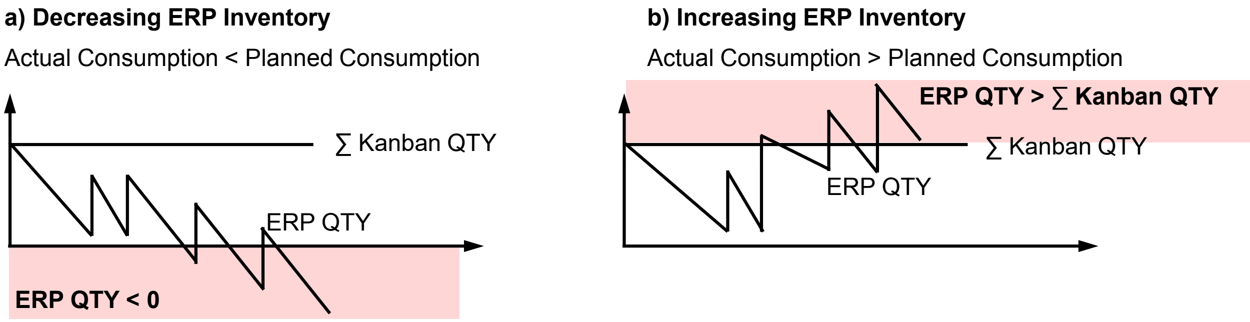


Figure 4: Detection of Inventory Deviations (Quantity)

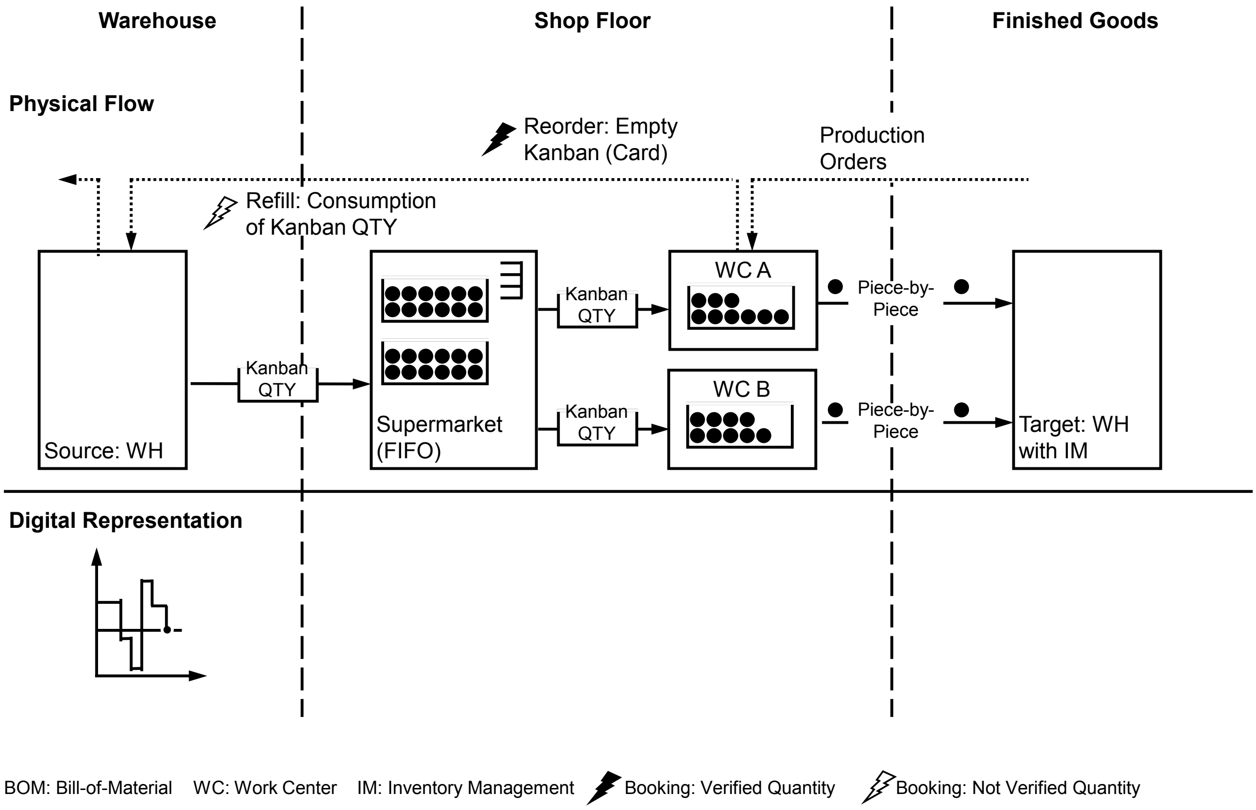


Figure 5: Classical Kanban (Physical shop floor Kanban)

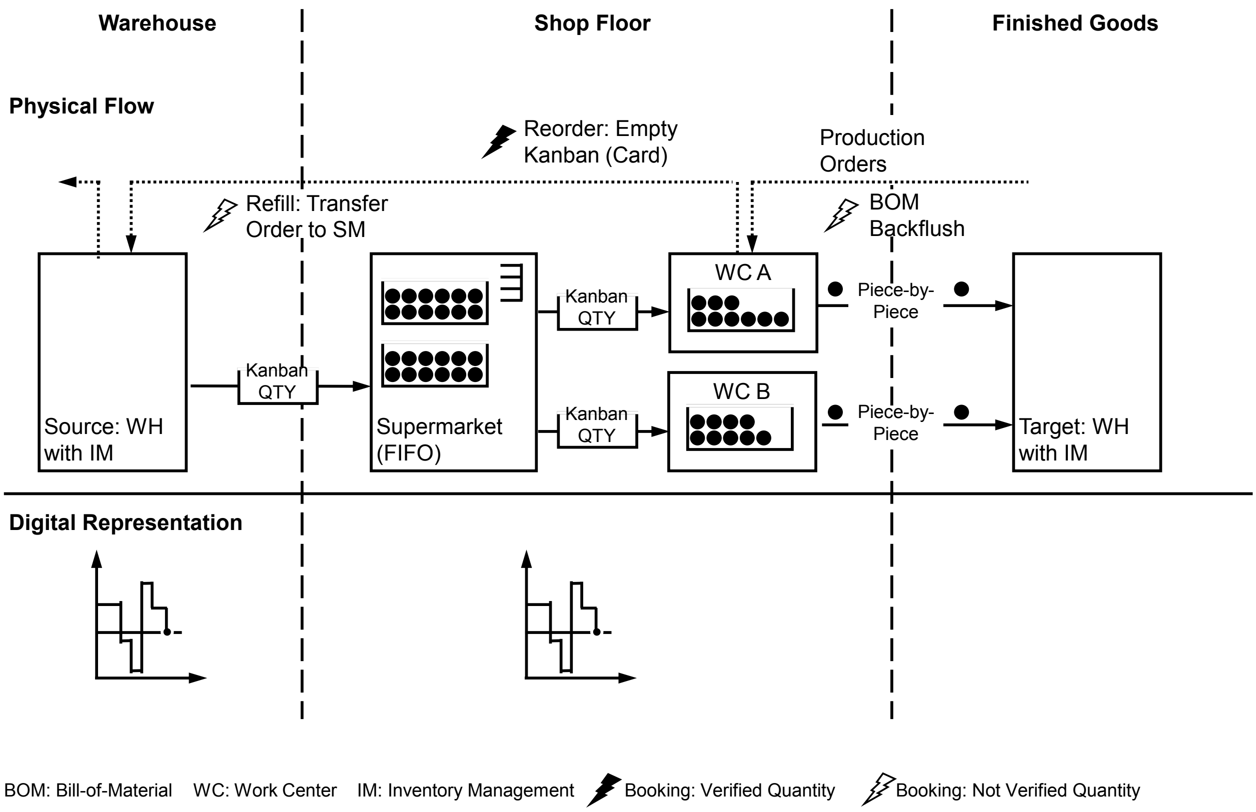


Figure 6: Robust Digital Kanban

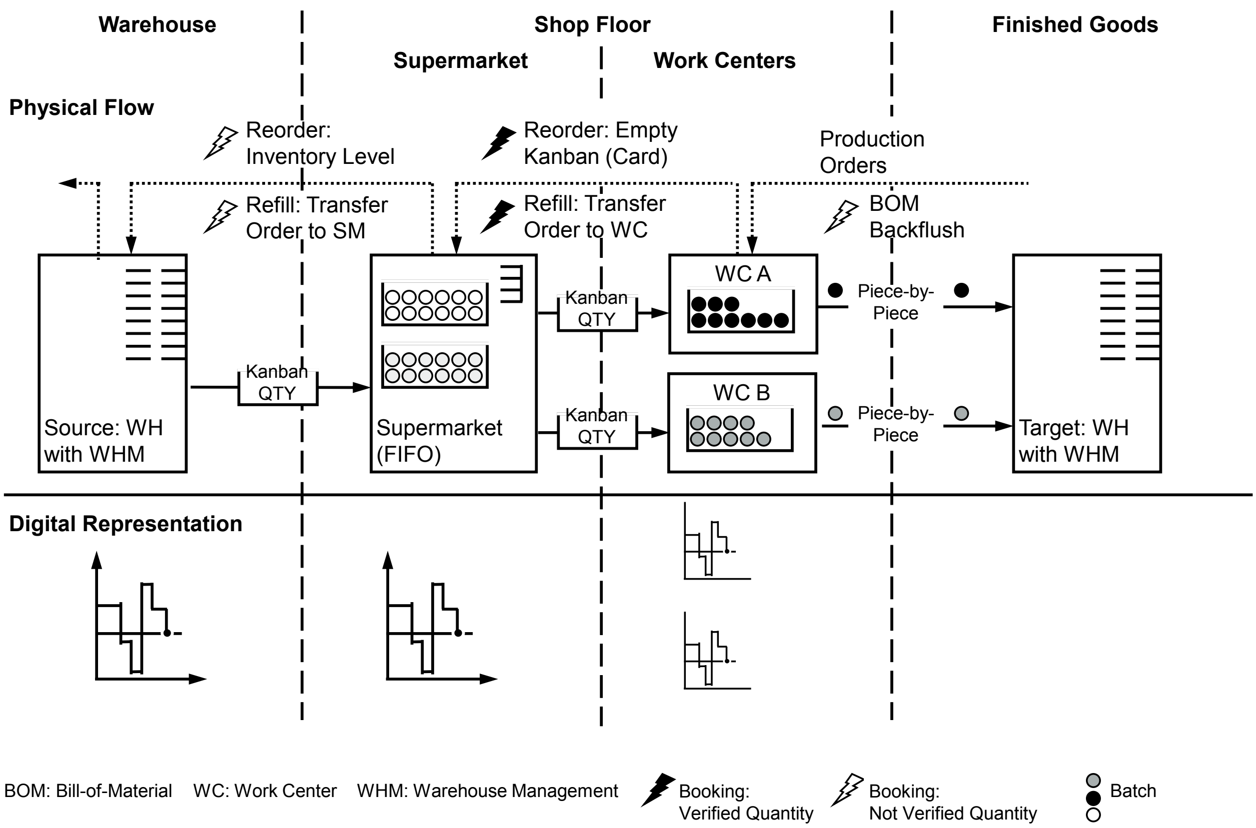


Figure 7: High resolution Kanban

References

[1] Baudin, M., 2023. Introduction to Manufacturing: An Industrial Engineering and Management Perspective. Taylor & Francis Group, Milton, 800 pp.

[2] Erlach, K., 2020. Wertstromdesign. Springer, Berlin, Heidelberg.

[3] Hänggi, R., Fimpel, A., Siegenthaler, R., 2021. LEAN Production – einfach und umfassend. Springer, Berlin, Heidelberg.

[4] Ford, M., 2014. Why are erp and mes so limited in electronics? SMT Surface Mount Technology Magazine 29 (2), 66–70.

[5] Haberfellner, R., Weck, O. de, Fricke, E., Vössner, S., 2019. Systems Engineering. Springer International Publishing, Cham.

[6] Erlach, K., Böhm, M., Hartleif, S., Leipoldt, C., Ungern-Sternberg, R., 2020. Gestaltungsrichtlinien in den Technikwissenschaften. Zeitschrift für wirtschaftlichen Fabrikbetrieb 115 (1-2), 77–81.

[7] Gross, J.M., McInnis, K.R., 2003. Kanban made simple: Demystifying and applying Toyota's legendary manufacturing process. AMACOM, New York, 259 pp.

[8] Rother, M., 2022. Toyota Kata Practice Guide: Practicing scientific thinking skills for superior results in 20… minutes a day. MCGRAW-HILL EDUCATION.

[9] Mumm, M., 2019. Kosten- und Leistungsrechnung: Internes Rechnungswesen für Industrie- und Handelsbetriebe, 3., überarbeitete und erweiterte Auflage ed. Springer Gabler, Berlin, Heidelberg, 361 pp.

[10] Reim, J., 2019. Kosten- und Leistungsrechnung: Instrumente, Anwendung, Auswertung: Anschaulicher Einstieg für Studium und Praxis. Springer Gabler, Wiesbaden, Heidelberg, 275 pp.

[11] Huang C.C., Kusiak A., 1996. Overview of Kanban systems. International Journal of Computer Integrated Manufacturing 9, 169–189.

[12] Lage Junior, M., Godinho Filho, M., 2010. Variations of the kanban system: Literature review and classification. International Journal of Production Economics 125 (1), 13–21.

[13] Sendil Kumar, C., Panneerselvam, R., 2006. Literature review of JIT-KANBAN system. Int J Adv Manuf Technol 32 (3-4), 393–408.

[14] Akturk, M.S., Erhun, F., 1999. An overview of design and operational issues of kanban systems. International Journal of Production Research 37 (17), 3859–3881.

[15] Braga, W.L.M., Naves, F.L., Gomes, J.H.F., 2020. Optimization of Kanban systems using robust parameter design: a case of study. Int J Adv Manuf Technol 106 (3-4), 1365–1374.

[16] Klug, F., 2016. A hybrid push/pull design of kanban systems during production ramp-up phase. IJSOM 24 (3), 397.

[17] MacKerron, G., Kumar, M., Kumar, V., Esain, A., 2014. Supplier replenishment policy using e-Kanban: A framework for successful implementation. Production Planning & Control 25 (2), 161–175.

[18] Sivakumar, G.D., Shahabudeen, P., 2008. Design of multi-stage adaptive kanban system. Int J Adv Manuf Technol 38 (3-4), 321–336.

[19] Sivakumar, G.D., Shahabudeen, P., 2009. Algorithms for the design of a multi-stage adaptive kanban system. International Journal of Production Research 47 (23), 6707–6738.

[20] Li, Z., 2013. Design and analysis of robust Kanban system in an uncertain environment. Zugl.: Karlsruher Institut für Technologie, KIT, Diss., 2013, Print on demand ed. KIT Scientific Publishing, Karlsruhe.

[21] Pekarcikova, M., Trebuna, P., Kliment, M., Mizerak, M., Kral, S., 2021. Simulation Testing of the E-Kanban to Increase the Efficiency of Logistics Processes. Int. j. simul. model. 20 (1), 134–145.

[22] Pekarcikova, M., Trebuna, P., Kliment, M., Rosocha, L., 2020. Material Flow Optimization through E-Kanban System Simulation. Int. j. simul. model. 19 (2), 243–254.

[23] Ricky, C., Kadono, Y., 2020. A Case Study of E-Kanban Implementation in Indonesian Automotive Manufacture, in: 2020 8th International Conference on Cyber and IT Service Management (CITSM). 2020 8th International Conference on Cyber and IT Service Management (CITSM), Pangkal Pinang, Indonesia. 23.10.2020 - 24.10.2020. IEEE, 1–7.

[24] Oh, S.-C., Shin, J., 2012. A semantic e-Kanban system for network-centric manufacturing: technology, scale-free convergence, value and cost-sharing considerations. International Journal of Production Research 50 (19), 5292–5316.

[25] Marikova, O. E-kanban and its Practical Use. Conference STČ 2008 2008.

[26] Huo, L., Liu, B., Tian, Z., 2010. Application of RFID Technology in JIT Production Control, in: ICLEM 2010. International Conference of Logistics Engineering and Management (ICLEM) 2010, Chengdu, China. October 8-10, 2010. American Society of Civil Engineers, Reston, VA, pp. 2544–2550.

[27] Su, W.G., Qin, P.P., Li, L., Huang, X., 2011. Research on JIT Production Logistics Management System. AMR 328-330, 717–720.

[28] Chu X., Savino M.M., Palmieri A., 2017. Shelf replenishment with RFID-ERP-Kanban system: A case study in large distribution.

[29] Ghelichi, A., Abdelgawad, A., 2014. A study on RFID-based Kanban system in inventory management, in: 2014 IEEE International Conference on Industrial Engineering and Engineering Management. 2014 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), Selangor Darul Ehsan, Malaysia. 09.12.2014 - 12.12.2014. IEEE, pp. 1357–1361.

[30] Scholz-Reiter, B., Gorldt, C., Hinrichs, U., Tervo, J.T., Lewandowski, M., 2008. Simulation of a RFID-based KANBAN system for the production industries. PPS Management 13, 16–19.

[31] Thomas, K., Tribhu, S., S.P., A., 2015. Implementation of RFID based kanban system in a manufacturing industry 10, 34475–34478.

[32] Haryono, K., 2016. Gap between physical inventory transactions and computing in accounting information systems, in: Proceedings of the 2nd International Conference on Communication and Information Processing - ICCIP '16. the 2nd International Conference, Singapore, Singapore. 26.11.2016 - 29.11.2016. ACM Press, New York, New York, USA, pp. 93–98.

[33] Brown, W.M., 1948. Measuring Physical Inventories. Journal of the American Statistical Association 43 (243), 377–390.

Biography

Roman Ungern-Sternberg (*1989) is group lead for Operational Excellence at Fraunhofer IPA in Stuttgart, Germany. His research focus is on designing systems for logistical transparency in high variety production systems. He is consulting on value stream design, factory planning and Operational Excellence.

Christoph Kilian Merz (*1992) studied industrial engineering at FAU Erlangen-Nuremberg and Stoke-on-Trent. Currently, he works as a research assistant at Fraunhofer IPA, focusing on Operational Excellence and Intralogistics.

CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
CPSL 2023-2

5th Conference on Production Systems and Logistics

A Concept For The Development Of A Maturity Model For The Holistic Assessment Of Lean, Digital, And Sustainable Production Systems

Olivia Bernhard[1], Michael F. Zaeh[1]
[1]Institute for Machine Tools and Industrial Management, Technical University of Munich, Boltzmannstraße 15, 85748 Garching, Germany

Abstract

Manufacturing companies today face a volatile environment with a variety of challenges. Particularly, external factors such as the climate change, the digitalization, the material scarcity, or the shortage of skilled workers can be noted. At the same time, these factors are forcing companies to take measures to remain competitive and ensure their production system's future viability. In this context, established paradigms such as Lean Production and Industry 4.0 promise optimization potentials in terms of efficiency, quality, and costs. A new paradigm has gained importance with the emergence of the topic of sustainability, which aims to improve companies' use of resources and the recyclability of their products. However, there is no transparent model that enables companies to assess the status quo of their production system regarding these three paradigms, considering the interdependencies between the paradigms, and at the same time showing the implementation potential of methods or technologies within these paradigms. To support companies in rationalizing, digitalizing, and making their production processes more sustainable, this scientific paper presents a three-stage concept for a holistic maturity model. By providing transparency about the status quo of production systems in terms of Lean Production, digitalization, and sustainability, the model contributes to ensuring the future viability of such production systems in this highly competitive environment and under the political, social, and regulatory challenges.

Keywords

Maturity Model; Lean Production; Industry 4.0; Sustainability

1. Introduction

Manufacturing companies today face a turbulent environment. Increasing cost pressure, changing consumer behaviors, the shortage of skilled workers, or the scarcity of resources are production-specific challenges that have an impact on almost the entire value chain [1]. At the same time, climate change is raising public and political expectations regarding the sustainability of manufacturing companies [2]. As a result, in addition to the existing economic challenges, there is an increasing focus and need for action concerning the responsibility of companies towards the environment, the society, and their employees.

The two developments Lean Production and Industry 4.0 have led many companies to transform their production in recent decades [3,4]. While Lean Production (LP) focuses on the waste reduction and the customer orientation [5], Industry 4.0 (I4.0) aims to increase the effectiveness and the efficiency to reduce costs by digitizing and networking corporate and production processes [6]. This requires companies to implement digital technologies in production [7]. However, there is still a lack of comprehensive and widespread implementation of LP and I4.0 in companies [8,9].

DOI: https://doi.org/10.15488/15280
ISSN: 2701-6277

In the context of the additional challenge of sustainability, industry and research are increasingly recognizing the opportunity to also improve the production's sustainability through the targeted use of digital technologies. One example is the use of additive manufacturing, which can help to decarbonize existing manufacturing processes and to make them more environmentally friendly, i.e., by reducing waste or material consumption [10]. The role of the people in production, and therefore the inclusion of soft factors in the assessment of a company and its production, is also becoming increasingly important. These requirements can be met both by considering all sustainability dimensions equally and by considering digital technologies from the perspective of supporting employees [11,12].

In recent years, an integrative view of the three paradigms LP, I4.0, and sustainability in production has received increasing attention in the academic environment [13–15], cf. **Figure 1**. The increasing speed, scope, and complexity of the challenges require companies to maintain their competitiveness through transparency of both the degree of implementation and the targeted identification of improvement potential in the lean, digital, and sustainable transformation [16]. In this context, maturity models can serve as supportive tools to assess the status quo of the company regarding the paradigms and also to allow for the identification of potentials for action [17,18]. Therefore, this paper presents a concept for a holistic maturity model for the assessment of lean, digital, and sustainable production systems that considers the interactions of the paradigms.

To this end, the first section provides an overview of the fundamentals of LP, I4.0, and sustainability (2.1), as well as maturity models (2.2), before presenting the state of the art and deriving the research gap (section 3). At the beginning of section 4, the concept is briefly introduced before the individual steps are presented in detail (4.1 – 4.4). The paper concludes with a summary and an outlook (section 5).

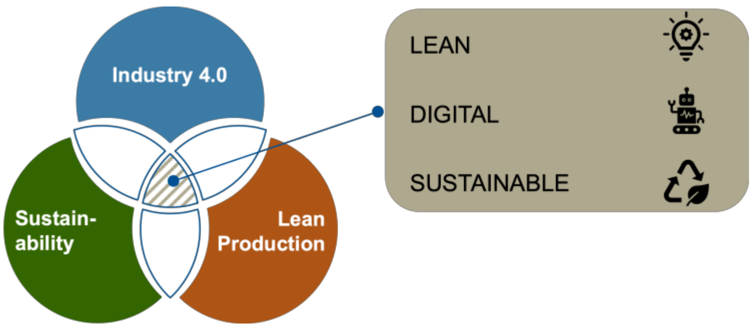


Figure 1: Lean Production, Industry 4.0, and sustainability as a holistic approach for future-proof production systems

2. Fundamentals

2.1 Lean Production, Industry 4.0, and Sustainability

"All we are doing is looking at the time line, from the moment the customer gives us an order to the point when we collect the cash [19]." This quote from Taichii Ono describes the principles of the Toyota Production System, which was introduced in the 1980s and forms the basis of the lean philosophy. At the heart of LP is the pursuit of the highest quality, the shortest lead times, and the lowest costs through systematic, employee-supported principles and methods such as waste elimination, stable and efficient processes, or a continuous improvement process. [5,20] In industry today, LP is often implemented and realized in the form of a Lean Production System (LPS), where LPS primarily describes the interaction of people, technology, and organization. VDI 2870-1 [21] describes an LPS as an "enterprise-specific, methodical system of rules for the continuous orientation of all enterprise processes to the customer". This clearly states that every company needs an individual adaptation of the production system as well as an overarching structuring of the methods like 5S or JIDOKA. Moreover, it is essential that the processes are aligned with the company's objectives using appropriate methods. [22]

The Fourth Industrial Revolution (Industry 4.0) is the latest revolution in the industrial environment and aims to optimize industrial value creation [23,24]. In this context, the term I4.0, which was introduced in 2011, describes the entire scope of the reorientation, redesign, and further development of existing production systems [23]. With the aim of creating new, intelligent factories, reducing production costs, and optimizing material and information flows along the value chain, I4.0 particularly characterizes the networking and digitalization of people, processes, plants, and products [24,25]. To achieve this goal, the data collected and analyzed play an increasingly central role [26]. In addition, various technologies such as the automatic identification of objects or people via data exchange or the additive manufacturing of products or tools have become established as part of the digital transformation, and their implementation is a building block on the way to the digital factory [27,28].

Driven by political and societal expectations and rules, e.g., penalties for failing to meet climate targets, the importance of sustainability in the industrial sector has increased significantly in recent years. The key challenge for future sustainable production is to achieve economic development without harming the environment [29]. The system of sustainability involves the use of a regenerative system in such a way that the essential characteristics of the system are preserved and natural regeneration of its stock is possible [30]. According to Elkington [31], the three dimensions of economic, environmental, and social sustainability are brought together under the term sustainability, and their equal consideration is becoming increasingly important. While the former focuses on a company's economic success, environmental sustainability focuses on reducing a company's negative environmental impact, such as CO_2 emissions, in order to protect natural resources [32,33]. Social sustainability places people and society at the center of consideration, focusing on the well-being of the company's employees [34,35]. Within these dimensions, different sustainability aspects like the educational support or the consumption of resources exist [32,36].

2.2 Maturity Models

Maturity models have gained importance in various industries and domains as they serve as basic frameworks to capture the current status quo of an organization and to define clear goals for further development or to reveal possible company-specific evolution paths [17,37]. By applying maturity models and thus revealing the current and desired state of a company in an area, companies are given a tool to improve the performance of a specific area within an organization [38,39].

According to Becker et al. [17], a maturity model comprises a sequence of maturity levels for a class of objects and thus describes an "anticipated, desired or typical evolution path of these objects shaped as discrete stages", starting from an initial stage to full maturity. Three maturity models can be distinguished depending on the purpose of the application or use: descriptive, prescriptive, and comparative maturity models [40]. Descriptive maturity models are particularly suitable for assessing the current state (of an organization, process, or domain), as they allow the current capabilities of an entity to be captured [17]. Prescriptive maturity models already identify concrete improvement or action options that can be used to achieve a target maturity level [17,18]. A comparative maturity model can be used for internal or external benchmarking to provide a comparative assessment across, for example, regions or industries [41,42,40].

The components of maturity models can be divided into four essential core components [41,43,37]. At the first level, there are the maturity levels, which form a kind of overarching framework in the maturity model through the targeted selection of labels, e.g., in the form of keywords (e.g., initial, repeatable, defined, managed, optimizing) [41]. The maturity levels clearly define the requirements for achieving each level [44]. They are in turn associated with key process areas at the second level, which are used to evaluate the measurement of the maturity level and within which certain targets must be achieved to reach a higher maturity level. The selection of suitable key process areas is therefore a difficult and an essential part of the development of the maturity framework, as they must comprehensively reflect the state of maturity and thus have a direct impact on the effectiveness of the model [42]. Common features at level 3 structure the key process areas into understandable sub-goals. Common features are in turn described by key practices, which are concrete activities that need to be carried out and build the fourth level. [41,43,37]

3. State of the Art

The literature review (LR) is a central starting point and a foundation for conducting a research project, as it captures the literature relevant to the topic under investigation, strengthening both the rigor and the relevance of the research [45]. An LR thus avoids re-examining knowledge that has already been developed and ensures that the existing knowledge base is fully utilized [46]. To obtain an overview of the state of the art in maturity models for the holistic assessment of production systems in the context of LP, digitalization, and sustainability, a systematic LR in SCOPUS was conducted following Webster & Watson [47] and Brocke et al [48]. The LR has shown that there are a variety of approaches to assessing maturity within the individual paradigms of LP, I4.0, and sustainability. Due to the holistic view of the paradigms aimed at in this concept, approaches that either combine LP and I4.0 or also consider sustainability are presented below.

3.1 Approaches in the Area of Lean Production and Industry 4.0

With the Production Assessment 4.0, Pokorni et al. [49] provide an approach to assess the maturity of a medium-sized manufacturing company concerning Lean Management (LM) and I4.0. The approach distinguishes between the three levels of the domain, the sub-domain, and the point of consideration (PoC). In this way, it covers an assessment of manufacturing and assembly processes or the organization through sub-domains such as the I4.0 target planning or the production leveling to points of consideration such as the digital factory layout. The two-stage assessment starts with an assessment of the capability levels (CL) of the PoCs belonging to a sub-domain. The average of the CLs of the PoCs finally results in the assessment at the sub-domain level and thus in the first identification of improvement potential. Subsequently, the sub-domains are systematized based on their allocation to the domains LM, I4.0 fundamentals, and I4.0 excellence. Rößler & Haschemi [50] also provide a methodology for assessing the Lean I4.0 maturity of production and logistics with their Smart Factory Assessment (SFA), which includes twelve categories such as the product and the material flow or the shop floor management and whose application aims to derive improvement paths towards Lean and I4.0 excellence. The seven Lean categories and five I4.0 categories have subcategories that are discussed during the factory visit in the expert-based SFA and rated on a five-point scale. These ratings are then consolidated and ultimately used to calculate the Lean and I4.0 criteria scores, representing the status quo. Finally, recommendations for action can be derived by comparing the target and the actual status. Even though the two approaches integrate both paradigms, LP and I4.0, none of them provides a comprehensive inclusion. The model of Pokorni et al. [49] focuses on small and medium-sized enterprises (SMEs) and uses different granularities in the evaluation of the paradigms of the same observation level. The maturity model proposed by Rößler & Haschemi [50] does not provide a uniform allocation of the LP and I4.0 paradigms.

3.2 Approaches in the Area of Lean Production, Industry 4.0, and Sustainability

The maturity model by Zoubek et al. [51], published in 2021, provides an approach for assessing CO_2 reduction taking into account I4.0 technologies in the dimensions of production, logistics, maintenance, and IT. Based on the core processes with environmental potential identified through value stream analysis, it shows how manufacturing processes can be shifted towards environmentally friendly production. The level of the dimensions depends on the assessment of specific indicators within these dimensions. Each dimension has been assigned three indicators describing environmental aspects, such as the degree of automation in production, energy sources and means of production, and environmental aspects of the production system. For the indicators considered, the authors propose an assessment of the carbon footprint (CF) in six levels, starting from level 0, where the company has a 0% CF reduction of the indicator considered, to level 5, which describes a carbon-neutral company. In their approach published in 2022, Wessing & Müller [15] consider Lean, Automated, Sustainable, and Digital (LAND) as the core characteristics of future production and develop a five-stage maturity model based on this. Nine areas form the pillars and foundation of their production of the future and assign the function of a pillar to sustainability, digitalization, and lean management, among others. The result of this approach is a five-level network diagram based on the I4.0 Readiness Study to assess the maturity of each pillar. The approach of Zoubek et al. [51] does not provide a general and comprehensive integration of individual LP methods, I4.0 technologies, and sustainability aspects within the dimensions for assessing the maturity of companies in the individual paradigms, as it only considers individual indicators under the aspect of CF. In the approach of Wessing & Müller [15], both a clear description of the individual maturity levels and a more specific consideration of the three paradigms LM, I4.0, and sustainability are missing. Furthermore, although interactions between the pillars are shown, a more detailed consideration at the level of methods, technologies, or aspects would be helpful.

It becomes apparent that research has so far lacked a comprehensive, general, and company-specific model for the assessment of future-proof production systems, which allows a holistic, multidimensional view of the maturity of LP, I4.0, and sustainability from the production system level to the level of methods, technologies, and aspects, considering the interdependencies of the three paradigms. By including interdependencies, it can made transparent how achieving a higher level of maturity in one paradigm depends on improving maturity in another paradigm. To fill this gap, the following section presents a concept for a holistic maturity model to create transparency and derive actions for future-proof production systems.

4. Concept

This paper aims to present a concept for a holistic, multidimensional maturity model for the assessment of lean, digital, and sustainable production systems. The maturity model to be developed should provide a transparent visualization of the status quo of a manufacturing company in terms of methods, technologies, and aspects within the three paradigms, considering the interactions between them. **Figure 2** illustrates the four-step approach to achieve this overarching goal. The four steps can be assigned to the two phases of the preparation and the development of the maturity model.

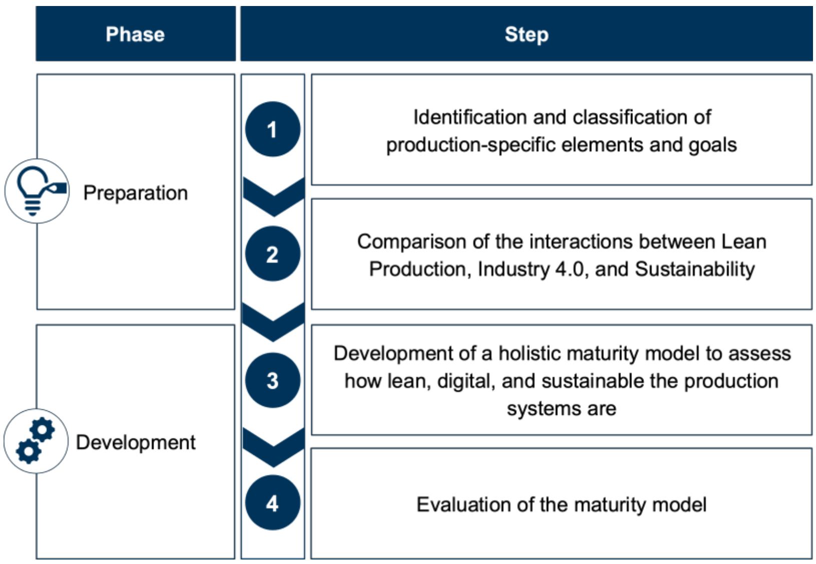


Figure 2: Concept for a holistic maturity model

Due to the presence of the sustainability paradigm, the first two steps of the concept are shown below for sustainability. The procedure is analogous for the two paradigms of lean production and digitalization in the sense of a holistic view and will be presented with the corresponding work results in further publications.

This builds on the previous preliminary work by Aull [52] and Dillinger et al. [27,53], which specifies the LP methods and the I4.0 technologies and analyze interdependencies.

To develop the holistic maturity model, the relevant elements (LP methods, I4.0 technologies, and sustainability aspects) within the paradigms must first be identified and classified. Here, elements are factors that help to improve LP, I4.0, or sustainability in the company by integrating new measures or developing existing ones. The first step is therefore a systematic analysis of the production-specific sustainability aspects, including all sustainability dimensions that are relevant to production. The next step is to examine the interactions within and between paradigms, with the focus of this concept is on the interactions within and with sustainability in production. Before a cross-paradigm comparison of the elements takes place, the interactions within the sustainability paradigm are examined at the beginning of the second step. The actual development of the maturity model starts with the elaboration of the third step. To achieve the third step, requirements for the maturity model to be developed are first derived, e.g., through design guidelines and company specifications. Furthermore, in the third step, a maturity model is developed based on the scientific approach of Design Science Research according to Hevner & Chatterjee [54]. The concept concludes with an evaluation of the maturity model, which, in addition to the scientific evaluation, includes a first industrial evaluation as a prototype. In the next section, the individual steps and the associated scientific procedure are described in more detail.

4.1 Step 1: Identification and classification of production-specific elements and goals

Due to the widespread importance of the sustainability paradigm in society, politics, and legislation, it is becoming increasingly important to select and to specify from the available sustainability aspects those whose implementation or further development in production directly affects the company's objectives. The first step for developing the maturity model is therefore to identify and then to classify the sustainability aspects relevant to production. With the help of a comprehensive LR, the extent to which the established dimensions of sustainability (economic, environmental, social) can be transferred to production systems and which aspects within these dimensions can be used to advance sustainability at the production level are examined (see **Figure 3**, left). Subsequently, the developed sustainability aspects are transferred into a multi-level, meaningful model with the help of a clustering procedure and finally evaluated for completeness and relevance from an industrial perspective. Following the development of the sustainability aspects (SA), existing production-relevant goals are analyzed from a sustainability perspective with the help of an extensive literature research and expert interviews. In this way, general sustainability goals are specified based on the three dimensions of economic, environmental, and social sustainability in the production context. The analyzed production-specific sustainability goals (SG) are then examined for existing correlations with the previously identified sustainability aspects, as shown in **Figure 3** on the right. This connection allows for a goal-oriented and therefore company-specific visualization of the relevant measures.

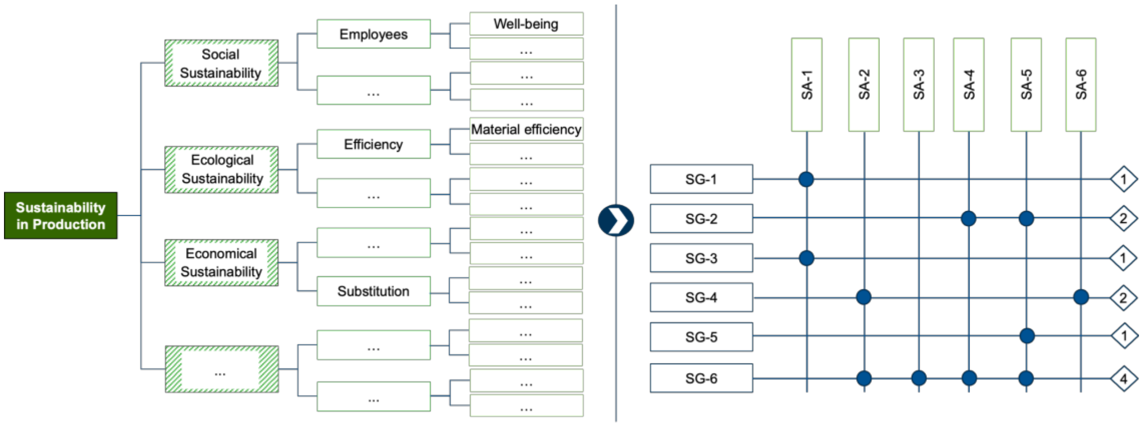


Figure 3: Production relevant sustainability aspects and goals

4.2 Step 2: Comparison of the interactions between Lean Production, Industry 4.0, and Sustainability

In the second step of the preparation phase, the extent to which the three paradigms LP, I4.0, and sustainability (SB) influence each other is examined (cf. **Figure 4**). The analysis of the interdependencies is initially carried out through a comprehensive literature review and is supplemented by an empirical study (e.g., a Delphi study). To elaborate and visualize the interdependencies, either a Domain Structure Matrix (DSM) or a Domain Mapping Matrix (DMM) is used, depending on the linkage, as they are intuitively readable and very compact [55].

At the beginning of the second step, an analysis of the interaction at the paradigm level (LP, I4.0, SB) is carried out. This means that it is analyzed to what extent there is a positive, negative, or no correlation between the paradigms. A positive correlation means that one paradigm supports the other, while a negative interaction means that one paradigm hinders the implementation or development of the other. In the case of no interaction, the paradigms can be considered or implemented independently. After the analysis of the interactions at the paradigm level, the second step is the interdependency analysis at the element level: lean methods (LP-1 to LP-y), I4.0 technologies (I4.0-1 to I4.0-z), and sustainability aspects (SA-1 to SA-x). Based on the SA identified in the first step, a paradigm-specific analysis of the SA is carried out to conclude whether the advancement of one SA (e.g., from the area of social SB) also influences another SA (e.g., from the area of environmental SB). For the elaboration and visualization of the paradigm-specific interdependencies, a DSM is used as described above. The paradigm-specific interdependency analysis is followed by the cross-paradigm analysis. Here it is examined to what extent LP methods or I4.0 technologies influence the implementation of SA or vice versa. The interdependencies are then compared in a DMM.

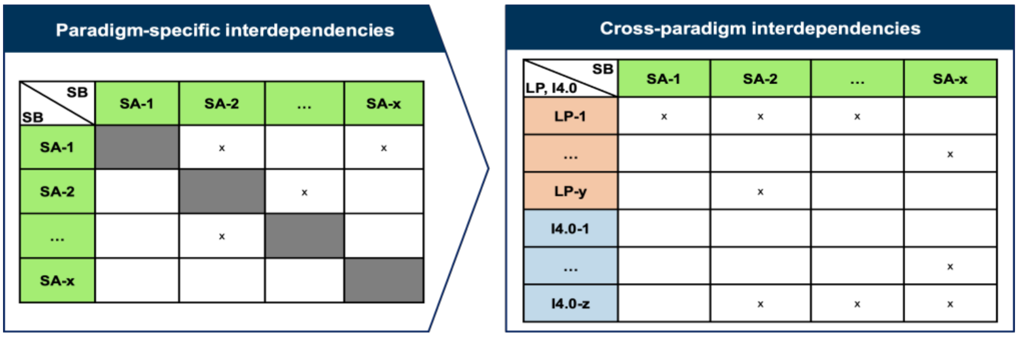


Figure 4: Comparison of interdependencies within and between the paradigms

4.3 Step 3: Development of a holistic maturity model to assess how lean, digital, and sustainable the production systems are

The third step aims to develop a holistic model for assessing the maturity of production systems in terms of their lean production, digitalization, and sustainability. At the beginning of the third step, requirements for the maturity model to be developed are defined, which include basic scientific quality criteria [56], and also design or functional principles [40] of the model. Furthermore, the identification of content-related requirements, such as paradigm-specific or cross-paradigm requirements, for a holistic maturity model is planned. For this purpose, the data obtained through expert interviews will be subjected to qualitative content analysis with inductive category formation [57]. The identification and definition of the requirements for the maturity model should ensure the later applicability and also the usefulness of the model, which is why the inclusion of the industrial perspective is planned in addition to the scientific preparation. In this way, it will also be possible to examine the extent to which the requirements of SMEs coincide with those of large companies. Subsequently, scientific approaches for the development of maturity models, such as those by Mettler [58], Becker et al. [17], or Maier et al. [42], will be compared and examined for their suitability for the use case considered in the research project. After the selection of a suitable procedure model for the development of the maturity model for the holistic assessment of lean, digital, and sustainable production systems, the individual phases will be executed step by step. This includes the definition of the level of abstraction, the selection of an assessment method, and the definition of maturity levels and maturity factors.

4.4 Step 4: Evaluation of the maturity model

In step 4, the final evaluation of the developed model regarding criteria such as validity, completeness, or unambiguity ensures that the result is independent of the user when the developed model is applied [41]. First, the maturity model should be subjected to a scientific evaluation. For this purpose, the previously developed model is evaluated in its entirety by research experts regarding the maturity architecture and maturity factors. To ensure a heterogeneous evaluation, an industrial evaluation of the suitability of the maturity model is also planned. Again, a sufficient number of experts are selected who have expertise in the three paradigms LP, I4.0, and sustainability in a production context and who are familiar with the handling of maturity models. The results of the evaluation will be used to validate the requirements previously defined in step 3 and to identify the potential for improvement. In addition, the results of the evaluation serve as a basis to initiate an iterative process to adapt and improve the maturity model if needed.

5. Conclusion and Outlook

For their future competitiveness, manufacturing companies should include the implementation status of the LP, I4.0, and sustainability paradigms in their target definition and control. The use of a holistic maturity model, which identifies the production-relevant elements of LP, I4.0, and sustainability, helps companies to assess their current implementation status in relation to their objectives, to identify gaps and weaknesses, and to derive measures for improvement. In addition to identifying areas for implementation and improvement, the inclusion of interactions can make transparent the extent to which achieving a higher level of maturity in one paradigm depends on improving the level of maturity in another paradigm. Moreover, the holistic maturity model can be used for benchmarking, e.g., by a plant manager to compare the maturity of his production system with the maturity of other production systems in his company, but also of competitors. In this way, experience in the companies' production network can be used to improve production systems if those with a higher maturity serve as inspiration or scale. Overall, by generating transparency, this model promotes the future viability of production systems and is becoming increasingly important, especially due to the growing demands for resilient and flexible production as well as the support of employees through digital technologies, such as through Industry 5.0 [59].

The validated maturity model resulting from this scientific project can be easily integrated into an organization's existing process environment. Furthermore, it can be directly linked to the company's strategic objectives, and selected values can be used as key performance indicators and, for example, as part of the company's balanced scorecard. In addition, through programming and software-based preparation, the model can be integrated into the company's tool landscape. In this way, the developed maturity model can become an integral part of management's daily leadership tasks. At the same time, the clear and in-depth approach with parameters helps employees and their lower management levels to easily understand and apply the model and its results, and at the same time to provide feedback to optimize the model for the specific needs of their company's production.

The four-step concept presented provides a general approach for multidimensional maturity assessments and thus for creating transparency of production systems in terms of their lean production, digitalization, and sustainability. The two main phases of preparation and development ensure that the required production-specific parameters are first comprehensively determined and that the basis for a holistic assessment is ensured by including cross-paradigm interactions before the systematic development and evaluation of the maturity model begins. The next step will be the detailed and systematic elaboration of these steps. Following the presented four-step concept, the topics will be elaborated in further publications.

Acknowledgements

The authors would like to thank the StMWi for the generous support within the research project IDEE-H (ROB-2-3410.20-04-10-21).

References

[1] Reinhart, G., 2017. Handbuch Industrie 4.0: Geschäftsmodelle, Prozesse, Technik. Carl Hanser Verlag GmbH Co KG.

[2] Carvalho, N., Chaim, O., Cazarini, E., Gerolamo, M., 2018. Manufacturing in the fourth industrial revolution: A positive prospect in sustainable manufacturing. Procedia Manufacturing 21, 671–678.

[3] Abele, E., Reinhart, G., 2011. Zukunft der Produktion: Herausforderungen, Forschungsfelder, Chancen. Hanser, München.

[4] Spath, D., Ganschar, O., Gerlach, S., Hämmerle, M., Krause, T., Schlund, S., 2013. Produktionsarbeit der Zukunft - Industrie 4.0. Frauenhofer-Verlag, Stuttgart, 1–150.

[5] Röhm, M., Wiendahl, H.-H., Denner, T., Schöllhammer, O., 2020. Ganzheitliche Produktionssysteme, in: Bauernhansl, T. (Ed.), Fabrikbetriebslehre 1. Management in der Produktion. Springer Vieweg, Berlin.

[6] Roth, A., 2016. Einführung und Umsetzung von Industrie 4.0: Grundlagen, Vorgehensmodell und Use Cases aus der Praxis. Springer-Verlag, Berlin, Heidelberg.

[7] Hess, T., 2019. Digitale Transformation Strategisch Steuern: Vom Zufallstreffer Zum Systematischen Vorgehen. Springer Fachmedien, Wiesbaden.

[8] Goschy, W., 2016. 25 Years of Lean Management: Lean Yesterday, Today and Tomorrow. https://www.staufen.ag/wp-content/uploads/STAUFEN.-survey_25-years-lean-management_EN.pdf. Accessed 5 July 2023.

[9] Raab, C., 2022. Industrie 4.0 - so digital sind Deutschlands Fabriken. https://www.bitkom.org/sites/main/files/2022-05/Bitkom-Charts_Industrie_4.0_240522.pdf. Accessed 5 July 2023.

[10] Lakshmanan, R., Nyamekye, P., Virolainen, V.-M., Piili, H., 2023. The convergence of lean management and additive manufacturing: Case of manufacturing industries. Cleaner Engineering and Technology, 100620.

[11] Steven, M., Klünder, T., 2018. Nachhaltigkeit schlanker Industrie 4.0-Netzwerke. Marktorientiertes Produkt-und Produktionsmanagement in digitalen Umwelten: Festgabe für Klaus Bellmann zum 75. Geburtstag, 201–222.

[12] Zizic, M.C., Mladineo, M., Gjeldum, N., Celent, L., 2022. From industry 4.0 towards industry 5.0: A review and analysis of paradigm shift for the people, organization and technology. Energies 15 (14), 5221.

[13] Roesch, M., Köberlein, J., Goldmanns, M., Hohmann, A., 2021. Green-Lean-Digital als Leitbild für die nachhaltige Fabrik der Zukunft. Zeitschrift für wirtschaftlichen Fabrikbetrieb 116 (1-2), 29–33.

[14] Varela, L., Araújo, A., Ávila, P., Castro, H., Putnik, G., 2019. Evaluation of the relation between lean manufacturing, industry 4.0, and sustainability. Sustainability 11 (5), 1439.

[15] Wessing, S., Müller, E., 2022. Produktion der Zukunft–Reifegradmodell als Analyseinstrument. Zeitschrift für wirtschaftlichen Fabrikbetrieb 117 (6), 410–414.

[16] Bernhard, O., Dillinger, F., Zaeh, M., 2023. Methodology for Transformation Processes in the Context of Lean 4.0 in Manufacturing Companies. 56th CIRP Conference on Manufacturing Systems.

[17] Becker, J., Knackstedt, R., Pöppelbuß, J., 2009. Developing maturity models for IT management: A procedure model and its application. Business & Information Systems Engineering 1, 213–222.

[18] Maier, A.M., Kreimeyer, M., Lindemann, U., Clarkson, P.J., 2009. Reflecting communication: a key factor for successful collaboration between embodiment design and simulation. Journal of Engineering Design 20 (3), 265–287.

[19] Ōno, T., 1988. Toyota Production System: Beyond Large-Scale Production, 1st ed. CRC Press.

[20] Schlick, C., Bruder, R., Luczak, H. (Eds.), 2018. Arbeitswissenschaft, 4. Auflage ed. Springer, Berlin, Heidelberg.

[21] VDI 2870-1. Lean production systems: Basic principles, introduction, and review.

[22] Dombrowski, U., Mielke, T., 2015. Ganzheitliche Produktionssysteme: Aktueller Stand und Zukünftige Entwicklungen. Springer, Berlin, Heidelberg.

[23] Bauernhansl, T., Hompel, M. ten, Vogel-Heuser, B. (Eds.), 2014. Industrie 4.0 in Produktion, Automatisierung und Logistik: Anwendung, Technologien, Migration. Springer Vieweg, Wiesbaden.

[24] Cohen, Y., Faccio, M., Pilati, F., Yao, X., 2019. Design and management of digital manufacturing and assembly systems in the Industry 4.0 era. Int J Adv Manuf Technol 105 (9), 3565–3577.

[25] Yao, X., Lin, Y., 2016. Emerging manufacturing paradigm shifts for the incoming industrial revolution. Int J Adv Manuf Technol 85 (5-8), 1665–1676.

[26] Huber, W., 2018. Industrie 4.0 kompakt – Wie Technologien unsere Wirtschaft und unsere Unternehmen verändern. Springer Vieweg, Wiesbaden.

[27] Dillinger, F., Bernhard, O., Kagerer, M., Reinhart, G., 2022. Industry 4.0 implementation sequence for manufacturing companies. Production Engineering 16 (5), 705–718.

[28] Veile, J.W., Kiel, D., Müller, J.M., Voigt, K.-I., 2020. Lessons learned from Industry 4.0 implementation in the German manufacturing industry. Journal of Manufacturing Technology Management 31 (5), 977–997.

[29] Gomes da Silva, F. J., Gouveia, R.M., 2020. Cleaner Production: Towards a Better Future. Springer Cham, Switzerland.

[30] Pufé, I., 2017. Nachhaltigkeit. UVK Verlagsgesellschaft, Konstanz, München.

[31] Elkington, J., 1997. Cannibals with Forks: The Triple Bottom Line of 21st Century Business. Capstone, Oxford.

[32] Correia, M.S., 2019. Sustainability: An overview of the triple bottom line and sustainability implementation. International Journal of Strategic Engineering (IJoSE) 2 (1), 29–38.

[33] Kropp, A., 2019. Grundlagen der Nachhaltigen Entwicklung: Handlungsmöglichkeiten und Strategien zur Umsetzung, 1st ed. Springer Fachmedien, Wiesbaden.

[34] Hauff, M. von, 2021. Nachhaltige Entwicklung: Grundlagen und Umsetzung. De Gruyter Oldenbourg.

[35] Pichler, C., 2020. Das Leitbild ‚Nachhaltige Entwicklung '- eine Einführung. Der öffentliche Sektor 46 (1).

[36] Tasdemir, C., Gazo, R., 2018. A systematic literature review for better understanding of lean driven sustainability. Sustainability 10 (7), 2544.

[37] Knackstedt, R., Pöppelbuß, J., Becker, J., 2009. Vorgehensmodell zur Entwicklung von Reifegradmodellen. Wirtschaftsinformatik Proceedings.

[38] Ahern, D.M., Clouse, A., Turner, R., 2004. CMMI distilled: a practical introduction to integrated process improvement. Addison-Wesley Professional.

[39] Paulk, M.C., Chrissis, M.B., Curtis, B., Weber C. V., 1993. Capability Maturity Model for Software Version 1.1. Software Engineering Institute.

[40] Pöppelbuß, J., Röglinger, M., 2011. What makes a useful maturity model? A framework of general design principles for maturity models and its demonstration in business process management.

[41] Bruin, T. de, Rosemann, M., Freeze, R., Kulkarni, U., 2005. Understanding the main phases of developing a maturity assessment model, 8–19.

[42] Maier, A.M., Moultrie, J., Clarkson, P.J., 2012. Assessing organizational capabilities: reviewing and guiding the development of maturity grids. IEEE transactions on engineering management 59 (1), 138–159.

[43] Fraser, P., Moultrie, J., Gregory, M., 2002. The use of maturity models/grids as a tool in assessing product development capability. IEEE International Engineering Management Conference 1, 244–249.

[44] Hecht, S., 2014. Begriffliche und theoretische Grundlagen. Ein Reifegradmodell für die Bewertung und Verbesserung von Fähigkeiten im ERP-Anwendungsmanagement, 9–39.

[45] Baker, M.J., 2000. Writing a literature review. The marketing review 1 (2), 219–247.

[46] Denyer, D., Tranfield, D., 2006. Using qualitative research synthesis to build an actionable knowledge base. Management decision 44 (2), 213–227.

[47] Webster, J., Watson, R.T., 2002. Analyzing the past to prepare for the future: Writing a literature review. MIS quarterly.

[48] 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.

[49] Pokorni, B., Schlund, S., Findeisen, S., Tomm, A., Euper, D., Mehl, D., Brehm, N., Ahmad, D., Ohlhausen, P., Palm, D., 2017. Produktionsassessment 4.0. Zeitschrift für wirtschaftlichen Fabrikbetrieb 112 (1-2), 20–24.

[50] Rößler, M.P., Haschemi, M., 2017. Smart Factory Assessment (SFA). Zeitschrift für wirtschaftlichen Fabrikbetrieb 112 (10), 699–703.

[51] Zoubek, M., Poor, P., Broum, T., Basl, J., Simon, M., 2021. Industry 4.0 maturity model assessing environmental attributes of manufacturing company. Applied Sciences 11 (11), 5151.

[52] Aull, F., 2013. Modell zur Ableitung effizienter Implementierungsstrategien für Lean-Production-Methoden. Herbert Utz Verlag, München.

[53] Dillinger, F., Tropschuh, B., Dervis, M.Y., Reinhart, G., 2022. A Systematic Approach to Identify the Interdependencies of Lean Production and Industry 4.0 Elements. Procedia CIRP 112, 85–90.

[54] Hevner, A., Chatterjee, S., 2010. Design science research in information systems. Design research in information systems: theory and practice, 9–22.

[55] Eppinger, S.D., Browning, T.R., 2012. Design structure matrix methods and applications. MIT press.

[56] Helfrich, H., 2016. Wissenschaftstheorie für Betriebswissenschaftler. Springer Gabler, Wiesbaden.

[57] Mayring, P., 2015. Qualitative Inhaltsanalyse, 12th ed. Beltz, Weinheim, Basel.

[58] Mettler, T., 2011. Maturity assessment models: a design science research approach. International Journal of Society Systems Science 3 (1/2), 81–98.

[59] Breque, M., Nul, L. de, Petridis, A., 2021. Industry 5.0 - Towards a sustainable, human-centric and resilient European Industry. Research and Innovation Paper Series.

Biography

M. Sc. **Olivia Bernhard** is currently a Research Associate and PhD Candidate at the Institute for Machine Tools and Industrial Management (*iwb*) at the Technical University of Munich (TUM). She studied Industrial Engineering and Management at the Technical University of Darmstadt and the TUM.

Prof. Dr. **Michael F. Zaeh** is director at the Institute for Machine Tools and Industrial Management (*iwb*) at the Technical University of Munich.

CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
CPSL 2023-2

5th Conference on Production Systems and Logistics

Backlog control in optoelectronic production using a digital twin

Jonas Schneider[1], Tobias Hiller[1], Peter Nyhuis[1]
[1]Leibniz University Hannover, Institute of Production Systems and Logistics (IFA), Hanover, Germany

Abstract

Digital twins are becoming increasingly popular in industry and are being used in various areas, such as production planning and control. Logistics performance still needs to be improved, especially in highly complex and automated production processes such as optoelectronics. The significant challenges faced by industrial companies today, such as stricter quality standards, smaller quantities and shorter product life cycles, exacerbate this phenomenon. In this context, digital twins offer a point of reference for improvement by providing an additional database that can be used to make more informed decisions in realtime. The novel contribution of this paper is the design of a simulation as a digital twin in the context of optoelectronic production. It is used to simulate a variety of backlog scenarios in production planning and to provide an additional source of data for backlog control. We also present an application example of how the digital twin can reduce backlogs in the production process. The simulation indicates that the designed model can effectively support the improvement of logistics performance by addressing the significant challenges in modern production.

Keywords

Production Planning and Control; Digital Twin; Simulation; Backlog; Optoelectronic Production

1. Introduction

Digital transformation, combined with increasingly complex production structures and customer logistics requirements, is not new [1]. In this context, achieving high logistics performance while reducing logistics costs is a fundamental objective for manufacturing companies [1–3]. To achieve sustainable advantages in a globalized competitive environment, these companies need to meet all the logistical requirements of their customers. For this reason, transparent analysis of logistics potentials and constraints is highly important [1]. However, this objective is not always feasible, given the complexity and diversity of the processes to be considered within the company's internal supply chain [1,4]. In particular, it is challenging to recognize the correlations between the logistical target variables and the possibilities of controlling them [1,4,5]. Beyond the market's logistical demands, companies must develop new processes to fulfil future requirements. Innovative, automated, and self-optimising production systems are required to meet these challenges. [1,6,7]

Digital twins (DTs) are one way to address these challenges [8]. DTs are a crucial concept in the context of Industry 4.0 [9] and a key driver in the digital transformation of production processes [6,8,10]. A DT can be defined as a virtual replica of a physical object, process, or system [11,12]. It enables realtime monitoring and analysis of the physical counterpart to optimize performance and improve overall efficiency [11–13].

Production planning and control (PPC) allows companies to respond to turbulent market conditions (e.g., maintaining production supply when backlogs occur) [1,14,15]. An efficient PPC system is critical to successfully executing production plans and achieving logistical goals [16].

DOI: https://doi.org/10.15488/15298
ISSN: 2701-6277

This paper aims to present the design of a simulation as a DT in the context of PPC to provide an additional data source for better production backlog control. For this reason, the investigations include a DT at the interface between production and feedback data collection to capture or infer conventionally unavailable information. We are trying to consolidate a database for dynamic adjustments and actions within the PPC. Our paper is based on the theoretical elaboration of Hiller et al.'s [17] conceptual backlog consideration for integrating a DT into the PPC control loop. The remainder of the paper is organized as follows: Section 2 discusses the basics of PPC, the principles of DTs, and how to integrate them into the PPC control loop. Section 3 introduces the use of DTs in optoelectronic production by presenting the real production process and the simulation as a DT. Section 4 presents an application example. Finally, section 5 concludes the paper.

2. Background

2.1 Queuing System in the context of PPC

PPC refers to loading, scheduling, sequencing, monitoring, and controlling the use of resources during production to fulfil production orders [4]. Loading is concerned with how much to do; scheduling is concerned with when to do things; sequencing is concerned with what order to do things; and monitoring and control are concerned with whether activities are going according to plan and corrective actions are needed to fulfil activities within the plan [18]. In this context, Enterprise Resource Planning (ERP) systems perform and coordinate those PPC activities [4,19]. However, ERP systems tend to be cumbersome and do not support the realtime decision-making required in today's market environment [4].

Production planning generally determines the production orders to be processed by scheduling the planned start and finish dates using detailed scheduling [20]. It defines the planned input and output of production and the planned sequence in which orders are processed [1]. Based on the production planning process, production control is responsible for the operational implementation and realization of the production plans. It includes order release, capacity control, and sequence planning [16]. As a continuous progress monitor, production control is used as a cross-cutting task of PPC. This task aims to measure the logistical performance of production processes, identify deviations from the plan, and make recommendations that lead to adjustments to the planned values in subsequent planning iterations. [16] The PPC provides the necessary planning data. The actual data will be collected and provided by DT in the future through the simulation results of this paper.

However, the goals of PPC and controlling can be divided into logistical cost goals (work in process and utilization) and logistics performance objectives (schedule reliability and throughput time), which together represent the economic efficiency of production [1,16,21]. For the remainder of the investigation, the focus of this holistic view will be backlog control in the context of PPC. Production backlog is the difference between actual and planned output ($\text{Backlog}(t) = \text{Output}_{\text{Actual}}(t) - \text{Output}_{\text{Planned}}(t)$). This control variable can be calculated at any time (t) in production [22,23]. The backlog determines the average schedule deviation of all orders in this system at the time (t) [22]. If the backlog is positive, orders will be completed later on

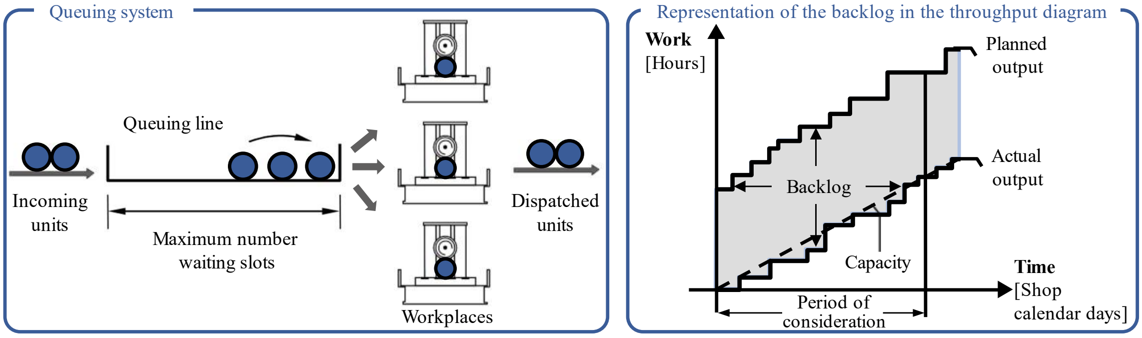


Figure 1: Elements of a queuing model and throughput diagram [1]

average; if the backlog is negative, orders will be completed earlier [22,24]. As a matter of principle, every production process should always be free of backlog [22].

In this context, the so-called queuing model can describe a production system, which allows, among other things, to model the backlog [1,25,26]. The basic concept of the queueing model is shown schematically in Figure 1 on the left. The model deals with processes in which specific units encounter bottlenecks to predict the length of the resulting congestion and waiting times. For example, the goal is to optimize capacity utilization or throughput times [1,26]. Jobs in the queue are postponed until an appropriate resource is available to process the job [1,25,27]. In this way, it is possible to take into account stochastic influences that occur in reality when planning and controlling the production process. The mathematical approach on which this model is based allows us to make the actual sequence of events theoretically understandable and predictable, given known input information about the average arrival and clearance rates of production objects at the work system. In particular, a detailed prediction of correlations between waiting times and queue lengths and the utilization of the considered work system is possible [1], which is highly relevant for backlog control. As shown in Figure 1, the queuing system consists of the queue itself and the individual workstations where the jobs are processed. Three similar workplaces are in charge of processing the orders in the queuing system shown. As soon as one of the workstations finishes processing a job, it starts processing a new job, which is taken from the queue. In simple terms, the ratio of the arrival rate to the dispatch rate can be used to calculate the variables wait time, number of jobs in the system, and utilization [1]. More detailed information can be found in [26].

The throughput diagram is used to further analyze the backlog and queue scheduling analysis. Figure 1 at right shows the basic diagram. The throughput diagram is a logistics model that visualizes processes and process parameters (e.g., output rate, range, work in process) [1,28]. This model is a tool that represents the process parameters in a time-dynamic curve. Apart from this approach, which focuses on the input and output of a working system, the throughput diagram can also be used to analyze the scheduling of the production process. [1,29] In the throughput diagram, the planned and actual output illustrates the schedule situation and, thus, the backlog. The vertical distance corresponds to the backlog in hours. The horizontal distance corresponds to the backlog in shop calendar days (backlog range) [1].

The problem that today's PPC planning systems are sluggish and often do not allow realtime analysis of the production process will be addressed below by developing a concept for DT in PPC.

2.2 Digital Twin: Fundamental principles and twinning in PPC control loop

Over the past 25 years, information technologies have drastically changed industrial production, including new and affordable sensors and virtually unlimited data storage and processing capabilities. In particular, the importance of simulation systems has become increasingly apparent and an integral part of industrial life [30]. The term DT is often used in this context. It's a concept that promises significant efficiency gains in planning and controlling production systems [17,31,32].

The first and widely accepted definition of a DT by Glaessgen and Stargel [13] has recently been adapted to new conditions and republished by many authors as technology has progressed [12,13]. For this reason, a current definition aims to bridge the gap between these partially divergent understandings of DT. By this definition, a DT is a digital representation of a physical system that collects and stores data from the real object in realtime for analysis and optimization [11]. This paper adopts the understanding of DTs according to this definition. In summary, the characteristics of a DT can be described by the terms realtime mirroring, interaction and convergence, and self-evolution [12].

Regarding the transfer of this universal concept to PPC, Negri et al. [31] have shown in research that there are already proven DT approaches in production systems [8,31]. In general, DTs can be used in a supporting role in various applications in the context of PPC. Initial approaches to integrating DTs into PPC have been identified in a literature review (see, for example [33–36]). In these examples, it is clear that they only address an isolated problem in PPC, and that backlog control has not yet been addressed in this context.

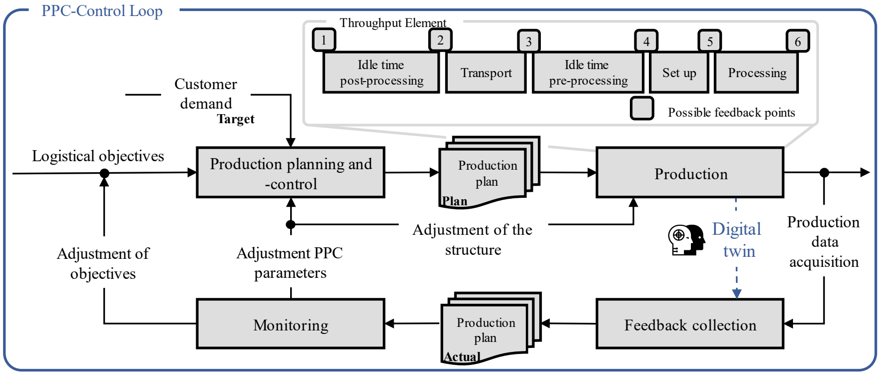


Figure 2: Integration of DTs in the PPC-Control Loop throughput element [17,37,38]

The remainder of this section discusses the integration of a DT into the PPC control loop. The PPC control loop shown in Figure 2 illustrates the control task that manufacturing companies must master to achieve their logistics goals [12]. Based on a company's objectives (e.g., performance targets) and customer requirements (e.g., quantity and timing), which represent the target values, the control loop systematizes the planning of production schedules (plan) and the control of processes during production. Furthermore, the PPC control loop represents the generation of production data based on operating and machine data. This feedback data is used as actual data to calculate deviations from the plan and thus for production control to derive improvement actions and increase target achievement. [38] The purpose of this comparison is to continuously check whether the target or plan values are being met, which is done successively using monitoring. If deviations are detected, they must be analyzed, and measures proposed and implemented. [1,38] Recording actual data requires time evaluation of the production process. In today's production, discrete time stamps are the most common form of time evaluation [20,38]. Figure 2 illustrates points where feedback data can be extracted from the production process as a throughput element. The data is typically generated digitally based on RFID technologies [38,39].

As seen in Figure 2, it is helpful to integrate the DT at the interface of production and data collection to perform realtime analysis that enables adjustments based on the plan and target data. In addition to the discrete time stamp data acquisition described, using DTs in production also provides the ability to simulate and analyze the production system virtually [8,40–42]. The literature suggests that information from realtime simulation, such as the actual progress of a production process, should be continuously accessible and evaluable to the PPC to analyze and organize the production process more transparently [17,43,44]. Using realtime data makes decisions faster, allowing adjustments to be made earlier and more efficiently. Realtime simulation can also provide continuous data for PPC control when using DTs in production. [17] This concept is discussed in the following chapter in the context of optoelectronic production.

3. Architecture of a simulation model in optoelectronic production

3.1 Real model: Optoelectronic production

The production of optoelectronic components is a highly complex, multi-stage process that requires exceptional support from modern technologies due to its high demands on quality. In addition to the generally high customer demands regarding timely delivery and quality requirements, manufacturers must develop new practices to meet market expectations. [45–49] On the one hand, new production technologies such as adaptive polishing [50] and two-photon polymerization [51] need to be embedded in the process chains to produce high volumes with high precision. On the other hand, digital technologies such as DTs are of great importance for this industrial sector, as they promise to increase quality and efficiency simultaneously. From a logistics perspective, this means that manufacturers in this sector must deal with high uncertainty about their capacities [50]. The associated planning uncertainties are, for example, due to variable production parameters, high-quality requirements, and rework in the production process [45,50].

The production process is described below to define the real twin for the following elaborations in the simulation context: Sand is the starting material for optoelectronic production. It is used to produce silicon. To obtain silicon wafers, molten silicon is pulled into a monocrystal. The monocrystal is then cut into silicon wafers less than 1 mm thick. [45,52] This step will not be detailed in the simulation, as this product is a purchased part. The first step to be considered is the polishing of the silicon wafer. This step significantly impacts the quality of the product, as polishing has a major effect on the mean roughness value, which is used in practice as a key quality indicator [45,52]. This is followed by the lithography process, which defines the structure of the wafer plate. For this purpose, the base plate is coated with a photoresist layer susceptible to light. The structure of the mask is then transferred to the material by exposure. [45,53] The light changes the chemical composition of the previously applied coating. The exposed parts of the coating are soluble and are removed in the manufacturing process. A subsequent etching process creates the resist structure on the wafer plate. A copper filling is then introduced into the etched structure as a conductive interconnect, and excess material is removed by polishing. This process is repeated several times until a three-dimensional chip structure is created. [52,54,55] The last production step is contacting the chip with an electrode. [52,56] These steps represent the production process to be simulated and, thus, the real twin.

The real twin serves as a reference process for the simulation where the required data is collected. This data is used in DT to run the simulation, analyze the collected data, and vary the parameters required to simulate the properties before the resulting parameters are reflected to the real twin.

3.2 Simulation model development design decisions

Based on the definition of a conceptual model in Robinson (2015) [57], this section formally describes the architecture of the DT to be simulated. The description shows the software independent structure and forms the basis for the simulation. The conceptual model of the simulation is based on different modules, which

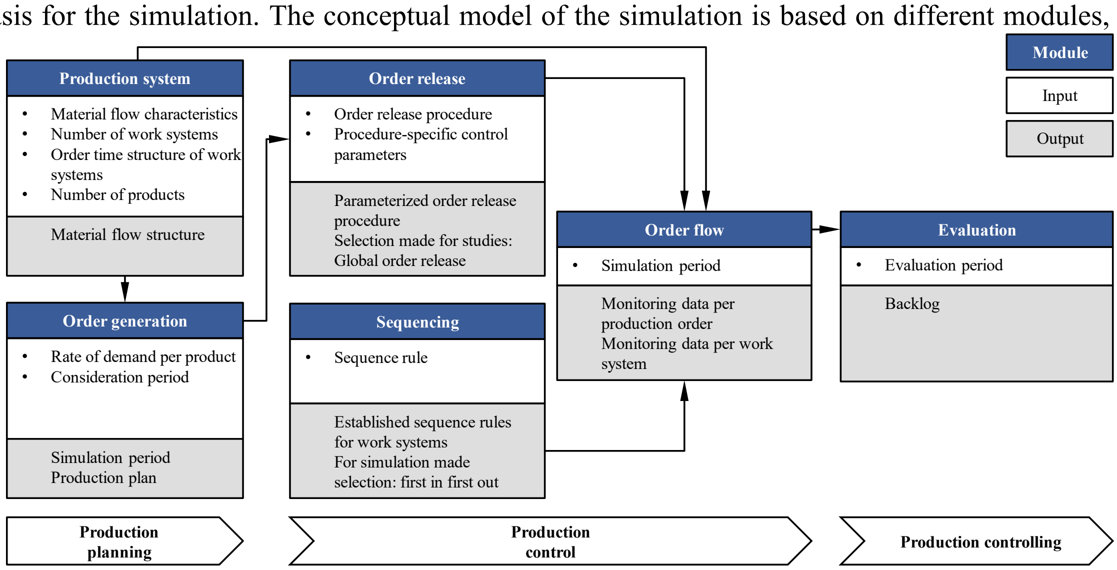


Figure 3: Schematic structure of the simulation as a conceptual model [57]

are assigned to the tasks of production planning, control and controlling. In the chosen representation, the inputs describe the experimental factors that are changed to run the simulation. The outputs are the reports that describe what state has occurred in the context of the simulation. The schematic structure of the simulation model is shown in Figure 3.

In production planning, the production system is defined by the material flow, the number of work systems, the order time structure, and the number of products. The module is used to output the structure of the material flow. In addition to this module, order generation is schematically structured in the context of production planning. For a complete description of order release, sequencing, and order flow in production control, see Figure 3. Based on the input and output information from production planning and control, the simulation is run for a specified simulation period. In the process, feedback data is generated for each work system. The production controlling module then evaluates the data concerning the backlog.

3.3 Simulation architecture of the digital model and its implementation

The digital model presented below must be permanently synchronized with the real system to reproduce the dynamic behaviour. Synchronization aligns the real production system and the digital model [58,59]. Once the initial digital model is synchronized, it can evaluate performance and optimize services. These functions allow a bi-directional flow of information [60]. The simulation of the DT of the production process was created based on the software Plant Simulation from Siemens. Specific customer orders trigger the process pulled through the production process by a pull control implemented by a method in Plant Simulation. The production orders are released globally based on this methodology. Following the production process, the initial polishing and the individual steps of the lithography process are performed, which in the simulation are carried out by individual workstations. An input/output control system centrally coordinates both workstations. For this purpose, the default methods programming environment was used in the settings of the workstations in Plant Simulation. After these two steps, detailed quality control is performed. This step plays a central role in the simulation because the quality characteristics of the wafer plates significantly impact the products' functionality. In the simulation, three products (BEs) are represented, which differ in product characteristics via quality. The customers' orders always refer to one of the three product qualities. Following the queue model, the wafer plates are contacted with the electrodes. The electrode is provided by a second source and considered a purchased part in the simulation. The queue's capacity is dimensioned in the simulation with three waiting slots. A product-dependent perturbation is implemented in the assembly step to simulate the quality-dependent factors described above (e.g., changing production parameters and reworking). Specifically, for all products of Quality 1 (low), an availability of 80% of the machine was randomly distributed over the simulation time, and a Mean Time to Repair (MTTR) of 10 minutes was assumed. For Quality 2 (medium) and Quality 3 (high) products, the availability is 75%. The MTTR is also 10 minutes in both cases. In addition, an open database connectivity interface is embedded to access external databases. The simulation results are transferred via a single-tier driver to a Microsoft Excel data source, which can be analyzed and transferred to the real twin.

In summary, the DT provides insight into optoelectronic production and a more detailed picture of the current performance of systems. This data can be used to make analyses more transparent and to detect

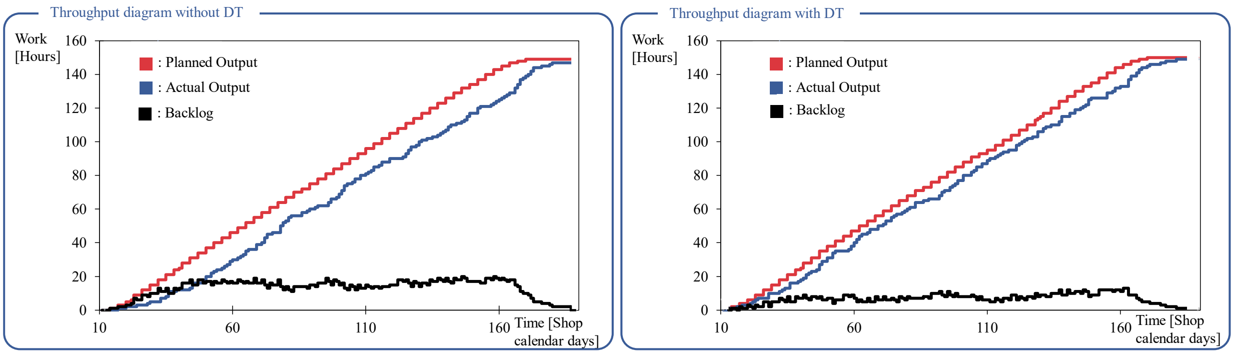


Figure 4: Simulation results as a throughput diagram

deviations from plan earlier. This provides additional information for timely corrective action. The results of a case study that demonstrates the benefits of simulation as a DT are presented in the following chapter.

4. Example of application – Potentials of simulation as a digital twin

This section aims to provide a detailed insight into simulation in the form of an example. The following shows how DTs can help improve the efficiency of implementing production control measures in the optoelectronic production process. As a concrete example for this consideration, backlog control in the production system was chosen. The DT captures the actual output in the simulation. Production planning explicitly specifies the planned output. Two scenarios were compared to demonstrate the benefit of the DT for backlog control in the example. Both are shown in Figure 4 in a throughput diagram to visually illustrate the positive effect of using a DT. The "conventional" scenario is on the left, where production runs without DT. In this case, response times are slow [17], and adjustments are often delayed, for example, when production parameters need to be adjusted or when quality problems occur [52]. The figure on the right shows the scenario where a DT supports production. DT support was simulated to the extent that an additional database was created to identify backlogs in the production process earlier and to adjust production capacity promptly. This additional database was made possible by continuously retrieving quality and progress data.

Figure 4 clearly shows the deviation between planned and actual output, combined and represented by the backlog. Ideally, the planned and actual output curves should be aligned, as the backlog would be zero according to the above equation. However, as can be seen, the ideal case is not present in both scenarios, as there is always a positive backlog during the production process. Based on the formula presented, we can see that the orders have a positive average backlog and, consequently, a time lag concerning the planned dates. However, comparing the two scenarios indicates that the backlog is lower on average in the case of support by a DT. Nevertheless, in the case of DT support, the backlog cannot be eliminated due to the implementation of a simulative manipulation of machine availability and a mean time to repair. The reduction of the backlog to zero towards the end of the simulation is because only a limited number of

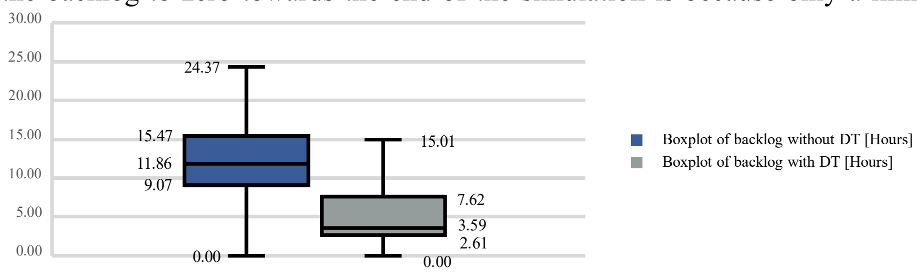


Figure 5: Boxplots of backlog with and without DT

orders were released, and the simulation continued until all orders had been processed. The parallel course of the planned and actual output curves indicates that the backlog could not have been cleared if more orders had been released. In addition, the parallel development of the two curves suggests that the backlog cannot be reduced without a capacity increase. Therefore, specific measures must be taken to adjust capacity in the short and medium term until the accumulated backlog is cleared [61].

In addition, the throughput diagram suggests that the scatter of the backlog is smaller due to the DT, as the actual output fluctuates less. As in the previous argument, this reduction in variability can be explained by the expanded and more transparent database. Additionally, the figure shows that the backlog range (horizontal distance between planned and actual output) is lower when using a DT. This reduction indicates that less time has to be invested in reducing the backlog in production with current capacity. This effect is an excellent description of the added value that DT has created in this application example. To examine this aspect in more detail and to demonstrate the added value of DT, a statistical analysis of the simulation results was performed using box plots, as shown in Figure 5. The previously inferred finding that the mean backlog and the scatter are on average lower when a DT is used is confirmed by these investigations. The simulation results show that support from a DT reduces the median from 11.86 hours to 3.59 hours. In this case, the location parameter characteristically shows that the spread has a much smaller backlog as the median is closer to zero. Thus, this measure provided a central tendency and was deliberately chosen for this application example because it is insensitive to outliers.

Comparing the two scenarios, the same interpretation can be made for the upper and lower quantiles. As shown in Figure 5, the box's height is smaller when a DT is used, and apart from the outliers, the minimum and maximum values of both data sets have a smaller range. The interquartile range (height of the box) can be interpreted as the mean 50% of the values being 1.39 hours ((15.47 hours - 9.07 hours) - (7.62 hours - 2.61 hours)) closer together when a DT is used. In terms of the minimum and maximum value, it can be said that the backlog varies by 9.36 hours less when a DT is used. Based on the findings that the box's height is smaller, the outliers have a smaller spread, and the simulation data reveal a lower median, the statement previously made based on the throughput diagram can be confirmed that the backlog is smaller on average and has a smaller scatter when a DT is used.

In terms of applications, these results were simulated by continuously recording and mirroring the actual data. The reduction of the median and the two quantiles of the backlog in Figure 5 is due to a depreciation of the idle times of the individual workstations in the production process. The reduction is caused by the additional database, as described above. The decrease in scatters is due to better coordination of production orders in general, a better adaptation of process control to changing production parameters, and early assurance of quality requirements. On the one hand, this example demonstrated the added value of simulation as a DT for PPC in general. On the other hand, the simulation presented in Section 3 could be practically applied and checked for plausibility.

5. Concluding remarks

The overall objective of our work is to present the design of our simulation model as a DT in the context of PPC to provide an additional source of information for backlog control. Initially, an overview of production control was given to communicate it comprehensibly. Then, the concept of a DT, which is crucial for this paper, was introduced, and its possible integration into the PPC control loop was shown. Finally, the conceptual model and simulation results were presented and demonstrated by an application example. Our results suggest that DTs in production can help to organize production control and monitoring tasks more efficiently. Thus, this approach can address and mitigate today's sluggish PPC systems, high-quality requirements, and global competitive pressures described in the introduction. The demonstrated benefits of DT are primarily due to the additional data generated. This provides an information advantage, as quality and progress data can be continuously retrieved in the production process to expand the discrete database. Ultimately, the DT simulation result provides an approach to improve the economics of manufacturing from a logistics perspective, as it has the potential to improve performance and reduce costs. More specifically, in practical application in the production process, the DT will provide detailed information in realtime, enabling the effects described above through a response advantage.

For practical applications in industry, the simulation model has the advantage that adjustments to the production process can be made much more quickly, resulting in better key figures. Evaluating the identified potentials based on simulations with further experimental or industrial datasets is necessary. Finally, it is essential to note that future research should focus on other PPC tasks besides backlog control and on how this additional information can be used to improve production control and monitoring.

Acknowledgements

Funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy within the Cluster of Excellence PhoenixD (EXC 2122, Project ID 390833453).

References

[1] Nyhuis, P., Wiendahl, H.-P., 2009. Fundamentals of Production Logistics: Theory, Tools and Applications. Springer.

[2] Zhang, T., Shi, Z.-Z., Shi, Y.-R., Chen, N.-J., 2022. Enterprise digital transformation and production efficiency: mechanism analysis and empirical research. Economic Research 35 (1), 2781–2792.

[3] Hon, K., 2005. Performance and Evaluation of Manufacturing Systems. CIRP Annals 54 (2), 139–154.

[4] Oluyisola, O.E., Bhalla, S., Sgarbossa, F., Strandhagen, J.O., 2022. Designing and developing smart production planning and control systems in the industry 4.0 era: a methodology and case study. Journal of Intelligent Manufacturing 33 (1), 311–332.

[5] Thürer, M., Fernandes, N., Stevenson, M., 2022. Production planning and control in multi-stage assembly systems: an assessment of Kanban, MRP, OPT (DBR) and DDMRP by simulation. International Journal of Production Research 60 (3), 1036–1050.

[6] Li, L., Lei, B., Mao, C., 2022. Digital twin in smart manufacturing. Journal of Industrial Information Integration 26, 100289.

[7] Chhetri, P., Hashemi, A., Lau, K.H., Lim, M.K., 2022. Aligning supply chain complexity with product demand and design characteristics. International Journal of Logistics Research and Applications 25 (8).

[8] 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.

[9] Durão, L., Haag, S., Anderl, R., Schützer, K., Zancul, E., 2018. Digital Twin Requirements in the Context of Industry 4.0. Product Lifecycle Management to Support Industry 4.0: 15th IFIP WG 5.1 International Conference, 204–214.

[10] Shahzad, M., Shafiq, M.T., Douglas, D., Kassem, M., 2022. Digital Twins in Built Environments: An Investigation of the Characteristics, Applications, and Challenges. Buildings 12 (2), 120.

[11] Stark, R., Damerau, T., 2019. Digital twin; the international academy for production engineering. CIRP encyclopedia of production engineering.

[12] Tao, F., Cheng, J., Qi, Q., Zhang, M., Zhang, H., Sui, F., 2018. Digital twin-driven product design, manufacturing and service with big data. The International Journal of Advanced Manufacturing Technology 94 (9), 3563–3576.

[13] Glaessgen, E., Stargel, D., 2012. The Digital Twin Paradigm for Future NASA and U.S. Air Force Vehicles.

[14] Rehman, A., Shakeel Sadiq Jajja, M., Farooq, S., 2022. Manufacturing planning and control driven supply chain risk management: A dynamic capability perspective. Transportation Research Part E: Logistics and Transportation Review 167, 102933.

[15] Kim, J.-H., Duffie, N.A., 2004. Backlog Control Design for a Closed Loop PPC System. CIRP Annals 53 (1), 357–360.

[16] Lödding, H., 2012. Handbook of Manufacturing Control: Fundamentals, description, configuration. Springer Science & Business Media.

[17] Hiller, T., Cevirgen, C., Nyhuis, P., 2021. Exploring the Potential of Digital Twins for Production Control & Monitoring. Journal of Production Systems and Logistics 1 (2021).

[18] Slack, N., Chambers, S., Johnston, R., 2010. Operations Management. Pearson Education.

[19] O'Leary, D.E., 2000. Enterprise Resource Planning Systems: Systems, Life Cycle, Electronic Commerce, and Risk. Cambridge University Press.

[20] Schäfers, P., Mütze, A., Nyhuis, P., 2019. Digital Production Order Processing Support System Using Real Time Data. International Conference on Competitive Manufacturing, 28–34.

[21] Wiendahl, H.-P., 1997. Fertigungsregelung: Logistische Beherrschung von Fertigungsabläufen auf Basis des Trichtermodells. Hanser.

[22] Lödding, H., Kuyumcu, A., 2015. Modelling schedule reliability. International Journal of Production Research 53 (9).

[23] Schmidt, M., Maier, J.T., Härtel, L., 2019. Data based root cause analysis for improving logistic key performance indicators of a company's internal supply chain. Procedia CIRP 86, 276–281.

[24] Othman, K.A., Meurer, T., 2022. Optimal Boundary Control for the Backlog Problem in Production Systems. IFAC-PapersOnLine 55 (20), 511–516.

[25] Lui, F.T., 1985. An Equilibrium Queuing Model of Bribery. Journal of Political Economy 93 (4), 760–781.

[26] Shortle, J.F., Thompson, J.M., Gross, D., Harris, C.M., 2018. Fundamentals of Queueing Theory. John Wiley & Sons.

[27] König, D., Stoyan, D., 1976. Methoden der Bedienungstheorie. De Gruyter.

[28] Mundt, C., Lödding, H., 2020. Order Acceptance and Scheduling with a Throughput Diagram. Advances in Production Management Systems. The Path to Digital Transformation and Innovation of Production Management Systems: IFIP WG 5.7 International Conference, APMS, 351–359.

[29] Stittgen, T., Schleifenbaum, J.H., 2020. Towards Operating Curves of Additive Manufacturing Equipment: Production Logistics and its Contribution to Increased Productivity and Reduced Throughput Time. Procedia CIRP 93, 14–19.

[30] Paula Ferreira, W. de, Armellini, F., Santa-Eulalia, L.A. de, 2020. Simulation in industry 4.0: A state-of-the-art review. Computers & Industrial Engineering 149, 106868.

[31] 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.

[32] Kunath, M., Winkler, H., 2018. Integrating the Digital Twin of the manufacturing system into a decision support system for improving the order management process. Procedia CIRP 72, 225–231.

[33] Yang, S., Arndt, T., Lanza, G., 2016. A Flexible Simulation Support for Production Planning and Control in Small and Medium Enterprises. Procedia CIRP 56, 389–394.

[34] Korth, B., Schwede, C., Zajac, M., 2018. Simulation-ready digital twin for realtime management of logistics systems. 2018 IEEE international conference on big data (big data), 4194--4201.

[35] Vachalek, J., Bartalsky, L., Rovny, O., Sismisova, D., Morhac, M., Loksik, M., 2017. The digital twin of an industrial production line within the industry 4.0 concept. 21st international conference on process control, 258–262.

[36] Sun, H., Li, C., Fang, X., Gu, H., 2017. Optimized throughput improvement of assembly flow line with digital twin online analytics. IEEE International Conference on Robotics and Biomimetics, 1833.1837.

[37] Schmidt, M., Schäfers, P., 2017. The Hanoverian Supply Chain Model: modelling the impact of production planning and control on a supply chain's logistic objectives. Production Engineering 11 (4), 487–493.

[38] Wiendahl, H.-P., 2019. Betriebsorganisation für Ingenieure. Carl Hanser Verlag.

[39] Li, X., Du, B., Li, Y., Zhuang, K., 2019. RFID-based tracking and monitoring approach of real-time data in production workshop. Assembly Automation 39 (4), 648–663.

[40] Bottani, E., Cammardella, A., Murino, T., Vespoli, S., 2017. From the Cyber-Physical System to the Digital Twin: the process development for behaviour modelling of a Cyber Guided Vehicle in M2M logic. Summer School Francesco TurcoIndustrial Systems Engineering, 1–7.

[41] Brenner, B., Hummel, V., 2017. Digital Twin as Enabler for an Innovative Digital Shopfloor Management System in the ESB Logistics Learning Factory at Reutlingen - University. Procedia Manufacturing 9, 198–205.

[42] Herlyn, W.J., Zadek, H., 2020. Der Digitale Steuerungs-Zwilling. Zeitschrift für wirtschaftlichen Fabrikbetrieb 115 (1), 70–73.

[43] Schleich, B., Dittrich, M.-A., Clausmeyer, T., Damgrave, R., Erkoyuncu, J.A., Haefner, B., Lange, J. de, Plakhotnik, D., Scheidel, W., Wuest, T., 2019. Shifting value stream patterns along the product lifecycle with digital twins. Procedia CIRP 86, 3–11.

[44] Uhlemann, T.H.-J., Lehmann, C., Steinhilper, R., 2017. The Digital Twin: Realizing the Cyber-Physical Production System for Industry 4.0. Procedia CIRP 61, 335–340.

[45] Malacara-Hernández, D., Malacara-Hernández, Z., 2003. Handbook of Optical Design. CRC Press.

[46] Brinksmeier, E., Riemer, O., Gläbe, R.M., 2012. Fabrication of Complex Optical Components: From Mold Design to Product. Springer Science & Business Media.

[47] Zhang, A.P., Qu, X., Soman, P., Hribar, K.C., Lee, J.W., Chen, S., He, S., 2012. Rapid Fabrication of Complex 3D Extracellular Microenvironments by Dynamic Optical Projection Stereolithography. Advanced Materials 24 (31), 4266–4270.

[48] Schmetz, A., Lee, T.H., Hoeren, M., Berger, M., Ehret, S., Zontar, D., Min, S.-H., Ahn, S.-H., Brecher, C., 2020. Evaluation of Industry 4.0 Data formats for Digital Twin of Optical Components. International Journal of Precision Engineering and Manufacturing-Green Technology 7 (3), 573–584.

[49] Ya Yi, Zhengbo Sun, Jia Li, Paul K. Chu, Xue-Feng Yu, 2019. Optical and Optoelectronic Properties of Black Phosphorus and Recent Photonic and Optoelectronic Applications. Small Methods 3 (10).

[50] Dittrich, M., Rosenhahn, B., Magnor, M., Denkena, B., Malek, T., Munderloh, M., Kassubeck, M., 2020. Dreaming Neural Networks for Adaptive Polishing. Proceedings of the euspen's 20 th International Conference & Exhibition, 263–266.

[51] Zheng, L., Reinhardt, C., Roth, B., 2020. Realization of high-quality polymeric photonic structures by two-photon polymerization. Advanced Fabrication Technologies for Micro/Nano Optics and Photonics XIII 11292, 50–58.

[52] Bliedtner, J., 2022. Optiktechnologie: Grundlagen - Verfahren - Anwendungen - Beispiele. Carl Hanser Verlag GmbH Co KG.

[53] Thompson, L.F., 1983. An Introduction to Lithography. ACS Publications.

[54] Fisher, G., Seacrist, M.R., Standley, R.W., 2012. Silicon Crystal Growth and Wafer Technologies. Proc. IEEE 100 (Special Centennial Issue), 1454–1474.

[55] Frittoli, L., Carrera, D., Rossi, B., Fragneto, P., Boracchi, G., 2022. Deep open-set recognition for silicon wafer production monitoring. Pattern Recognition 124.

[56] Rizzoni, G., 2007. Principles and applications of electrical engineering. cGraw-Hill Higher Education.

[57] Robinson, S., 2015. A tutorial on conceptual modeling for simulation. Winter Simulation Conference (WSC), 1820–1834.

[58] Lugaresi, G., Lin, Z., Frigerio, N., Zhang, M., Matta, A., 2019. Active Learning Experience in Simulation Class Using A Lego®-Based Manufacturing System. Winter Simulation Conference (WSC), 3307–3318.

[59] Nelson, B.L., 2013. Foundations and Methods of Stochastic Simulation. A first course. International series in operations research & management science 187.

[60] Lugaresi, G., Gangemi, S., Gazzoni, G., Matta, A., 2022. Online Validation of Simulation-Based Digital Twins Exploiting Time Series Analysis. 2022 Winter Simulation Conference (WSC), 2912–2923.

[61] Lödding, H., 2005. Verfahren der Fertigungssteuerung, 2nd ed. Springer.

Biography

Jonas Schneider, M.Sc. (*1997) studied industrial engineering at TU Clausthal and has been working as a research assistant at the Institute of Production Systems and Logistics (IFA) since 2022 in the field of production management with a focus on production planning and control.

Tobias Hiller, M.Sc. (*1990) studied industrial engineering at the Otto von Guericke University Magdeburg and management at the Georg August University of Gottingen. He has been working as a research assistant at the Institute of Production Systems and Logistics (IFA) since 2019 in the field of production management with a focus on production analytics, and production management.

Prof. Dr.-Ing. habil. Peter Nyhuis (*1957) studied mechanical engineering at the Leibniz University Hanover and subsequently worked as a research associate at the Institute of Production Systems and Logistics (IFA). After obtaining his Dr.-Ing. doctorate, he was habilitated before working as an executive in the field of supply chain management in the electronics and mechanical engineering industry. He has been head of IFA since 2003.

5th Conference on Production Systems and Logistics

Reducing Customer Complaints in Air Conditioning Installation Services through Lean and MRP Tools: A Case Study

Silvana Aguilar-Cevallos[1], Yersson Aguilar-Cevallos[1], Juan Carlos Quiroz-Flores[1*] and Yvan J. García-Lopez[1]

[1]*Facultad de Ingeniería, Carrera de Ingeniería Industrial,Universidad de Lima, Perú*
**Corresponding author: jcquiroz@ulima.edu.pe*

Abstract

In Latin America, the business services sector is constantly searching for continuous improvement to improve the performance of service operations and service quality. However, merchandise availability must be guaranteed to prevent stockouts and preserve high customer satisfaction. Therefore, managing a warehouse inside a service organization is challenging. In this way, a model for improvement was created to address the issues raised above, combining Lean Service tools such as ABC, 5S, and standardization of work with a Material Requirements Plan (MRP) to reduce the claims rate, which is currently 60 percent owing to ineffective management of the tool ordering and installation processes. After implementing the pilot plan and the simulation in the Arena software, a significant variation in the claims rate was evidenced by reducing it to 30%. This study contributes to the validation of lean tools in the air conditioning service industry and will continue to contribute to future managers with similar processes.

Keywords

Warehouse management; claims; Lean Warehousing; 5S; ABC classification; Standardization Work; Material Requirements Planning (MRP); customer satisfaction; air conditioning installation.

1. Introduction

In Peru, the business services sector contributes 1.69 percent of the national GDP, and the services sector, in general, generates the most jobs [1]. Additionally, the subsector of services rendered to businesses increased by 3.4 percent owing to higher activity in advertising and market research (4.9 percent) and administrative and support service activities (3.0 percent) [2]. However, close to May 2020, the business services sector fell by 40.84 percent [3]. This result shows that service companies need help in fulfilling their proposals. In this case, warehouse management is paramount to ensuring a correct service process. This must balance the quantity of stock to offer its clients while keeping the goods and materials in a good shape [4]. This study attempts to lower the volume of claims for services provided to consumers in response to issues created in warehouse management in service businesses. A preventive, corrective, or installation service procedure that needs to be better managed may result in considerable loss of business.

High cycle delivery times, poor service process performance, poor cooperation, and ineffective communication throughout the process are issues noted because of the industry's lack of adaption [5]. This issue was discovered in another study. For instance, lean services and BPM tools can be used in an MSE in the distribution industry to optimize the leading warehouse management indicators. This has led to improvements in inventory record accuracy, location record accuracy, coverage, cycle time, and productivity of 16 percent, 32 percent, 57 percent, 3 percent, and 24 percent, respectively [6]. Previous research has

DOI: https://doi.org/10.15488/15319
ISSN: 2701-6277

established a multi-method approach to examine how firms might differentiate between value-added and non-value-added activities and methods to reduce waste and enhance warehouse operations. It has been shown that employing many methods improves our comprehension of how longer lead times affect non-value-added distribution warehouse operations [7].

Therefore, it is essential to ensure inventory availability to avoid stock-outs and maintain high customer satisfaction. Therefore, managing a warehouse inside a service organization is challenging. As a result, a case study was selected to represent the industry's issue with a restricted full-service capability brought on by inadequate management of the tool order process and, therefore, of the installation process, which led to a high rate of claims for the services provided. By Combining Lean Service techniques such as ABC, Jidoka, and Work Standardization with a Material Requirement Plan, a model for improvement was developed to solve the problems above (MRP). The introduction, Literature Review, Proposed Model, Validation, Discussion, Conclusions, and Recommendations for Future Research are the sections of this scientific work.

2. Literature Review

2.1 Lean philosophy in material storage processes in the service sector

Previous studies have shown that the Lean Warehouse approach incorporates many lean concept elements to customize them to a company's storage procedures and reduce inefficiencies in logistics operations [8]. To boost the effectiveness and efficiency of business storage systems, Lean Warehouse, which integrates many methods based on lean philosophy, such as 5S, standardization of work, and ABC, was used in our study. By enhancing working conditions to decrease downtime and travel lengths, these warehouse solutions boost the company's overall productivity [9]. Conversely, the effective use of these technologies may result in fewer out-of-stock situations and higher distributor satisfaction owing to shorter wait times [10],[11].

2.2 Application of ABC to control inventory in warehouse.

ABC classification is a technique that may be used to group various items into several situations. According to the Pareto analysis principle, this approach divides data into three classes, A, B, and C, to create categories based on the consumption values [12]. By separating inventory items by financial categorization using ABC analysis, efforts may be focused on fewer items while being directed toward things with greater representativeness, and thus, better outcomes [13]. It has been demonstrated that ABC can improve the level of service by correctly classifying and distributing the goods in the warehouse, rationally managing its inventories, and identifying those with higher demand, and therefore, higher turnover [14],[15], [16]. ABC has typically been used to streamline the flow of materials to reduce inventory lead times.

2.3 5S Methodology for Improving Warehouse Efficiency.

The finest firms in the world use 5S, a continuous improvement or kaizen approach or tool, which consists of five acts that must be carried out in a particular order to be successful. Putting the 5S into practice may keep workplaces neat, organized, and clean, creating a pleasant working environment. Although this applies to offices and warehouses, its influence on plants or industrial sectors is the greatest. By shortening lead times, cutting costs, raising quality, and eliminating waste, the company seeks to satisfy customers. In addition, it dramatically aids businesses in earning national or worldwide certifications. [17].

2.4 Work standardization to have established processes within an organization when performing specific tasks

One of the most effective lean techniques, work standardization, is least used in business. It consists of choosing the best practices, what each operator does well, or what is shown to achieve the most remarkable results to create a work methodology that all employees must adhere to. Every organization should utilize it to continually improve its production process. The goal is for all operators to perform their tasks consistently in a single manufacturing process [18]. Research has shown that this tool and its components are crucial for integrating intelligent technologies, developing a better order, and ensuring that the staff have the necessary training to do their jobs [6].

2.5 MRP to calculate the need for materials in the warehouse

The Material Requirement Planning (MRP) system is a record where purchase orders are placed with suppliers to meet the demand on the established date, which involves a simple method to identify the number of components, materials, and parts required to generate a final product [19]. The MRP program is efficient, economical, and easy to use [20]. Owing to the established tracking, it was feasible to integrate the operation of an MRP system based on a material BOM, a master production plan, and inventory record. This immediately affected the decrease in purchase orders caused by materials [21], [22], [23].

3. Proposed Model

The model proposed in this study is based on the application of tools, 5s, ABC classification, standardized work, and MRP. These mixed methodologies were selected to moderate the root causes identified in the problem tree. First, the 5s model was implemented to organize the processes. Then, the ABC classification is used to identify high-impact materials. In addition, standardized work will be executed to improve work performance. Finally, MRP is implemented to control the company's stock breakage. Figure 1 shows the proposed model for the case study.

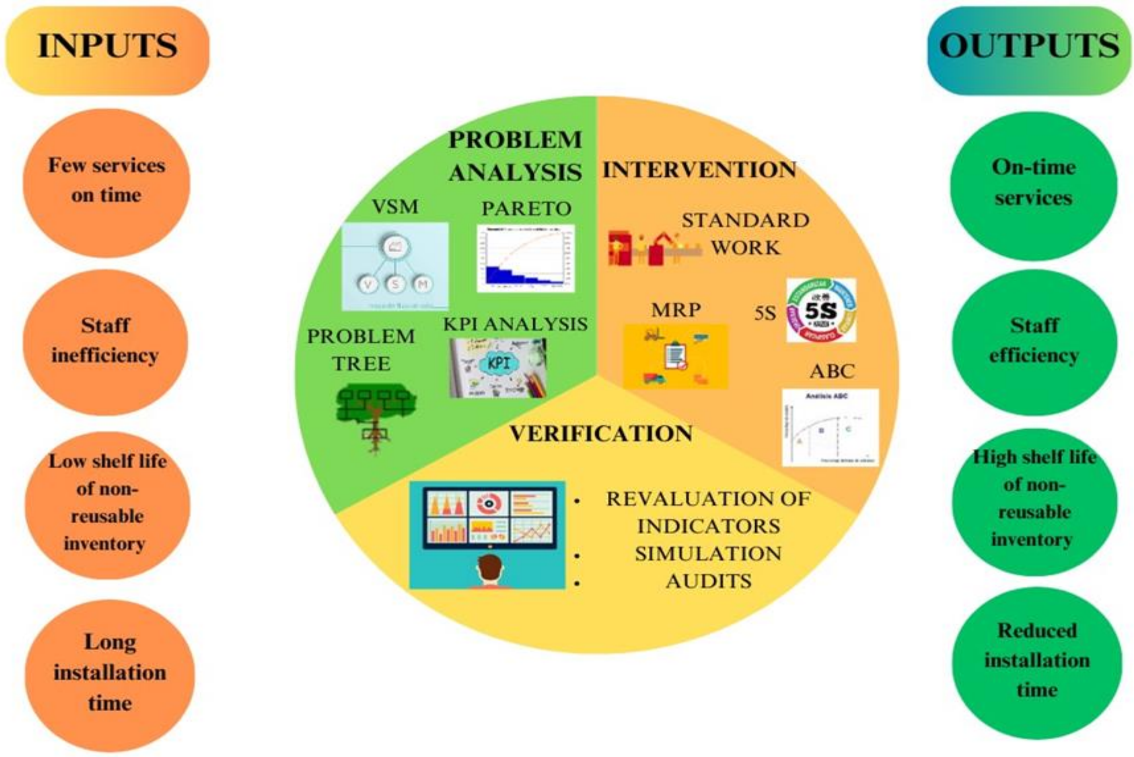


Figure 1: Proposed improvement model

3.1 Model components

The proposed model is divided into three components, as described below.

3.1.1 Component 1: Problem analysis

This component consists of all activities before applying the proposed model. First, data (time) were collected for the construction of the VSM to identify the sequence of the company's activities and the times generated in these activities, as well as to obtain a macro image of the behavior of its operations until dispatches were made. Second, the activities that involve the most time wasted are identified, and the causes are evaluated to determine which has the most significant impact, using Pareto to obtain the most critical root causes. Third, a problem tree is developed to identify the root causes of these problems. After identifying the root causes, Key Performance Indicators (KPIs) were established to measure the root causes of the current situation and find the variation once the model tools were implemented.

3.1.2 Component 2: Intervention

The second part involves implementing technologies, such as 5S, ABC Classification, Standardized Work, and MRP, to improve the quality of services.

a) Application of 5S: In Seiri, unnecessary objects will be eliminated; in Seiton, an ABC classification will be carried out to identify the materials with the most significant impact; in Seiso, elements will be designed to help eliminate sources of dirt inside the warehouse; in Seiketsu, a time study will be carried out on remote tasks inside the warehouse; and finally, in Shitsuke, a checklist will be drawn up to help with the review of important points. Audits will then be performed to ensure these conditions.
b) Application of the ABC Classification: A classification is made to identify high-impact materials according to their cost, level of use, and if they are imported. These three factors will be measured on a scale of importance, which the warehouse operator and air-conditioning technician will determine. In this case, policies will be created to ensure the availability of high-impact materials (CLASS A), such as increasing purchase frequency or dedicating more outstanding care within the warehouse.
c) Standardization of work application: A time study will be carried out to define the standard times of the processes; then, the rules for each procedure will be built, and we will put them into practice. For this, a procedure manual was created to establish the guidelines, requirements, and actions to be carried out by the service operators. Finally, the operation of the strategy is monitored.
d) MRP application: A forecast of the demand for required services will be made with historical information about the company, the materials and tools that are most frequent by date will be determined, and the quantity in stock will be analyzed, after which the amount needed for such a period and the time of anticipation that must be ordered according to the lead time of the suppliers will be determined.

3.1.3 Component 3: Verification

The last component consisted of evaluating the KPIs established before implementation to determine the impact of the changes produced by the model tools used, ensuring the development of the improvement model. In addition, an audit format was used to verify whether the suggested activities were being carried out before and after implementing the tools to ensure their sustainability. The last step was to verify the plan using the outcomes of the pilot test. Finally, the effect of the suggested method is shown using the Arena Software's simulation of the air conditioning installation process in conjunction with the new indications. The suggested model's implementation process is shown in Figure 2

Figure 2: Proposed process

3.2 Indicators

The indicators of the proposed model, which were used to verify and control the improvements proposed in the case study, are presented below. Table 1 lists these indicators and their calculation formulas.

Table 1: Indicators

Indicator	Formula
Claims Index	$\frac{Number\ of\ claims}{Total\ number\ of\ services}\ 100$
5S Audit	$\sum(5S\ audit\ score)$
Duration of non-reusable inventory	$\frac{Ending\ inventory}{Average\ sales}\ x100$

On-time services	$\frac{Services\ delivered\ on\ time}{Total\ services\ delivered}\ x100$
Average cycle time	$\frac{Service\ processing\ time}{Completed\ services}\ x100$

4. Validation

4.1 Initial diagnosis

The proposed model was applied to a company's warehouse that offers air-conditioning installation services. The company did not find a warehouse with a classification of materials according to their level of importance, so it was not possible to identify and distinguish what was needed. It was also observed that it was not kept clean or organized, and the tools did not have a specific location. The tools do not have a specific location. Because there is no classification, there are always problems with the missing materials. There is no service-level agreement with equipment suppliers or a specific material requirement plan. Likewise, the processes must be standardized, resulting in low operator efficiency. All of these factors generate a high rate of customer complaints. Figure 3 shows the problem tree for the case study.

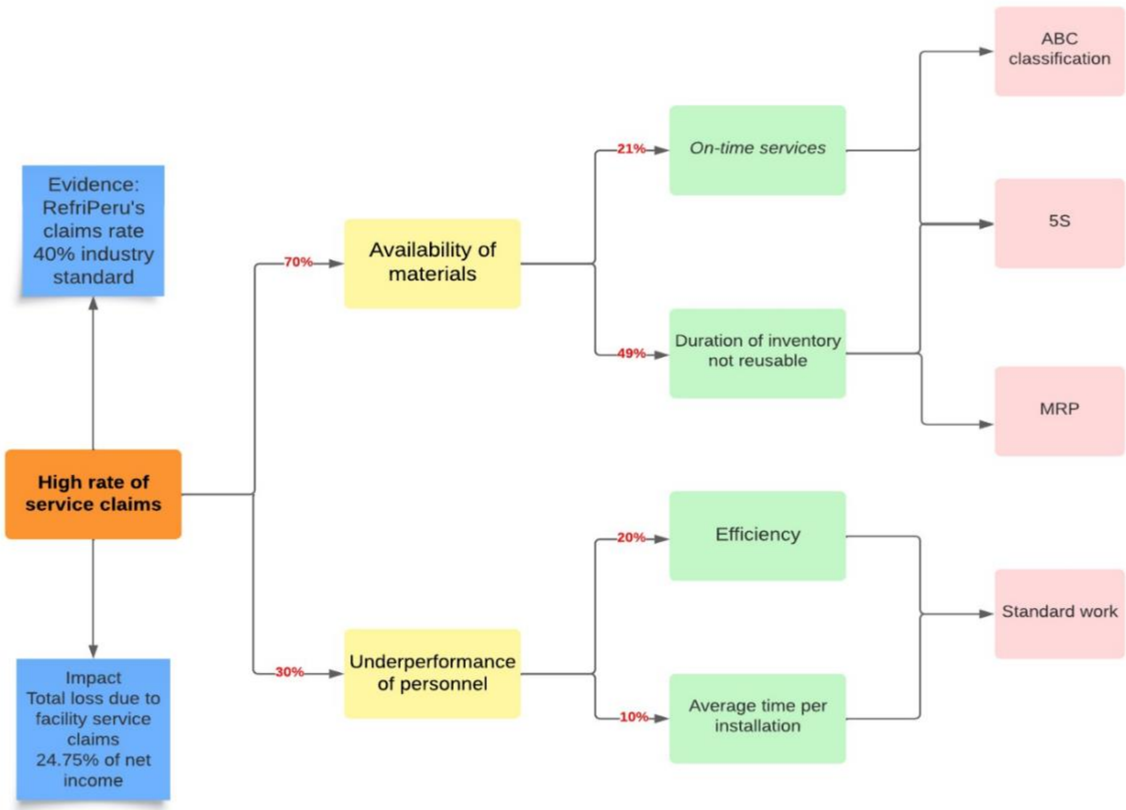


Figure 3: Problem Tree

4.2 Validation of the design and comparison with the initial diagnosis

To execute and assess the changes achieved, a test or pilot plan for the 5S technique was carried out in the warehouse. The MRP and Standardized Work tools were simulated using the Arena program and the indications gained were assessed.

4.3 Improvement

4.3.1 5S Pilot

For the 5S methodology, an initial audit was performed to evaluate the level of implementation of the 5S, and areas requiring improvement were identified. In addition, an ABC classification of the materials and tools in the service warehouse was performed. To help manage and prioritize inventory items effectively, focusing on those with the most significant impacts and costs. As a result, there was a considerable reduction in the tool search time from 15 to 5 min. Additionally, the average 5S audit indicator score increased significantly from 1.86 to 4.1 points. Figure 4 shows the results of the 5S audits before and after the implementation of the pilot.

In this way, the aim is to encourage workers to perform the task with awareness and commitment. As they become part of their daily routine, habits of cleanliness and order are generated, which will positively impact all their actions. This gradual and consistent approach will help establish a more efficient and organized work culture in which everyone is committed to maintaining a clean and orderly environment. Figures 5 and 6 show the warehouse before the implementation of the 5S pilot and Figure 7 shows the same warehouse after the implementation of the 5S pilot.

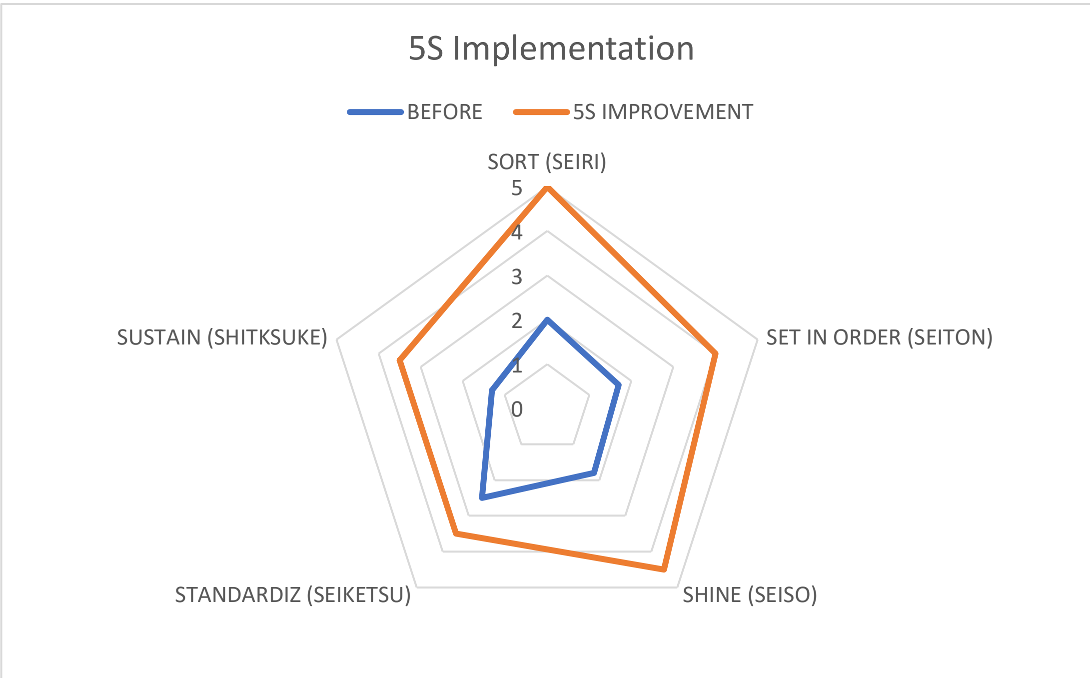


Figure 4: 5S Audit chart before and after implementation

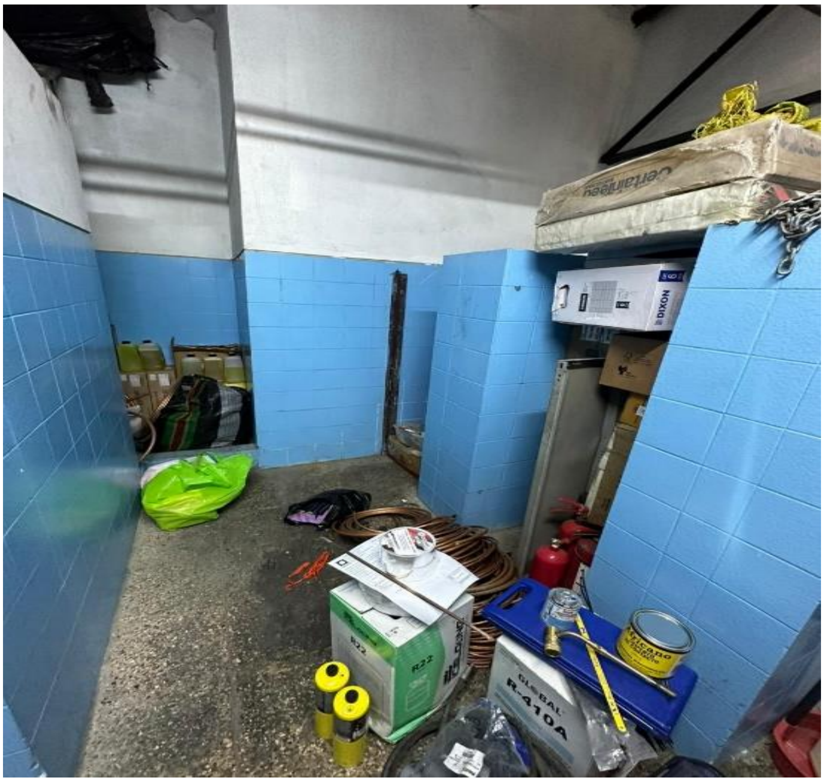


Figure 5: Warehouse before implementation

Figure 6: Warehouse before implementation

Figure 7: Warehouse with 5S Philosophy

Figure 8: Fully sorted warehouse

4.3.2 Simulation proposal

For the simulation, the entire process of an air conditioning installation service was considered, from the arrival of requests to the verification and confirmation of the service. Among the activities that occupied most of the time were the search for tools and review of the stock of materials in the warehouse. It was also observed that the time taken by the operators to install the air conditioning was very high, and many operators needed clear instructions on how to handle specific tools and materials. Therefore, it was decided to implement MRP to determine how much is needed for a certain period and the time in advance that should be ordered according to the lead time of the suppliers. With this, there is no shortage of materials in the warehouse. In addition, purchasing third parties due to a lack of inventory will be avoided.

Additionally, Standardized Work was chosen to be implemented to reduce downtime in the facilities and decrease customer complaints. The simulation was performed using the Arena software version 16.1. Figure 8 shows the simulation of the situation before the improvement.

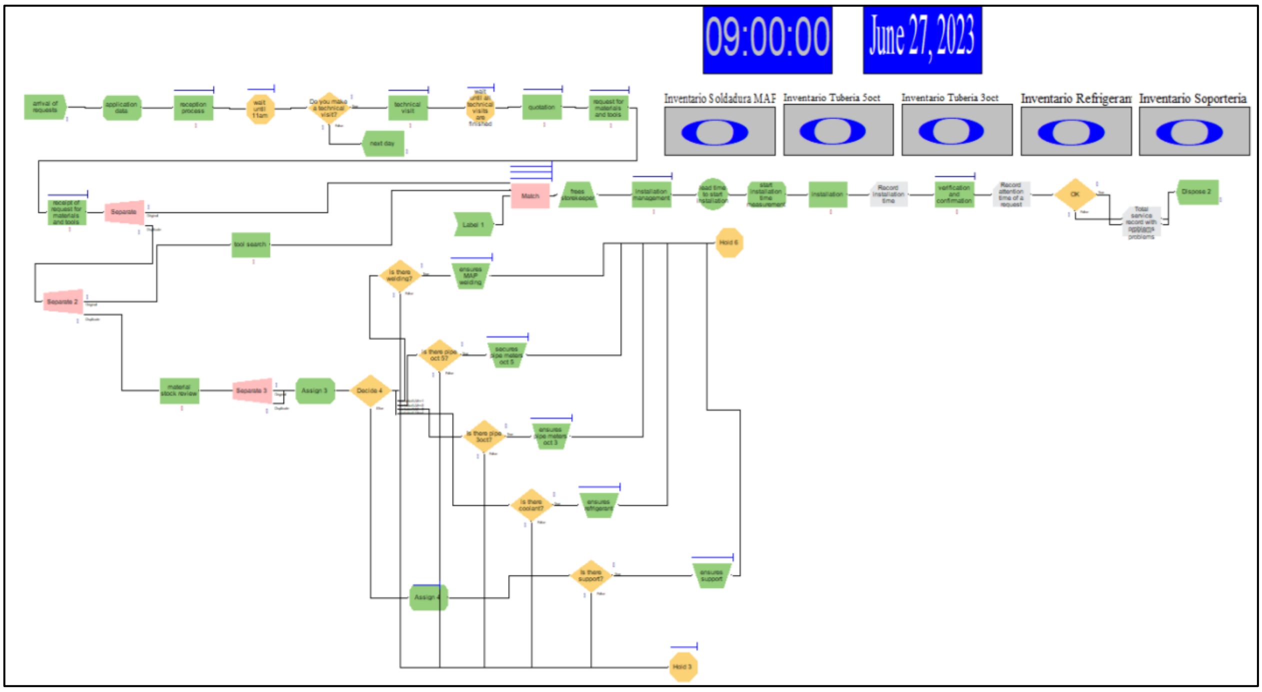


Figure 9: Simulation in Arena Simulator software of the situation before improvement

The Input Analyzer program received data collected from 30 observations to create a proper distribution in the model. An initial sample of 30 duplicates was collected to determine the required number of repetitions in the simulation. Three runs, with a mean width of 0.795, were performed. The last one produced 154 replicas. Along with the introduction of the MRP and the decrease in installation time per service made possible by using Standardized Work, the rearrangement and cleanliness of the warehouse were also considered for the enhanced model. An Output Analyzer program was used to extract and analyze the model indications, and 500 random variables were created for each variable. A better simulation scenario is shown in Figure 9.

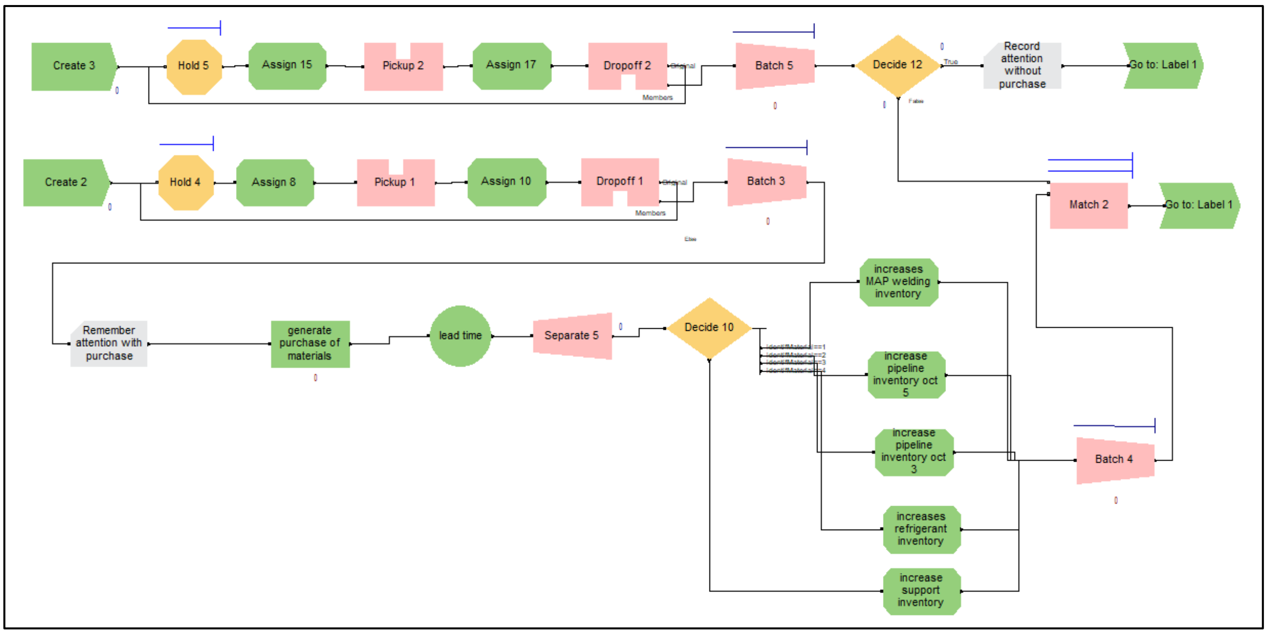


Figure 10: Simulation in Arena Simulator software of the improved situation

In the observations within the warehouse, a total cycle time of 75.15 hours per request was handled, and an average time of 5.49 hours per installation was obtained. In addition, the tool search time was reduced from 15 to 5 min per request. In the current simulation, a cycle time of 72.92 hours and an average time of 4.25 hours were obtained, as well as a near-perfect service with no third-party purchases with four out of five services serviced daily. With the improved scenario, significant variation was obtained in the claims index, which was reduced from 60% to 30%. Similarly, the efficiency percentage of the installation service process increased from 75% to 90%. Table 2 presents the dashboards of the research results.

Table 2: Results Comparison

	Indicators	Current	Target	Improved
General	Efficiency (%)	**75%**	**95%**	**90%**
	Claims Rate (%)	**60%**	**30%**	**35%**
	On-time services in one day (max. 4)	**2**	**4**	**3**
5S	Time to search for tools (min)	**15**	**4**	**5**
	Audit 5 "S	**1.86**	**4.5**	**4.1**
Standardized Work	Average time per installation (hrs)	**5.49**	**4.5**	**4.25**
	Application cycle time (hrs)	**75.15**	**70**	**72.92**
MRP	Duration of Reusable Inventory (days)	**8**	**5**	**6**
	Attention of a service without Purchases (5 services per day)	**3**	**5**	**4**

5. Discussion

The proposed model, based on reducing the rate of similar claims in an installation services company using Lean Warehousing and MRP tools, can be adapted to other companies in the same sector that present problems related to the low availability of materials and low performance of personnel. Causing problems with customers and therefore, their claims The claims rate was reduced by an average of 28%, achieving the research objective of keeping its claims rate below 30%. Another objective is to reduce the average time per installation, which decreases to almost two hours for each installation. In addition, the entire process was reduced to 5.15 hours, thereby optimizing a specific current situation. Finally, we increase the number of services without purchases to five, which is the maximum possible number per day. This means that the company's objective of not resorting to any purchase for any installation service is yet to be reached.

It is essential to note that the validation and scenarios have certain restrictions owing to their execution with the Arena software. This implies that results may vary depending on the particularities of each company. To correct the model implementation with different scenarios, changes must be made to the engineering tools implemented as a solution. In this case, the 5S, work standardization, and MRP. This is because the results were obtained using these tools. When implementing engineering tools, it is crucial to consider the different areas related to the primary process. This is because these problems relate to different areas.

6. Conclusions

This study shows that implementing lean warehousing can substantially improve the productivity of companies in the refrigeration sector. The results are encouraging, showing remarkable improvements in all indicators established for the company's current situation. In particular, the claims index was reduced by more than 50%, a significant achievement that positively impacted a company's financial health, correcting the economic impact of 87,300 soles, as foreseen in the study's objectives. In addition, this implementation increases the net profit generated.

Implementing MRP and standardizing the work proved fundamental for optimizing the primary process.

These actions made it possible to carry out services without resorting to external purchases, a long-standing obstacle that generated significant loss of time and resources. The efficiency in this area has reached 90%. A substantial reduction in installation time was also achieved, decreasing by almost 2 h compared to the usual duration, and reaching a total of more than 5 h for the primary case study process. Additionally, implementing 5S proved critical to the company's service warehouse, improving efficiency and productivity through organization, cleanliness, and standard setting. Consequently, search times were reduced by more than 67%, which minimized waste, contributed to improved workplace safety, and promoted a culture of continuous improvement. The results of these scenarios were positive, indicating that the project is viable in the business context.

References

[1] INEI. (2019). INEI. Obtained of http://m.inei.gob.pe/prensa/noticias/sector-servicios-prestados-aempresas-crecio-396-en-abril-2019-y-acumulo-comportamiento-positivopor-vigesimo-cuarto-mes-continuo-11629/

[2] BCR. (Abril de 2020). BCR. Obtained of https://www.bcrp.gob.pe/docs/Publicaciones/Notas-Estudios/2020/notade-estudios-28-2020.pdf

[3] Comercio, E. (30 de Julio de 2020). El Comercio. Obtained of https://elcomercio.pe/economia/peru/inei-sector-servicios-prestados-aempresas-cayo-4084-en-mayo-nndc-noticia/

[4] E. Ramos, TJ Pettit, M. Flanigan, L. Romero y K. Huayta, “Modelo de gestión de inventario basado en cadena de suministro ajustada para aumentar el nivel de servicio en un distribuidor del sector automotriz”, Int. J. Gestión de la cadena de suministro, vol. 9, núm. 2, págs. 113 a 131, 2020

[5] Suárez-Barraza, M. F., & Ramis-Pujol, J. (2010a). Implementation of Lean Kaizen in the human resource service process. Journal of Manufacturing Technology Management, 21(3).

[6] Ambrosio-Flores, K. L., Lazo-de-la-Vega-Baca, M., Quiroz-Flores, J. C., & Cabrera-Gil-Grados, E. (2022). Warehouse management model integrating BPM-Lean Warehousing to increase order fulfillment in SME distribution companies.

[7] Dave, B. (2017). Business process management – a construction case study. Construction Innovation, 17(1), 50–67. https://doi.org/10.1108/CI-10-2015-0055

[8] Nunez-Castaneda, Y., Moreno-Samanamud, M., Shinno-Huamani, M., Maradiegue-Tuesta, F., & Alvarez-Merino, J. (2019). Improvement of Warehouses of Distribution Companies through Lean Warehouses and an Allocation Algorithm.

[9] Balavarca Garro, R. I. de L. Á., & Lindo Córdova, C. N. (2022, mayo 11). Modelo de gestión de inventarios basado en Lean Warehousing para incrementar los pedidos perfectos en empresas confiteras de Lima.

[10] Abhishek, P.G., & Pratap, M. (2020). Achieving Lean Warehousing Through Value Stream Mapping. South Asian Journal of Business and Management Cases, 9(3), 387–401.

[11] Ruiz-Ocampo, D., Ñañez-Rebatta, A., & Quiroz-Flores, J. (2023). A Quality Model Based on Lean Service Quality Philosophy and the PMBOK to Reduce Non-compliant Products from a Retail Store in Peru. AIP Conference Proceedings, 2613. https://doi.org/10.1063/5.0119319.

[12] Serna-Ampuero, M. A., Arias-Navarro, M., & Quiroz-Flores, J. C. (2022). Inventory Management Model under the Lean Warehousing Approach to Reduce the Rate of Returns in SME Distributors.

[13] Naranjo-Mantilla, M., Llorens Cervera, S., & Tenesaca, G. (2022). ABC Inventory Control System Based on an Office Automation Tool (pp. 662–666). https://doi.org/10.1007/978-3-031-19679-9_84

[14] Silva, A., Roodbergen, K. J., Coelho, L. C., & Darvish, M. (2022). Estimating optimal ABC zone sizes in manual warehouses. International Journal of Production Economics, 252, 108579. https://doi.org/10.1016/j.ijpe.2022.108579

[15] Pérez Mata, C. E., & Romero Dessens, L. F. (2022). Implement an inventory management system to improve the material flow of expanded polystyrene (EPS) products.

[16] Villacrez Zelada, A. S., & Liñer Hernández, J. S. (2022). Propuesta de modelo de gestión de inventarios y almacén para incrementar el nivel de servicio utilizando herramientas de Lean Warehousing en una pyme comercializadora.

[17] Velasquez-Costa, J. (2022). Impact of the 5S methodology in the optimization of resources in metalworking companies.

[18] Roncal-Coronel, M., Tarazona-Ballon, F., & Quiroz-Flores, J. C. (2023). Warehouse Management model to reduce return rate applying Lean Manufacturing Techniques and Multicriteria ABC in a SMEs in the textile sector. In ACM International Conference Proceeding Series (Vol. 1, Issue 1). Association for Computing Machinery. https://doi.org/10.1145/3587889.3587913.

[19] Chase, R., Jacobs, R., & Aquilano, N. (2017). Administración de Operaciones: Producción y Cadena de Suministros. McGraw Hill Education

[20] Yimsri, B., Watanapa, A., & Wiyaratn, W. (2022). Flexible applications of MRP-based prototyping software for production planning and diversified raw material inventory management.

[21] Miclo, R., Lauras, M., Fontanili, F., Lamothe, J., & Melnyk, S. A. (2019). Demand Driven MRP: assessment of a new approach to materials management. International Journal of Production Research, 57(1), 166–181. https://doi.org/10.1080/00207543.2018.1464230.

[22] Lopez-Uchuya, K., Zamudio-Guido, V., & Altamirano Flores, E. (2022). Lean Manufacturing and MRP to streamline the production of metal structures in the construction industry.

[23] T. Rohaan y C. Groothuis- Oudshoorn, «Using Supervised Machine Learning for B2B sales forecasting: A case study of spare parts sales forecasting at an after-sales service provider, 2021.

Biographies

Silvana Aguilar-Cevallos (*1999) bachelor's degree in industrial engineering from Universidad de Lima, Peru. She works at the PUCP in Academic Management of Planning and Evaluation. Her research areas are finance and logistics.

Yersson Aguilar-Cevallos (*1998) studied Industrial Engineering at the Universidad de Lima, Peru. He is currently in his last cycle of the race.

Juan Carlos Quiroz-Flores holds an MBA from Universidad ESAN. He is an Industrial Engineer from Universidad de Lima and Ph.D., in Industrial Engineering from Universidad Nacional Mayor de San Marcos and Black Belt in Lean Six Sigma from Universidad Peruana de Ciencias Aplicadas. He is currently an undergraduate Professor and researcher at the University of Lima. He is an expert in lean supply chain and operations with over 20 years of professional experience in operations management, process improvement, and productivity.

Yvan Jesus Garcia-Lopez is a Ph.D. (c) in Engineering and Environmental Science, UNALM, MBA from Maastricht School of Management, Holland, MSc in Computer Science, Aerospace Technical Center - ITA, Brazil. Stage in Optimization of Processes and Technologies, University of Missouri-Rolla, USA, and Chemical Engineer from the National University of Callao. He has over 25 years of extensive experience managing investment projects, execution, and commissioning in Peru, Colombia, USA, Brazil, and China.

Conference On Production Systems And Logistics
CPSL 2023-2

5th Conference on Production Systems and Logistics

From Complexity To Clarity In Sustainable Factory Planning: A Conceptual Approach For Data-driven Integration Of Green Factory KPIs In Manufacturing Site Selection

Michael Riesener[1], Tobias Adlon[1], Esben Schukat[1], Jan Salzwedel[1], Carsten Engeln[1], Felix Paßlick[1]

[1]*Laboratory for Machine Tools and Production Engineering (WZL), RWTH Aachen, Campus-Boulevard 30, 52074 Aachen, Germany*

Abstract

The selection of manufacturing facility locations entails high costs and long-term consequences. This necessitates an objective approach to mitigate uncertainties associated with subjective decision-making. Our paper builds upon previous research on data-driven location selection and conceptually extends it to integrate sustainability potential evaluation. By combining Green Factory Key Performance Indicators (KPIs), the authors aim to facilitate and standardize long-term decision-making in sustainable factory planning.

After outlining the requirements, current state of the art, and limitations of location selection, we emphasize the need for integrating region-specific Green Factory KPIs with new data sources for site selection. Therefore, we propose a methodology involving a review of scientific literature and other sources to identify data sources for site selection, establishing research criteria for determining data suitability. The results include suitable subsets for location selection and future steps such as criteria application and target data determination.

This paper contributes to paving the way for implementing sustainability-driven location selection strategies in factory planning. In conclusion, we outline a roadmap for further development and suggest two areas for future research: data collection and integration, as well as developing and validating a location selection app.

Keywords

Factory Planning; Site Selection; Sustainability; Digitalization; Green Factory

1. Motivation

Sustainability and digitalization, among the most significant global megatrends, still need to be sufficiently considered in established factory location selection approaches. This publication aims to demonstrate these gaps and outlines ways to consider them in data research for objective and sustainable factory location selection. The authors' long-term aim is to develop an application for factory location selection. Future publications building on this publication will describe the data selection for analysis and the functionalities of an application that analyses this data (see Figure 1).

The approach of this publication is based on the initial description of the motivation and process for factory location selection. The gaps between state-of-the-art and demands in two factory planning trends (digitalization and sustainability) are analyzed. Strategies to close these gaps are derived, starting with systematic and holistic data research as the first step of factory location selection.

DOI: https://doi.org/10.15488/15325
ISSN: 2701-6277

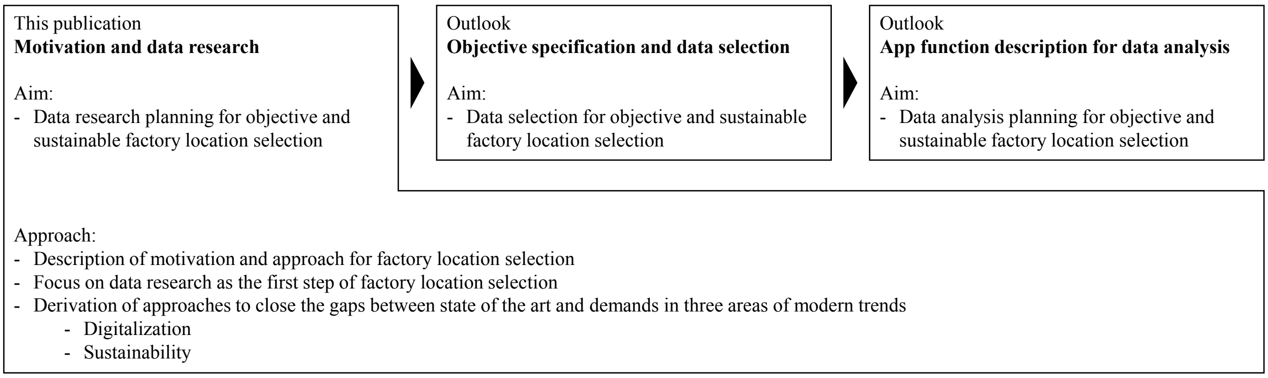


Figure 1. This paper aims to use data research planning as a basis for future research

Two fields of focus are considered in this paper. The first field, digitalization, necessitates and enables new approaches for data research, selection, and analysis for decision support. The second field, green factories, enables new considerations of environmentally sustainable location factors to meet the increasing demand for sustainable production.

2. Factory location selection approach

Factory location selection is crucial for business success. The selection of new factory locations is based on location search and evaluation. This strategic decision is critical in gaining competitive advantages and ensuring operational efficiency for manufacturing companies [1], especially in light of supply shortages, growing market uncertainties, skilled labor shortages, and increasing interconnectedness of production locations [2]. Location selection is a continuous process for most corporations and medium-sized enterprises, with decisions every two years on average [1].

This publication is based on an established approach for factory location selection. In this approach, potential location options are gradually narrowed down: first on a global level, then on a regional level, and finally on a local level. The first step of location selection is the definition of site requirements. These requirements may be derived from the overarching, long-term corporate strategy and the motives for the new site establishment [2]. The second step of the location selection process is the description of possible location alternatives through several location factors. These factors differ depending on the level of planning. [3] This paper builds upon this approach and focuses on location selection from the super-regional to the local level.

This publication focuses on data research since it is a crucial initial step for factory location selection. Location criteria are derived from quantitative and qualitative location factors according to company-specific requirements and can be distinguished into knockout, minimum, and wish criteria. Location selection criteria are selected and weighted differently depending on each case. The location options are either quantitatively or qualitatively evaluated according to these criteria. Quantitative methods mainly calculate expected costs and revenues via net present value [4]. Qualitative methods consider factors not quantifiable in monetary terms primarily via utility analyses and weighted criteria [2]. Quantitative approaches feature the manual selection of alternatives and heuristics or optimizations, enabling automatic decision-making [5]. The most used location selection methods are utility analyses, a qualitative approach [1]. Location selection, therefore, highly depends on the data to be analyzed.

3. Digitalization

Digitalization increases the availability of high-quality data that business decisions need to consider [6]. Decisions must be supported by digital analysis of relevant, high-quality data [7].

The first identified gap (1) lies between the predominant consideration of quantitative factors and the increasing demand for consideration of qualitative factors in location planning. Due to the severe consequences of wrong location selection decisions, they primarily depend on the objective analysis of quantitative information [1]. However, neglecting the systematic consideration of less tangible influencing factors such as political stability or availability of personnel [5] can lead to wrong location selections that are costly or impossible to be reversed later.

The second gap (2) relates to the insufficient number of typically considered influencing factors for strategic decisions [8]. The need for consideration of interconnected location criteria, including emerging dimensions like sustainability [9], calls for a more expansive approach.

The third gap (3) centers around the challenge of identifying and assessing a growing number of factors while simultaneously meeting the demand for more in-depth research, selection, and preparation of these factors. Usually, after matching internal company requirements with specific and weighted location criteria, information is gathered about the locations' external environments for qualitative and quantitative analysis [2]. Hence, data research, selection, and preparation are the basis for any location selection analysis [1].

The fourth gap (4) lies in the increasing complexity and subjectivity in decision-making, necessitating the acceleration of simpler, objective decisions. Established location selection methods need to consider this current complexity [10]. Complexity reduction is necessary for accelerating decisions while ensuring high decision quality for strategic decisions with long-term consequences [11].

The fifth gap (5) lies between current quasi-rational and subjective location decisions, intuitively made by expert teams [8], the demand for uncertainty reduction, and the uncertainty-increasing need for a wider variety of influencing factors. The subjective location decisions are based on uncertain qualitative and quantitative information [12], resulting in long-term, complex, and difficult-to-reverse decisions [9]. Additional information reduces these uncertainties [13].

Closing the first gap (1) requires systematically considering all available and suitable quantitative and qualitative factors in location planning. Examples of such data can be found in the fifth chapter. A guideline is to be developed for low-effort factor selection from these databases.

Closing the second gap (2) requires a method of analysis that allows for flexibly increasing the number of considered factors. A preselection of factors should be developed that require little preparation for evaluation and, therefore, are easy to incorporate into a location selection analysis.

Closing the third gap (3) requires streamlining the research, selection, and preparation of numerous factors to be considered. A thorough analysis of standard databases can significantly reduce the research workload.

Closing the fourth gap (4) requires accelerating less complex objective decisions. Factory planners need decision support to understand the effects that can be derived from the diverse planning information [14]. Decision support systems are methods and tools for data analysis, system modeling, and identification of optimal solutions [5]. Schuh et al. proposed a new data-based method for high-quality location selection decisions featuring a company-specific quantitative assessment of soft and hard factors. This method involves four key steps: industry analysis, regional determinants examination, location comparison through target functions, and sensitivity and scenario analysis of ranked alternatives. The method may be enhanced by dynamically analysing upcoming boom regions, enabling first-mover benefits. [1]

Closing the fifth gap (5) requires balancing a comprehensive approach to reduce uncertainty with a focus on the most critical factors. Due to today’s uncertainties, the comprehensibility of location selection is especially important [2]. The level of detail or aggregation of the decision support determines the trade-off between low-effort usage and result accuracy [15]. Low-effort decision-making requires focus on the most essential aspects with minimal effort for information gathering [13].

Table 1. Summary of the gaps to close in factory location planning concerning digitalization

	State of the art	Demand	Closing the gap
First gap to close (1)	Predominance of quantitative factors	Consideration of qualitative factors	Guideline for factors selection
Second gap to close (2)	Low number of considered factors	High number of influencing factors	Expandable factor preselection
Third gap to close (3)	High difficulty for data research	Large scope of data research	Expandable data base preselection
Fourth gap to close (4)	High complexity of subjective decisions	Low complexity of objective decisions	Digital decision support
Fifth gap to close (5)	High uncertainty of subjective decisions	Low uncertainty of objective decisions	Comprehensibility and low-effort usage

4. Sustainability

The importance of sustainability as an influencing factor in manufacturing business decisions increases along with environmental policy pressure. This pressure originates from the public (government organizations, non-governmental organizations, customers) and the environment. Therefore, circular economy principles and the risks of climate change cannot be disregarded in the long run. This necessitates the consideration of sustainability in business activities with long-term implications, such as optimizing the supply chain and, consequently, the location selection for factories. [16,17] Besides, such considerations of ecological factors can result in economic and strategic benefits [18]. Without considering sustainability in location selection, the introduction of, e.g., European Sustainability Reporting Standards (ESRS) and legally mandatory sustainability targets for industrial sectors and locations will inevitably lead to costly factory modifications. Yet established approaches for location selection do not consider the various factors influencing sustainability, e.g., the possibilities for using and generating renewable energies.

Closing this gap requires the introduction of measurable and applicable Green Factory KPIs into the location selection process. This requires a methodological framework for translating Green Factory KPIs into location selection criteria [19]. Factors to be considered include, for example, the Green Factory KPI "CO_2 emissions of logistics". This Green Factory KPI can be incorporated into the location selection process by considering supply chain distances from a sustainability and economic perspective. The Green Factory KPI "Waste Recycling" can also be included in the location selection process by considering the proximity to suitable waste processing industries and the emissions generated during transportation. Furthermore, the choice of location influences not only Green Factory KPIs based on transport distances but also other factors, such as the proportion of internally generated renewable energy. This can be considered in the location selection process, for example, by taking the varying availability of solar-capable land into account.

5. Resulting Data Research Approach

In conclusion, the result regarding digitalization is the need for digital decision support systems. Such systems decrease the uncertainty, subjectivity, and complexity of location decisions. Uncertainty is reduced via analysis of extensive factors and data sets. Subjectivity is reduced by evaluating according to ranked individual objectives and unveiling development patterns invisible without algorithmic analysis. Complexity is reduced via digital automation of typical analysis steps. Therefore, this publication proposes a data research approach to identify suitable data for such decision support systems as a first step. One of the next steps in our future research will be the selection of databases to integrate into a decision support system.

The result regarding sustainability is the need for quantitative analyses of green factory KPIs to enable location selection according to sustainability objectives. The following steps are supposed to mitigate the non-consideration of sustainability in state-of-the-art location. First, we evaluate which Green Factory KPIs have the highest significant impact on overall sustainability performance of planned productions. Then, a cause-and-effect analysis will be carried out to examine how the choice of location influences the manifestation of these Green Factory KPIs. This cause-and-effect analysis can be conducted through a questionnaire-based empirical study involving experts in factory planning [20]. Taking into account the identified relevance of Green Factory KPIs on overall sustainability performance, the benefits of incorporating Green Factory KPIs in the location selection process must be assessed.

The data content is the first assessment dimension. The data must enable consideration of as many relevant location factors as possible. Only a fraction of the potential factors are suitable for any location selection case. The following ten main categories provide an overview of established assessment dimensions that each contain many location factors: market potential (C1), supply infrastructure (C2), freedom of trade (C3), labor market & workforce (C4), transfer payments & subsidies (C5), legal certainty (C6), political stability (C7), macroeconomic stability (C8), simplicity of business establishment (C9) and transportation infrastructure (C10). [1] A holistic selection of relevant factors and corresponding data sets is enabled by closing the described gaps regarding sustainability. We propose an extension of the ten categories by the following category: sustainability (C11). Thus, eleven categories of location factors are offered to assess the data content.

Data suitability is the second assessment dimension. In this dimension, the data can be assessed regarding the context fit of the contained information via three aspects: relevance (S1), trustworthiness of the source (S2), and trustworthiness of the included information (S3). In addition, the data can be assessed regarding the data structure quality via two aspects: comprehensiveness (S4) and granularity or level of detail (S5). In addition, the data can be assessed regarding the data value quality via two aspects: precision (S6) and currency, actuality, or timeliness (S7). In addition, the data can be assessed regarding its environment, including knowledge and governance, via one aspect: usability (S8). [21] Relevance (S1) in this context describes whether the content of data records meets the respective information needs. Trustworthiness of the source (S2) in this context describes whether the data source is perceived as reliable. Trustworthiness of the contained information (S3) in this context describes whether the data creation method is perceived as reliable, e.g., the data may be perceived as less reliable if it contains subjective interpretations recorded in surveys. Comprehensiveness (S4) in this context describes whether the data includes all entities in the desired scope about which information is required, e.g., if all states of the world are included. In this context, granularity or level of detail (S5) describes whether all entities contain the required information, e.g., if locations are broken down into countries, counties, or other classes. Precision (S6) in this context describes whether numerical values contain the desired number of places beyond the decimal point; e.g., they may not be considered precise if rounded. Currency actuality or timeliness (S7) in this context describes whether the data represents the required point in time. Usability (S8) in this context describes whether the data is findable and accessible.

The resulting data assessment method follows the described two dimensions (see Table 2). The aim is a holistic but practical assessment for identifying suitable data sets. Therefore, for each data suitability aspect, each blank would be filled with a brief description according to the influencing factors described above and a simple rating according to case-specific preferences. It is the basis for further research to identify suitable databases and analysis methods.

Table 2. Method for data assessment regarding content and suitability

		Data suitability							
		Context fit			Data structure quality		Data value quality		Governance
Data content		Relevance	Trust in source	Trust in information	Comprehen-siveness	Granularity	Precision	Currency	Usability
Main categories	Data set	(S1)	(S2)	(S3)	(S4)	(S5)	(S6)	(S7)	(S8)
Market potential (C1)	Data set 1								
	Data set 2								
	Data set 3								
Supply infrastructure (C2)	Data set 4								
	Data set 5								
…	…								

6. Summary, conclusion and outlook

In summary, digitalization necessitates digital decision support systems to reduce uncertainty, subjectivity, and complexity in location decisions. Sustainability requires quantitative analysis of green factory KPIs to incorporate sustainability objectives in location selection. The proposed data assessment method follows the dimensions data content and data suitability, providing a practical approach to identifying appropriate data sets and databases for informed decision-making as well as further research and analyses.

In conclusion, such a targeted approach supports the further development of factory site selection processes. By incorporating two main future megatrends (sustainability and digitalization), the approach enables enterprises to realize strategical advantages. For example, factories strategically situated with a strong emphasis on ecological sustainability are likely to exhibit superior ecological performance, thereby facilitating adherence to regulatory frameworks and increasing long-term resource efficiency. This, in turn, translates into heightened resilience in the face of potential energy supply crises and shifts in legislation.

As an outlook, additional research leading to further publications is proposed. Next, the assessment method will be detailed to select location factors and suitable databases. Later, a prototypical software application will be presented. Its aim is the decision support in factory location selection based on analyzing the selected databases. Finally, the application will be evaluated. Further studies may be necessary to select data analysis methods and the desired form of results to be included in the decision support system.

Acknowledgments

Funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany‘s Excellence Strategy – EXC-2023 Internet of Production – 390621612.

References

[1] Schuh, G., Gützlaff, A., Adlon, T., Schupp, S., Endrikat, M., Schlosser, T.X., 2022. Datenbasierte Standortauswahl. Zeitschrift für wirtschaftlichen Fabrikbetrieb 117 (5), 258–263.

[2] Verhaelen, B., Peukert, S., Lanza, G., 2021. Site Selection Processes in Global Production Networks, in: Friedli, T., Lanza, G., Remling, D. (Eds.), Global Manufacturing Management. Springer International Publishing, Cham, pp. 101–115.

[3] Grundig, C.-G., 2021. Fabrikplanung: Planungssystematik – Methoden – Anwendungen, 7th ed. Hanser, München.

[4] Abele, E., Kluge, J., Näher, U., 2006. Handbuch globale Produktion. Hanser, München.

[5] 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.

[6] Faisal Imran, Khuram Shahzad, Aurangzeab Butt, Jussi Kantola, 2021. Digital Transformation of Industrial Organizations: Toward an Integrated Framework. Journal of Change Management 21 (4), 451–479.

[7] Harkonen, J., Mustonen, E., Koskinen, J., Hannila, H., 2020. Digitizing Company Analytics – Digitalization Concept for Valuable Insights, in: 2020 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM). 2020 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), Singapore. 14.12.2020 - 17.12.2020. IEEE, pp. 1012–1016.

[8] Afra, S., Aders, C., 2000. Shareholder Value Konzepte: eine Untersuchung der Dax 100 Unternehmen, 2nd ed. KPMG Consulting GmbH, Frankfurt am Main, 43 pp.

[9] Nyhuis, P., Großhennig, P., Mühlenbruch, H., 2006. Das Globale Varianten Produktionssystem: Eine Globalisierungsstrategie für kleine und mittelständische Unternehmen. Zeitschrift für wirtschaftlichen Fabrikbetrieb 101 (5), 282–286.

[10] Burggräf, P., Schuh, G., Dannapfel, M., Esfahani, M.E., Hoeschen, A., Ivanescu, S.-M., Jasinski, T., Kupke, D., 2021. Standortplanung, in: Burggräf, P., Schuh, G. (Eds.), Fabrikplanung, 2 ed. Springer Vieweg, Berlin, Heidelberg, pp. 63–121.

[11] Ferdows, K., Vereecke, A., de Meyer, A., 2016. Delayering the global production network into congruent subnetworks. Journal of Operations Management 41 (1), 63–74.

[12] Blohm, H., Lüder, K., Schaefer, C., 2012. Investition. Vahlen.

[13] Spetzler, C.S., 2016. Decision quality: Value creation from better business decisions. John Wiley & Sons Inc, Hoboken, New Jersey.

[14] Bejjani, C., Utsch, J., Thiele, T., Meisen, T., Jeschke, S., Burggräf, P., 2018. Flow Chart Based Information Modeling for Factory Planning. Procedia CIRP 72, 410–415.

[15] 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.

[16] Bhinge, R., Moser, R., Moser, E., Lanza, G., Dornfeld, D., 2015. Sustainability Optimization for Global Supply Chain Decision-making. Procedia CIRP 26, 323–328.

[17] Schönsleben, P., 2020. Supply Chain Design: Standortplanung und Nachhaltigkeit, in: Schönsleben, P. (Ed.), Integrales Logistikmanagement. Springer Berlin Heidelberg, Berlin, Heidelberg.

[18] Schuh, G., Mauß, W., Potente, T., Schmitz, S., Adlon, T., Maetschke, J., Neumann, H., Salzwedel, J., Kozielski, S., Luckert, M., Reuter, C., Schmidhuber, M., Witthöft, J., 2023. Green Re-Assembly Upgrade Factory, in: Empower Green Production - Conference Proceedings. AWK '23, Aachen. 11.05.-12.05.2023, pp. 314–338.

[19] Günther Schuh, Andreas Gützlaff, Tino X Schlosser, Martin Welsing, Lisa Balgar, 2022. How to measure ecological sustainability in manufacturing? - A literature review of indicator frequency and relevance (Preprint).

[20] Gläser, J., Laudel, G., 2010. Experteninterviews und qualitative Inhaltsanalyse als Instrumente rekonstruierender Untersuchungen, 4. Auflage ed. VS, Wiesbaden, 347 pp.

[21] Sebastian-Coleman, L., 2022. Meeting the Challenges of Data Quality Management. Academic Press Inc, San Diego, 28 pp.

Biography

Dr.-Ing Michael Riesener (*1986) studied Industrial Engineering at RWTH Aachen University. Afterwards, he worked as a research assistant, group leader, and chief engineer at the Chair of Production Systems at the Laboratory for Machine Tools and Production Engineering, WZL of RWTH Aachen University. In 2015, he earned his Ph.D. in Innovation Management. He is also Managing Chief Engineer at the WZL, where he is particularly responsible for the Innovation Factory on the RWTH Aachen Campus.

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 Chief Engineer/ Head of the Factory Planning Department.

Esben Schukat (*1993) holds two degrees from RWTH Aachen University in the field of Mechanical Engineering and Economics and has been a research associate and group leader (assembly planning) at the Chair of Production Systems at the Laboratory for Machine Tools and Production Engineering, WZL of RWTH Aachen University, since 2019. Since 2023, he has been Chief Engineer/ Head of the Factory Planning Department while continuing his research activities on matrix-structured assembly systems.

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 longevity, resource efficiency, and other ecological and economic sustainability KPIs in factory planning.

Carsten Engeln, M.Sc. (*1994) studied production engineering at RWTH Aachen University, Germany. Since 2022, he has worked as a research associate with the WZL of RWTH Aachen University. His Ph.D. project focuses on enabling factory optimization via automated creation of digital value stream transparency.

Felix Paßlick, B.Sc. (*1998) studies industrial engineering at RWTH Aachen, Germany, and business administration at Chulalongkorn University Bangkok, Thailand. Since 2021, he has been a student research assistant and is currently a master's thesis student at the Laboratory for Machine Tools and Production Engineering, WZL of RWTH Aachen University.

CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
CPSL 2023-2

5th Conference on Production Systems and Logistics

Concept And Exemplary Application Of Industrialized Re-Assembly To An Automotive Use Case In The Context Of Circular Economy

Michael Riesener[1], Maximilian Kuhn[1], Nikolai Kelbel[1] and Günther Schuh[1,2]

[1]Laboratory for Machine Tools and Production Engineering WZL, RWTH Aachen University, Aachen, Germany
[2]Fraunhofer Institute for Production Technology IPT, Aachen, Germany

Abstract

To reach set climate goals recent paradigms of production need to be reconsidered. Within the automotive industry, approaches like electric mobility focus on the use phase. However, the production of an electric car is resource and energy intensive, which diminishes the ecological advantage of electrification in the use phase. Established approaches aiming for the production phase often involve saving energy or resources, which is in a single-digit range when it comes to the reduction of emissions. In contrast to that, applying the concept of Circular Economy can reduce the ecological impact of products over their lifetime significantly. This paper introduces Re-Assembly as a plannable concept to extend the lifetime of products while reducing emissions and increasing the margins for the OEM. By combining the concept of Re-Assembly with other R-strategies, this paper aims to demonstrate the ecological and economic potential of circular business models, especially in the automotive sector. This is done by introducing the results of a use case and deriving specific enablers for the concept. The resulting enablers can be understood as fields of action for establishing Re-Assembly in practice.

Keywords

Sustainability; Re-Assembly; Remanufacturing; Circular Economy; Production

1. Introduction

In the context of the sustainability transformation, manufacturing companies are on the edge of a paradigm shift. According to the Circularity Gap Report 2023, 70% of the global greenhouse gas emissions are produced by the handling or usage of materials [1]. To limit the consequences of climate change to a temperature rise of 1.5 degrees Celsius a maximum of 400 Gt of CO_2-equivalences can be emitted, calculated from the beginning of 2020. With constant emissions, this CO_2-budget will be depleted in a few years [2]. At the same time, the manufacturing industry is characterized by over-production and over-capacity. For instance, a tooling machine has a 34% capacity utilization on average [3]. In the automotive industry, it is common to produce a disproportionate variety of vehicles that result in only 20-30% of profitable variants [4]. Focusing on the automotive example, the profuseness becomes clearer when looking at the usage phase. Private vehicles are only used with 1.5% of their loading and time capacity [5]. Furthermore, the mobility shift, driven by the EU's ban on internal combustion vehicles [6], is leading to an increased production of electric vehicles with increasing battery sizes. This leads to a significantly worse environmental footprint of an electric vehicle in production compared to an equivalent combustion vehicle [7]. In summary, there is a high level of overproduction, overcapacity and resource consumption in the automotive industry.

A possible solution for these issues is the concept of Circular Economy and the associated R-strategies. This paper aims to introduce the concept of Re-Assembly as a possible strategy for the transformation of the automotive industry. By giving an overview of approaches from science and practice the paper demonstrates the ecological and economic potential of Re-Assembly in combination with other R-strategies and summarizes with the main enablers for this concept.

In the following chapter, the basic terms are defined and relevant research is summarized. Chapter 3 contains a description of the paper's research approach. In Chapter 4 the overall concept of the latter, its enablers alongside its potential are outlined. Chapter 5 concludes the paper with a summary and outlook.

2. Fundamentals

In this chapter, the basic terms "Circular Economy" and R-strategies are defined and differentiated. Subsequently, related work is summarized.

2.1 Circular Economy and R-strategies

Circular Economy is defined as an economic model that is able to decouple economic growth and resource consumption by using them in circulation. In contrast to that, the linear model is based on a "take-make-waste pattern". It is built on the assumption of cheap and easily accessible materials and energy. [8] Ellen MacArthur visualized the two fundamental cycles of Circular Economy, the technical cycle and the biological cycle, as shown in Figure 1. The cycles display how the linear model can be transferred to a circular model [9].

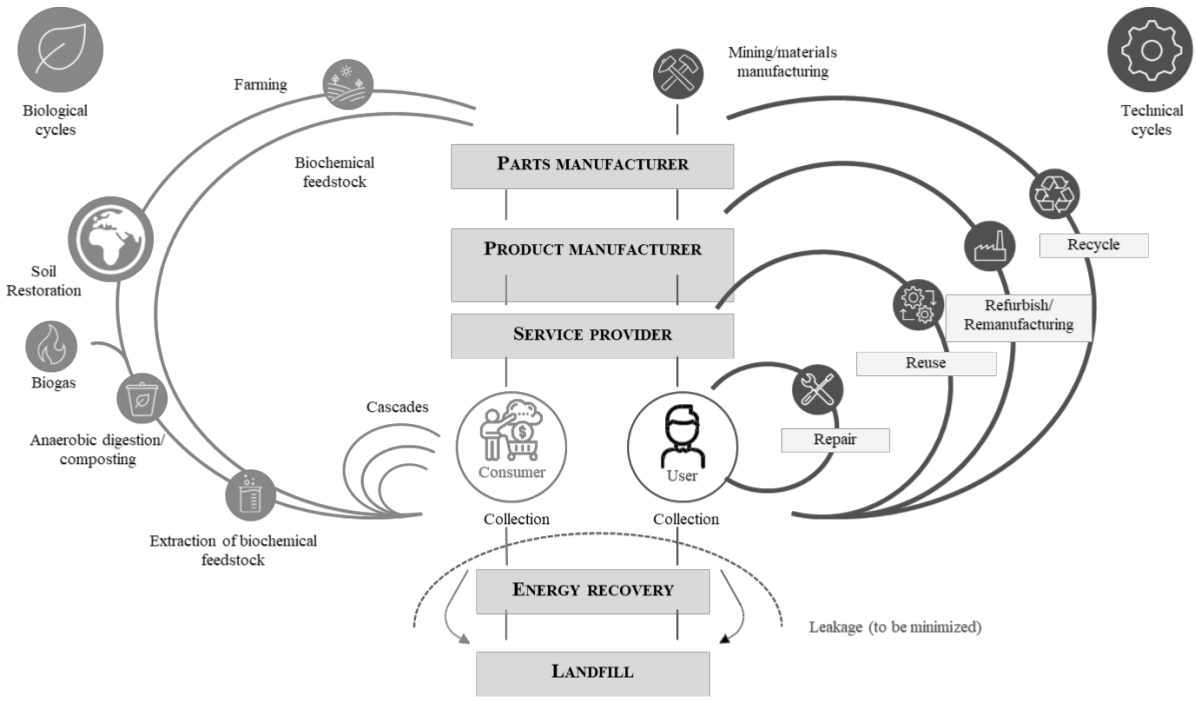


Figure 1: Butterfly model displaying the cycles of Circular Economy by Ellen MacArthur [9]

However, when reviewing these cycles the prioritization of the circles and their goals besides ecological sustainability do not become clear. The linear model, which is used today, has worked so well because it was economically beneficial. To be successful the circular model needs to become comparably profitable. Sustainability is already pursued today in the form of energy saving, efficiency and recycling. Though, life-extending measures and functional product expansions have potentially more ecological impact while being profitable as well. So, Circular Economy has to be a tool to align economic and ecological goals. Figure 2 shows which approaches need to be considered to make profitable sustainability work. This paper uses these approaches to introduce Re-Assembly as a new strategy to achieve this goal.

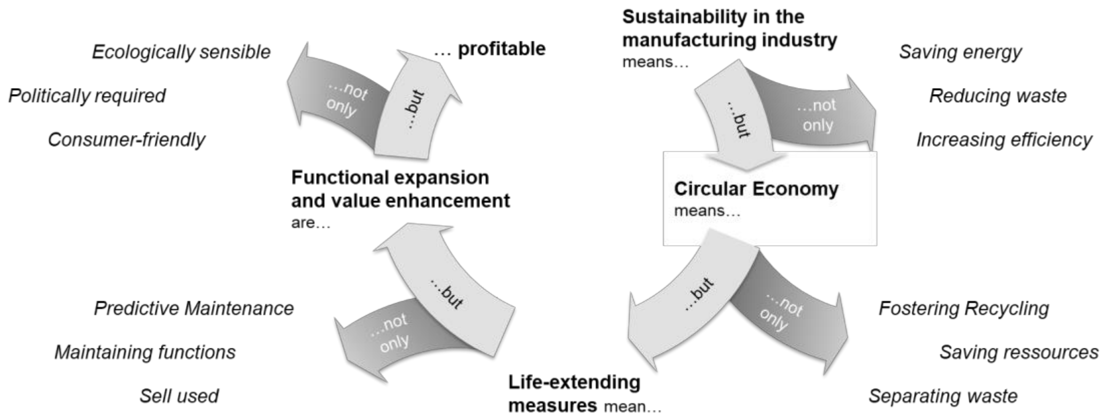


Figure 2: Aspects of a profitable Circular Economy [10]

Re-Assembly and other R-strategies serve to operationalize the Circular Economy. An example from the automotive industry demonstrates the ecological and economic added value of R-strategies. It shows that remanufacturing requires up to 80 % less energy than the production of new components [11]. In addition, water consumption is reduced by 88 % and the amount of waste by 70 % [11]. In this example, remanufactured parts are up to 40 % cheaper than new ones [11]. This means that customers can be offered an economically viable way to extend the lifetime of their product, saving further resources and emissions. Another advantage is the reduction of dependence on primary resources. Closed material cycles can achieve material savings and industries such as the automotive industry benefit from this in particular [12]. Since Re-Assembly shares and extends the ideas of remanufacturing, it is likely to have even greater potential.

Various R-strategies have been defined by several authors to help operationalize the concept of Circular Economy. In the following, this paper will refer to ten R-strategies that have been defined by Potting et al. and are listed in Table 1. Potting et al. have ranked them so that the strategies at the top of the list are those that embrace circularity the most. They require less energy and effort for realization and therefore have less impact on the environment [13].

Table 1: R-strategies by POTTING ET AL. [13]

R-strategy	Description
Refuse	Make product redundant by abandoning its function or by offering the same function with a radically different product
Rethink	Make product use more intensive (e.g. through sharing products, or by putting multi-functional products on the market)
Reduce	Increase efficiency in the product manufacture or use by consuming fewer natural resources and materials
Reuse	Reuse by another consumer of discarded product which is still in good condition and fulfils its original function
Repair	Repairs and maintenance of defective product so it can be used with its original function
Refurbish	Restore an old product and bring it up to date
Remanufacture	Use discarded product or its parts in a new product with the same function
Repurpose	Use discarded product or its parts in a new product with a different function
Recycle	Process materials to obtain the same (high grade) or lower (low grade) quality
Recover	Incineration of materials with energy recovery

However, referring to Figure 2, remanufacturing is the most noteworthy R-strategy despite its location in the middle of the list. Remanufacturing has the potential to optimize the ratio between renewed input and product value. Due to the usage of existing components and modules, resources, energy and value can be preserved and enhanced. As a value generating process remanufacturing enables the industry to be sustainable and profitable, build a circular business model and maintain employment. Other R-strategies prevent or reduce value creation since they are based on minimizing consume or restricting the maintenance of the original value of the product.

This paper introduces the term “Re-Assembly” as an additional R-strategy and advancement of remanufacturing that aids to operationalize Circular Economy. Re-Assembly is the replacement of components with refurbished and newly developed components for the short-term provision of a product that is at least as good as new with a warranty and, if necessary, an extended range of functions, while at the same time preparing for the recycling of the components. To distinguish this from remanufacturing, it is crucial to emphasize the upgradeability of the product. In addition, unlike remanufacturing, Re-Assembly should be plannable and carried out on an industrial scale. By considering all product modules and applying other R-strategies on a module level as well, this aims to minimize the product carbon footprint over the entire life cycle of the product and to close the loop for all resources used. To summarize, Re-Assembly aims at an industrial and scalable production of products and modules for lifetime extension and value enhancement in an “Upgrade Circular Economy”.

2.2 Related work

This chapter provides an overview of related terminologies to help outline the field of Re-Assembly. It shares the shown characteristics with them.

LANGE explains that **remanufacturing** offers great savings potential in terms of resource efficiency and energy efficiency. Although transport and reprocessing of the components generate additional emissions and require additional resources, these are significantly lower than those required for a new production. In addition, remanufacturing often requires less energy than recycling with subsequent new production of the component. Remanufacturing results in significantly lower production costs, which leads to a higher profit margin and can be passed on to the customer in the form of lower purchase prices if required. [14]

VAN LOON ET AL. name product categories where **remanufacturing** can achieve savings. Remanufacturing is suited for products that create a large part of their environmental impact during manufacturing. If the majority of the environmental impact is caused during the use phase, it is more expedient to substitute these with new, more efficient products. For products that lose efficiency over their lifetime and use more energy as a result, it may be better to replace them with new ones than to extend their lifespan. [16]

KAMRAD ET AL. describe the current concept for **upgradeable products** and developed a model to indicate under which circumstances this concept is profitable for companies. The concept divides the product into stable and improvable components. Improvable components can be exchanged and replaced by new ones with new features. This enables the customer to always be up to date with the latest technology without having to purchase a completely new product. In addition, only some of the components need to be adapted during development, which in turn reduces the time and cost of the development process. From an environmental perspective, this can reduce waste from obsolete products. The authors mention various scenarios in which the use of upgradeable products is suited for companies, including small market sizes, high production costs or different innovation speeds of individual components. [17]

PENG ET AL. present requirements for the development of **Open Architecture Products** (OAPs). OAP are in demand due to growing market requirements in terms of adaptability and cost efficiency and allow other manufacturers to adapt existing products to meet customer needs. An OAP is enabled by an adaptable design process; commonality and modularization are therefore not sufficient. The authors introduce a design process and give an example of an electric vehicle with an open architecture concept that can be adapted during its life cycle. [18]

LIANTO ET AL. try to show the different aspects of **Continuous Innovation** (CI) with their study. CI is understood as an innovation process that continuously and in a structured way generates innovations so that sustainable and growth can be achieved in the long term. This enables companies to quickly adapt to a fluctuating market and new customer demands. With CI development times can be reduced and the frequency of new products increased, which helps companies to remain competitive. In their study, the authors identify fundamental capabilities that enable CI. Among them are mainly intangible resources such as knowledge management or the social environment in the company. [19]

Re-Assembly as a term combines and enhances the characteristics of the established approaches shown. It serves as a overarching concept to describe an industrial and scalable (re-)production of products and modules for lifetime extension and value enhancement in an “Upgrade Circular Economy”. The literature so far lacks a suitable compilation of enablers for Re-Assembly. To derive a conceptual framework this paper presents the enablers of Re-Assembly in the following.

3. Research approach

This paper is designed as a qualitative and exploratory case study as described by [20] that draws on both literature and semi-structured interviews with researchers of the Laboratory for Machine Tools and Production Engineering WZL of RWTH Aachen University and a local automotive start-up, which focuses on a circular business model. The central research question was how Re-Assembly could have an ecological and economic impact on the automotive industry. The economic and ecological potential of the concept is demonstrated by referring to industry examples and literature on related concepts like “remanufacturing”, “upgradeable products”, “open-architecture-products” and “continuous innovation”. The research is supported by the findings of the “Re-Assembly-Factory case study” of the Machine Tool Colloquium of Aachen (AWK) in 2023. The AWK is an international platform for industry and research collaboration that is hosted by the WZL since the year 1948. In 2023 the topic was the transformation to a value-enhancing Upgrade Circular Economy. Part of the program were multiple case studies to demonstrate current research findings. One of those was the “Re-Assembly-Factory case study” which focused on the practical demonstration of a Re-Assembly factory concept in the automotive sector. The introduced potentials have a theoretical character and are to be understood as impulses for further research.

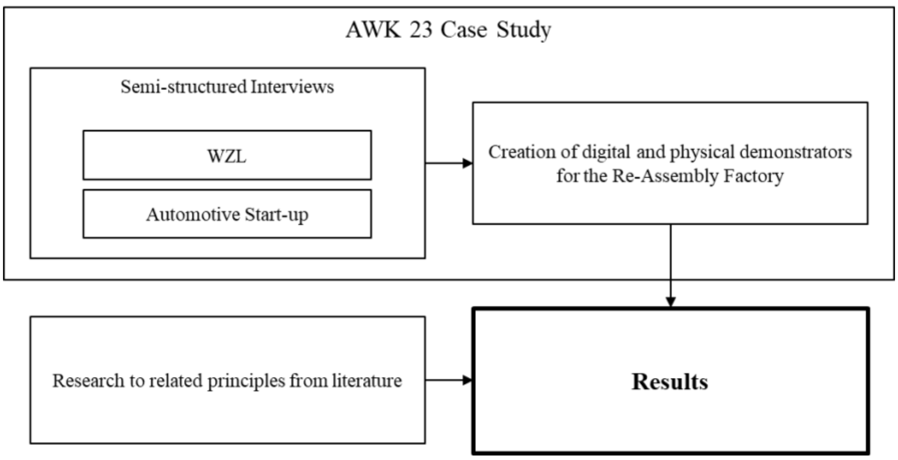


Figure 3: Research approach for determining relevant enablers for Re-Assembly

4. Re-Assembly Concept

This chapter aims to outline how a Re-Assembly concept can be established in practice. First, the Re-Assembly Factory use case is described. Second, the enablers for Re-Assembly which have been derived from that project are outlined.

4.1 Re-Assembly Factory at RWTH Aachen Campus

In the course of the AWK, a pilot project for a Re-Assembly Factory (Figure 4) was presented. In particular, the reassembly of the vehicle's outer skin components was shown. The first step was to dismantle the body parts from the vehicle. The disassembly was carried out with little effort since many components are fastened with quick-release fasteners. What remains is the so-called 'core', the part of the product that remains after disassembly [21], e.g. the vehicle frame in this case. This consists of components that have a long lifetime. The preservation of such components leads to emissions savings.

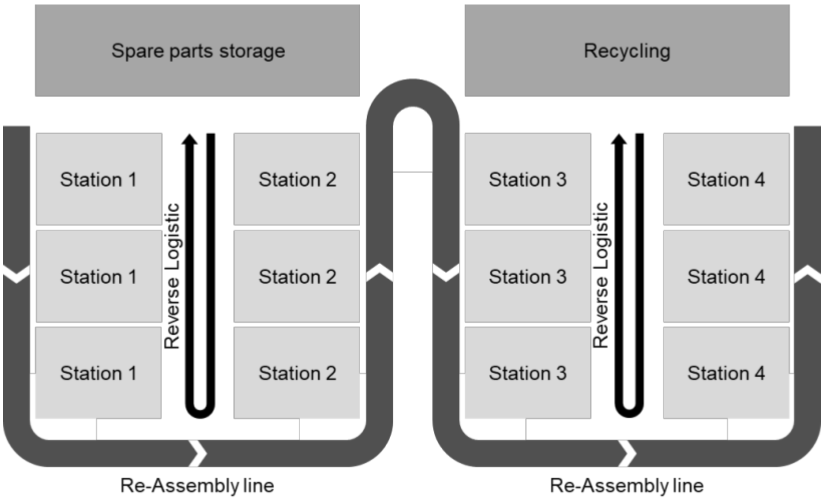


Figure 4: Concept of an Upgrade Re-Assembly Factory

During disassembly, the dismantled components can be assessed with regard to their quality and, based on this assessment, can be fed to the appropriate further processing [21]. Here, mainly remanufacturing and recycling approaches are considered. In particular, remanufacturing can take place directly at the same factory site or even directly on the assembly line. This reduces transport costs and can enable economic remanufacturing processes. In this use case, the vehicle’s seats were presented as an example of remanufacturing. The lifetimes of individual components of the seat can differ significantly. Remanufacturing allows to fully utilized the differing lifetimes of the components. This is achieved by replacing components after their useful lifetime while others can still be used. This leads to savings in emissions and resources.

In the second process station, new components - either remanufactured or newly produced ones, depending on customer requirements - were re-assembled. New components with functional enhancements can not only preserve the value of the original product but also increase its value [21]. Such extensions may be cameras or sensors for assistance systems. In the use case, other components such as the dashboards or headlights were also replaced. The final step was to test the re-assembled product. Here, the product must fulfil at least the same requirements as a comparable new product. If this is also given, the product can be delivered. [21]

During this use case, the enablers of Re-Assembly were identified and displayed via digital demonstrators. The results are incorporated in the following chapter.

4.2 Enablers for Re-Assembly approaches

The following chapter deals with several enablers for Re-Assembly concepts that have been identified through the case study. It serves as list of topics to engage with to establish Re-Assembly in practice.

4.2.1 Flexible Factory Concepts

Although Re-Assembly is considered “plannable” when compared to remanufacturing this does not result in a similar level of production certainty as it is usual in scalable linear production. In the context of Re-

Assembly "plannable" means that the upgrades and revision of products are intended since the product development. However, due to the longer lifetime of the product, the uncertainty regarding the condition is increased. Different customer requirements over the period of usage add to this tendency as well. Consequently, every upgrade cycle differs from product to product and which upgrade cycle the product is currently in. Although Re-Assembly has to be industrialized to unlock its full economic potential, a regular linear factory concept is not sufficient. Therefore, a matrix organization has been used in the described case study (Figure 4). A matrix factory concept represents a compromise between the flexibility of a workshop and the scalability of a line production [22]. This concept helps to level out the remaining uncertainties and enables spontaneous adaptations to unpredicted deviations regarding the product's condition. It also eases the organization of reverse logistics streams.

4.2.2 New Modularity

To enable Re-Assembly concepts and foster the ecological sustainability of products the modularization of products needs to be revised [25]. While in the past the goal of product modularization was cost reduction and the management of variant complexity [26] the dimension of sustainability establishes as a new factor in product development. Thinking about recycling, it is beneficial to design modules with the aim of easy separation of materials. Regarding Re-Assembly modularization has the goal to minimize disassembly effort by designing modules taking into account different lifetimes and the accessibility of components. This can result in a fundamentally different product architecture. Referring again to the term "plannable Re-Assembly", thinking ahead in product development plays a vital role in enabling efficient Re-Assembly concepts.

4.2.3 Open-Architecture Products

When thinking about upgradeability and new paradigms for modularizations the concept of open-architecture products comes into mind. Originally a concept from software development, it represents the idea of enabling third-party products to be compatible with the product. The main product serves as a platform on which a variety of other products work as components, comparable with an operating system of a smartphone and its applications. This has the potential for more customization with significantly less internal complexity. However, the producer needs to open up and adequately aggregate constructional data to third parties. Furthermore, the establishment of new hardware interfaces, that are potentially more complex and expensive, and security standards are prerequisites.

4.2.4 Hardware Interfaces

Reconditioning used products may be not profitable if the process is too complex. To reduce labor costs and takt time in a Re-Assembly factory the products need to be disassembled easily. While automated disassembly can be complicated due to the variety of conditions in which the products are returned to the factory, manual disassembly can be expensive. Especially if Re-Assembly factories are located in high-wage countries to enable efficient and ecological reverse logistics the disassembly process must become highly efficient. One option to support that is to modify the product's hardware interfaces. While conventional products often have inseparable interfaces which are glued or welded circular products need to be dismountable without damaging a component. This can be done by reintroducing quickly detachable screw connections or similar interfaces. The resulting higher costs are compensated by the product's extended lifetime.

4.2.5 Digital Product Pass

The most effective tool to eliminate the uncertainty of a Re-Assembly system is the utilization of usage data. A digital product pass serves as an enabler to collect, store and present such data to the relevant stakeholder. The product pass collects data through the entire lifecycle. This is especially reasonable on the level of components. The pass stores data about the product's architecture, the materials used, information for maintenance, energy and emission data to calculate the product carbon footprint [23]. It collects usage data to enable predictive maintenance or to foster further customization. Every component has its own set of data even if assembled into another product which is crucial for products that rely on homologation. Moreover, the digital product pass supports the workload planning for the Re-Assembly factory by calculating the upgrade scope for the next Re-Assembly appointment with a use of usage and customizing data. However, due to the storage in a cloud system, the issue of data privacy must be clarified beforehand.

4.2.6 Homologation

One issue when trying to upgrade products, especially in the automotive sector, is homologation. Modifying or upgrading a safety-relevant component can lead to the invalidity of the vehicle's homologation. One approach to tackle this is to pre-homologate possible component combinations so that if the product leaves the Re-Assembly factory with an upgrade it is already certified. However, this complex legal issue should not be discussed further here. Rather, this should be an appeal that the homologation processes of circular products must change in the future.

4.2.7 Subscription Business Models

Although it is possible to operate a Re-Assembly concept with a transactional business model, there are several reasons to switch to a subscription model. In general, to foster the transformation to a Circular Economy incentives need to be created for both customer and producer. Subscription models are characterized by the ownership of the product which remains at the producer [24]. The customer pays for the usage of the product. This leads to several advantages that synergize with Re-Assembly concepts. Firstly, the producer has an intrinsic motivation for the product to have a longer lifecycle and develops more robust products. Secondly, due to the ownership, the producer keeps the right to retrieve the products for an upgrade to extend the lifetime of the product. Thirdly, it becomes easier to get the right to utilize usage data. Moreover, customers benefit from periodically lower payments instead of high initial investment costs, the value preservation and up-to-dateness of the product.

5. Summary and outlook

This paper addresses the paradigm shift needed in manufacturing companies in the context of the sustainability transformation. To tackle this challenge the paper proposes the concept of an Upgrade Circular Economy with the associated R-strategies and the concept of Re-Assembly. This has been done by referring to related research and practical experiences from the authors. The case study and interviews that have been carried out revealed the challenges and prerequisites of the concept. With the provided input this paper summarized and outlined relevant enablers of Re-Assembly. Flexible factory concepts are needed to deal with the uncertainty of the product's condition which can be reduced by collecting life cycle data via a digital product pass. To enable upgradeability products need to be designed with quick-release interfaces and modularized for disassembly and compatibility with third-party components. Subscription business models can help to establish planned upgrade cycles and pre-homologate new component combinations. More research is needed to investigate how the enablers of Re-Assembly need to be designed in detail. Furthermore, it needs to be explored to what extent the applicability of Re-Assembly depends on the industry. Lastly, it must be emphasized that Re-Assembly is still a concept that needs to be further developed and tested in practice. It holds significant potential when it comes to circularity but represents a major shift with regard to the predominant concept of linear economy.

Acknowledgements

Funded by the German Federal Ministry for Economic Affairs and Climate Action.

Gefördert durch:

Bundesministerium
für Wirtschaft
und Klimaschutz

aufgrund eines Beschlusses
des Deutschen Bundestages

References

[1] Circle Economy, 2023. The circularity gap report. https://ic-ce.com/wp-content/uploads/2023/01/63c6986f0a57abe2fb9180d7_CGR-2023-Report-1-compressed.pdf. Accessed 5 June 2023.

[2] Mercator Research Institute on Global Commons and Climate Change (MCC), 2023. Remaining carbon budget. https://www.mcc-berlin.net/en/research/co2-budget.html. Accessed 5 June 2023.

[3] Bergs, T., 2021. Internet of Production – Turning Data into Sustainability.

[4] Boos, W., 2021. Die Produktionswende - Turning Data into Sustainability.

[5] World Economic Forum, 2021. Raising Ambitions: A new roadmap for the automotive circular economy. https://www.weforum.org/reports/raising-ambitions-a-new-roadmap-for-the-automotive-circular-economy. Accessed 5 June 2023.

[6] European Parliament, 2022. EU ban on sale of new petrol and diesel cars from 2035 explained. https://www.europarl.europa.eu/news/en/headlines/economy/20221019STO44572/eu-ban-on-sale-of-new-petrol-and-diesel-cars-from-2035-explained. Accessed 5 June 2023.

[7] Del Pero, F., Delogu, M., Pierini, M., 2018. Life Cycle Assessment in the automotive sector: a comparative case study of Internal Combustion Engine (ICE) and electric car. Procedia Structural Integrity 12, 521–537.

[8] European Parliament, 2023. Circular economy: definition, importance and benefits. https://www.europarl.europa.eu/news/en/headlines/economy/20151201STO05603/circular-economy-definition-importance-and-benefits. Accessed 5 June 2023.

[9] Ellen MacArthur Foundation, 2023. Circular economy principle: Circulate products and materials. https://ellenmacarthurfoundation.org/circulate-products-and-materials. Accessed 5 June 2023.

[10] Schuh, G., Schmitz, S., Lukas, G., Niwar, L., Welsing, M., Calchera, R., 2023. Framework for Circular Production Economy.

[11] Ellen MacArthur Foundation, 2021. Europe's first circular economy factory for vehicles: Renault. https://archive.ellenmacarthurfoundation.org/case-studies/europes-first-dedicated-circular-economy-factory-for-vehicles. Accessed 8 June 2023.

[12] World Economic Forum, Ellen MacArthur Foundation, 2016. Intelligent assets: Unlocking the circular economy potential.

[13] Potting, J., Hekkert, M., Worrell, E., Hanemaaijer, A., 2017. Circular Economy: Measuring Innovation In The Product Chain. https://www.researchgate.net/publication/319314335_Circular_Economy_Measuring_innovation_in_the_product_chain.

[14] Lange, U., 2017. Ressourceneffizienz durch Remanufacturing - Industrielle Aufarbeitung von Altteilen. VDI ZRE, Berlin.

[15] Peng, S., Ping, J., Li, T., Wang, F., Zhang, H., Liu, C., 2022. Environmental benefits of remanufacturing mechanical products: a harmonized meta-analysis of comparative life cycle assessment studies. Journal of environmental management 306, 114479.

[16] van Loon, P., Diener, D., Harris, S., 2021. Circular products and business models and environmental impact reductions: Current knowledge and knowledge gaps. Journal of Cleaner Production 288, 125627.

[17] Kamrad, B., Schmidt, G.M., Ulku, S., 2013. Analyzing Product Architecture Under Technological Change: Modular Upgradeability Tradeoffs. IEEE Trans. Eng. Manage. 60 (2), 289–300.

[18] Peng, Q., Liu, Y., Gu, P., Fan, Z., 2013. Development of an Open-Architecture Electric Vehicle Using Adaptable Design, in: Azevedo, A. (Ed.), Advances in Sustainable and Competitive Manufacturing Systems. Springer International Publishing, Heidelberg, pp. 79–90.

[19] Lianto, B., Dachyar, M., Soemardi, T.P., 2018. Continuous Innovation: A Literature Review and Future Perspective. International Journal on Advanced Science, Engineering and Information Technology 8 (3), 771.

[20] Yin, R.K., 2018. Case study research and applications: Design and methods, Sixth edition ed. SAGE, Los Angeles, London, New Dehli, Singapore, Washington DC, Melbourne, 319 pp.

[21] Schuh, G., Mauß, W., Potente, T., Schmitz, S., Adlon, T., Maetschke, J., Neumann, H., Salzwedel, J., Kozielski, S., Luckert, M., Reuter, C., Schmidhuber, M., Witthöft, J., 2023. Green Re-Assembly Upgrade Factory.

[22] Schmidtke, N., Rettmann, A., Behrendt, F., 2021. Matrix Production Systems - Requirements and Influences on Logistics Planning for Decentralized Production Structures, in: Proceedings of the 54th Hawaii International Conference on System Sciences. Hawaii International Conference on System Sciences. Hawaii International Conference on System Sciences.

[23] Jensen, S.F., Kristensen, J.H., Adamsen, S., Christensen, A., Waehrens, B.V., 2023. Digital product passports for a circular economy: Data needs for product life cycle decision-making. Sustainable Production and Consumption 37, 242–255.

[24] Dudenhöffer, F., Paul, A., 2022. Auto-Abos oder Subscription-Modelle verändern den Markt nach individueller Mobilität, in: Bruhn, M., Hadwich, K. (Eds.), Smart Services. Springer Fachmedien Wiesbaden, Wiesbaden, pp. 499–520.

[25] Schuh, G., Kuhn, M., Keuper, A., Patzwald, M., Schenk, L., Guo, D., Feucht, M., Kantelberg, J., Rossmair, G., Schroth, H., Viethen, U., Zeller, P., 2023. New Modularity and Technology Roadmapping.

[26] Williamsson, D., Sellgren, U., 2016. An Approach to Integrated Modularization. Procedia CIRP 50, 613–617.

Biography

Dr.-Ing. Michael Riesener (*1986) has been Managing Chief Engineer at the Chair of Production Engineering at the Laboratory for Machine Tools and Production Engineering (WZL) of RWTH Aachen University since 2017. Furthermore, he holds several positions in various entities at RWTH Aachen Campus connecting science and industry.

Dr.-Ing. Maximilian Kuhn (*1991) has been Chief Engineer in the Innovation Management Department at the Chair of Production Engineering at the Laboratory for Machine Tools and Production Engineering (WZL) of RWTH Aachen University since 2021. He is also the Managing Director of the Complexity Management Academy and the Innovation Factory Aachen.

Nikolai Kelbel (*1995) has been research associate at the Laboratory for Machine Tools and Production Engineering (WZL) of RWTH Aachen University since 2022.

Prof. Dr.-Ing. Günther Schuh (*1958) has been head of the Chair of Production Engineering at the Laboratory for Machine Tools and Production Engineering (WZL) of RWTH Aachen University since 2002. He is Director of FIR e.V. as well as a member of the Board of WZL and Fraunhofer IPT. He is also a member of numerous technical-scientific committees and founder and CEO of several start-ups in the field of electromobility.

5th Conference on Production Systems and Logistics

Scenarios Of Glass Disposal In Australia From Circular Economy And Life Cycle Assessment Perspective

Brian Smith[1], Shiva Abdoli[1]

[1]*School of Mechanical and Manufacturing Engineering, The University of New South Wales, 2052, Australia*

Abstract

The growing rate of consumption has drawn attention to measurable environmental impacts leading to the development of sustainability tools that can inform environmental, economic and social decisions. Façade glass is a widely used material that is highly recyclable material and is an important material for sustainable assessments as it promotes ideas of Circular Economy if it is done properly after taking into account the quantification of environmental impact associated with recycling activities. Design of sustainable products requires having a lifecycle perspective, including analyzing various End-of-Life (EoL) scenarios. This paper aims to investigate scenarios of when glass is disposed to demonstrate the applicability of glass in a Circular Economy. Life Cycle impact Assessment (LCA) and Circular Economy (CE) literature is critically reviewed to identify progress in research, methodologies employed and areas that require more research which this paper aims to resolve. It was determined recovery, also known as EoL, strategies for glass used in the Australian built environment lacked research despite the growing imperative of sustainable consumption. A typical glazing unit in a facade system was selected for assessment along with three (3) disposal scenarios. Quantifying the environmental impacts are to be interpreted in a LCA along with glass recovery strategies involving recycling, landfill and/or incineration with heat recovery. A CE assessment is performed by interpreting LCA environment impacts associated with the activities required to achieve circularity in a typical apartment in Sydney, Australia. This provides insights supports decision-makers who seek sustainable consumption through ideas of Circular Economy.

Keywords

Life Cycle impact Assessment; Circular Economy; Glass Disposal

1. Introduction

In this section first the importance of sustainable development and Circular Economy are explained. Then LCA as a method to quantify environmental impact is explained, followed by glass production/consumption as the focus of this paper, which is about analysing various disposal scenarios to assess their effectiveness from the Circular Economy perspective by using the LCA method. This section is concluded by clarifying the paper scope.

1.1 Sustainable development, Circular Economy, and LCA

Sustainable development seeks solutions to reduce environmental impact of various activities including product development. LCA is a widely used method for quantifying environmental impact of a product in its lifecycle from material to End-of-Life (EoL). “Circular Economy” was first seen in 1988 in Population and Development Review journal discussing the economics of natural resources [1]. It was not until a decade

DOI: https://doi.org/10.15488/15275
ISSN: 2701-6277

ago that the idea became receptive on an international level. During this era, it was understood that Circular Economy presented an opportunity to enable economic growth all the while not comprising the environment. A focus on disposal of materials helps to generate a cyclical model of production allowing value to be recaptured that would otherwise be lost [2].

1.2 Glass Product System

Glass has critical applications in industry and has paved the way for a growing glass industry. The $155.16 billion glass industry in 2021 has been expected to grow by 6.35% to $165.01 billion in 2022 [3]. Glass is commonly used in construction as glazing units and are essential elements, which provide vision, daylight, solar heat gains, and acoustic comfort. Critically, glass can be melted, recycled, and repurposed for many industrial applications all the while being non-toxic to the environment. This can promote a Circular Economy whereby the efforts to recycle glass are environmentally sound. Despite these favourable properties, a lack of focus persists in the waste management sector when capitalizing on these potential environmental benefits [4]. The current rate of glass recycling in NSW, Australia is around 46% [5]. In 2017-2018, 0.58 million tons of glass packing was recycled in Australia, however this was a 200,000 reduction since the year 2006-07 with indications this rate has fallen in the past five years [6].

The current consensus estimates the built environment consumes about 35-40% [7] of the world's energy and emits about 30% of the worlds CO2 [8]. With this contribution the International Energy Agency (IEA) estimates direct building CO2 emissions needs to be reduced by 50% and indirect emissions by 60% by 2030 to achieve a net-zero target by 2050 [9]. Current estimates for the global building and construction markets growth are approximately ~3% with Australia in 2022 commencing 50,200 dwelling units for construction [10]. Due to the multidecadal lifetime of a building, it is known the operational energy use is a significant contributor to environmental load for a typical residence. A 2001 study in Hong Kong showed the embodied energy for a building can contribute as much as 40% of the total life cycle energy [11]. Further, two other studies found the embodied energy may account for up to 43% [12] and 60% [13] of the total energy.

1.3 Scope

All levels of government in Australia endorsed the National Waste Policy Action Plan (NWPAP) issued in 2019 [14]. This plan proposes targets to guide national efforts through to 2030 such as reducing waste generated by each person by 10% and obtain a national waste recovery rate of 80%. In January 2021, Commonwealth Scientific and Industrial Research Organisation (CSIRO) published a guiding report [15] on how to integrate highly consumed materials such as plastic, glass, and paper into a Circular Economy. This was in response to a sweeping need to switch from waste management to a Circular Economy. To support sustainable product development, it is needed to have a lifecycle perspective at the design stage and addressing the sustainability from material to the EoL. Particularly from the Circular Economy perspective, it is needed to analyze various EoL scenarios at the design stage [16-18]. This study presents a comparative evaluation of the environmental impact of a typical glazing unit in Sydney Australia under different EoL treatment scenarios for the glass. A LCA is undertaken to support the hypothesis that glass recyclability can promote a Circular Economy all the while being environmentally sound.

2. Literature Review

Many studies have been in the context of Circular Economy, LCA, and glass production. This paper only reviews those literature that used LCA as method to quantify various glass production and recovery scenarios.

LCA is a powerful tool that can compare various products and/or scenarios environmental impact. A study compared three (3) concrete mix designs using SimaPro to assess the performance of sustainable concrete

[19]. Ensuring compliance by designing concrete blends according to a British standard, it was identified that it is possible to produce concrete that is more sustainable with minimal impact to its structural performance. However, this case study contained many assumptions that were highly specific to the assessed location and may produce results that are not applicable to a different study. Moreover, the study had a primary focus on CO2 emissions and did not consider other impact categories (section 5.3). In built industry, SimaPro Software has been used to perform an LCA of an Egyptian residential building [20]. All phases of the life cycle are incorporated including disposal (recycling, landfill and/or incineration) using a functional unit of 1m2 area of the building. Over a lifetime of 50 years, it was found the operation phase of the building contributed 71% of the environmental load and disposal strategies positively impacted environment by 12%. The LCA results aligned with the established need of energy conservation and sustainable fuels which would have the greatest impact to offset the operational usage. The study provides insights that would lead to more sustainable consumption however did not consider various scenarios of production, construction, and disposal. LCA has been used in studies to assess the improvements by implementing energy conservation technologies. Insulated externals walls, energy efficient windows (double-glazed) and rubber gaskets to reduce drafts were assessed in school buildings in Mendoza, Argentia [21]. It was discovered most conservative technologies applied at this school improved the environment, except for brick baking which used wood as fuel to increase photochemical ozone formation. All calculations used the SBID database provided by the Danish Building Research Institute and is unclear how comparable these results are to the proposed study located in Australia. Crushed glass that is remelted is known as cullet and studies have been performed to use this cullet in alternative industrial processes. Post-use glass packaging underwent a LCA to document the environmental burdens when cullet is recycled into sodium silicate which can be used in various products (cement, refractory, textiles) [22]. It was identified that the electricity required for this recycling process was the biggest contributor to environmental load. It was stated using cullet in this manner led to downstream processes that were more environmentally benign but offered no specific impact categories or comparison detailing the range of improvement. A 2021 paper in the journal of applied energy assessed ways to recycle the constituent materials that make up a photovoltaic (PV) panel [23]. This study compared the results to other publications and was found using two recovery lines; one for glass recovery and the other for secondary raw material such as aluminium, copper, silver and silicon, was environmentally favourable. It reflected the current standard of recycling whereby disposal methods are chosen based on the material to be recycled. It was identified in the reviewed literature that scant attention has been paid to quantify the environmental load of glass under various disposal scenarios in Australia to inform circularity possibilities, which this paper aims to address this research gap as its contributions.

3. Context of Research

A typical glass unit presents a recovery challenge as it is a hybrid of a mixture of materials and assemblies from which it is not feasible to repurpose the salvaged raw material without planning and coordination from interested parties. Recycled glass known as cullet can be used to produce more glass or processed as an input to another process. Due to the increased use of glass in the built environment, strategies and consideration for disassembly and recovery are highly relevant. Glazing units used in facade systems have grown in variety and installation methods and may require different recovery methods. Advanced glazing may be more difficult to dismantle and repurpose. Further, glass with a special treatment (e.g., non-reflective coatings and low-emissivity coatings) may be more challenging to recycle and used in industrial processes that require glass of a certain composition. This presents a trade-off wherein designing for end-of-life recovery can come at the disadvantage of operational performance (thermal, daylight, acoustic comfort), and vice versa. However, there remains no major technical challenge in repurposing glass for some processes and a glass bottle that is used from recycled glass (cullet) can reduce the energy required for production up to 75% [24]. Further, glass has the favourable property of being inert, however, because of this it becomes relatively cheap and easy to send to landfill. The primary method of dismantling involves an excavator that pries the metal frames of the facade. The glass falls as a mixture with concrete and other materials where it is separated on-site. Metal is separated and are sold to a recycling facility whereas the mixed glass is sold as an aggregate at a cheaper price or simply sent to landfill [25]. In the event of successful glass recovery some downstream problems may occur. These include the demand for reuse is low due to lack of supply and material failures, structural testing required for reused materials, bespoke nature of glazing makes compatibility challenging and limited capacity to separate composite glazing units.

Despite these challenges, potential energy conservation can be realized through direct replacement of glazing units or proper recycling as there are no major technical issues when transporting them to be recycled in a furnace. Glass may also be incinerated with some proportion of useful heat recovery that can be used to generate electricity [26]. More commonly, glass is crushed with other buildings elements and sent to landfill [27]. Other elements in a typical glazing unit such as sealants, gaskets, packers and spacers are assumed to be the same in all scenarios and are excluded from the proposed study. The production of glass is a significant environmental burden and scenarios of manufacturing to produce the glass can prove to be insightful. However, the variety of manufacturing is limited to the predominant float glass process and databases do not account for specialized processes such as magnetron sputtering which is used to deposit thin films on glass. Further, there is no recognized standard or protocol for the waste management, recycling and reuse of materials for a building during demolition and predicting the material flows at the end of the lifetime of a building (50-60yrs) can create significant uncertainty. For this reason, disposal scenarios are necessarily simplified. This paper highlights the importance of engineering design at the level of individual processes and at a system level. Engineering decisions around the design of production processes, transportation logistics and disposal facilities all directly influence the extent to which the environment is impacted.

4. LCA and Circular Economy Methodology

LCA requires an inventory of resources and processes implemented and the corresponding environmental impact. The account of these factors is based on the scope of the study and the system boundary. LCA aims to gives an understanding about the environmental impact associated with industrial activities from the initial extraction of raw materials, until the constituent materials from which the product is made are returned to the earth. It is therefore sometimes referred to as a ‘cradle-to-grave assessment’ As per ISO 14040, LCA consists of four (4) phases: goal and scope definition, life cycle inventory analysis, life cycle impact assessment and life cycle interpretation. These phases are classified as interdependent as results from one phase inform results for another phase. For Circular Economy opportunities, it is important to note which parties govern a particular stage. Raw material extraction, manufacturing, logistics and retail operations are controlled by supplier, whereas use phase and disposal are typically controlled by the consumer. Each product may split these categories differently or are not concerned with a particular category. Understanding the processes and parties that govern each stage facilitates greater communication which is imperative when discussing ideas of a Circular Economy. Since LCA is a tool to examine environmental impact during a product life cycle, it does not account for technical, social, and economic aspects and interactions happening outside product foreground and background system. Other methods can be used to assess these factors and are outside the scope of this paper.

It remains important to all sectors of production to prolong the value of products and resources in the economy for as long as possible. This is typically accomplished through the repurposing of material which provides a supply chain that is designed to be environmentally sound, regenerative, and restorative [28]. This is the essence of circular economies which use all means necessary (reuse, recycle, refurbish, sharing, remanufacturing, repair etc.) to create a closed-loop system. Historically, most production systems follow a linear consumption model in which a products life has a definite start and finish at which point it provides no further purpose. It is understood transforming the dominant model enshrined during the industrial revolution requires key changes to our production and consumption patterns. The growing necessity of conserving natural resources and the environment coupled with the unsustainable nature of waste management had led to a growth of research, policy curation and other sustainable initiatives in the service of these needs.

CE is a relatively new concept. In this context, a comprehensive framework for evaluating the circularity of a process remains difficult due to the variations of industries and sectors, the interactions between various indicators and the lack of agreed upon terms. Many papers review the various metrics and taxonomy for a circularity assessment and call attention to the lack of a consensus on these terms [29]. A review [30] of 62 papers concluded little work has been done to integrate relevant technologies into information systems that can deal with the complexity of a circularity assessment. A more comprehensive Circular Economy study of 318 papers [31] in the built environment similarly detailed the need for a business model that included Circular Economy principles and integrates stakeholders in the value chain. CE frameworks and principles have been proposed, and some tested, which offer some signs of progress for a settled circularity assessment [32]. LCA is the predominant method to determine circularity and is the method by which Circular Economy scenarios are evaluated in this paper. Other methods such as Material Circularity Indicator (MCI) [33], Environmentally Extended Input-Output Analysis [34], Material Flow Analysis [35], Operations Research [36] have been proposed to evaluate circularity of a product system. Examining LCA impact categories is a strategy by which circularity will be determined and is discussed in next section.

5. System Modelling

The software used for LCA is OpenLCA 1.11.0 and databases Ecoinvent and Environmental Footprint were imported for this assessment. The impact assessment used is IPCC 2013 GWP 100a. Certain processes are parameterized in the model to produce these scenarios. The boundary of the system in consideration accounts for production, transportation, and disposal. As mentioned, glass production may contain a proportion of crushed recycled glass known as cullet. The percentage of cullet used in production can be assigned and is set at values to match that of the recycling rate. For example, if 80% of the glass is recycled, 80% of the production will use cullet. This is meant to reflect the circular nature of this assessment whereby all recycled glass is reused as cullet in production. Parameters are applied to the waste processes of landfill, recycling, and incineration, and are adjusted to reflect a given disposal scenario. Fig. 1 demonstrates the developed model in OpenLCA, demonstrating the phases of the life cycle accounted for in this assessment.

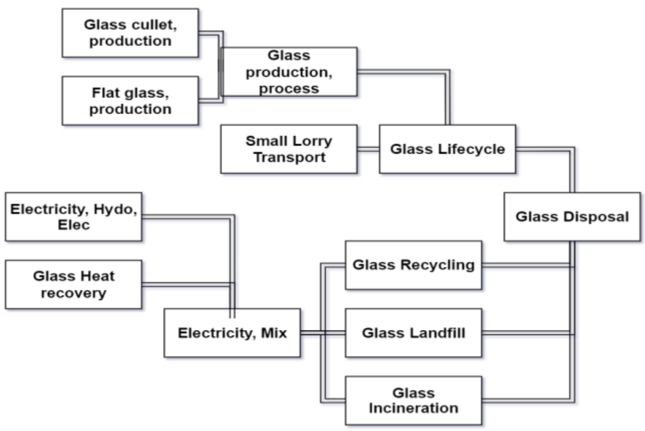


Figure 1. Developed product system model including lifecycle phases in OpenLCA 1.11.0

It was ensured processes demonstrated above were selected that were local to reflect the disposal scenarios in Sydney, Australia. Databases used in this LCA are limited to those that have been verified and tested for inclusion into the software, primarily in the region of Europe and North America. Research for the various

LCA databases was undertaken to determine which was the most available and comprehensive. EcoInvent and Environmental Footprint databases were selected and specific processes for the region of Australia were limited, and substitutions are made where possible. A reference flow of 20kg of glass was considered to reflect the mass of one standard 2100mm x 2650mm single glazing unit. A small lorry is assumed to be the only mode of transportation and the small lorry transportation process demonstrated in Fig. 1 accounts for the total distance travelled between facilities for a given scenario. Transportation in the model has the unit of 'tons multiplied to kilometer' and is adjusted depending on the amount of glass the truck carries and the distance it must travel between facilities. Basic flows of carbon dioxide and electricity were assigned as outputs to all three (3) disposal scenarios. The amount of electricity and carbon dioxide produced for a kilogram of glass that is recycled, incinerated and/or sent to landfill is summarized in the table below.

Table 1: Electricity and CO2-eq associated with developed EoL Scenarios

Disposal Scenario	kgCO2-eq / kg glass	kWh energy / kg glass
Recycling	0.5 [37]	1.1
Landfill	0.3 [38]	0.5
Incineration	1.7 [39]	3.15 [40]

The results are general estimates based on the current literature and are derived from a typical tone of waste. They are to represent the energy and CO2 equivalent associated when machinery and processes conduct a given disposal scenario. Further, estimates for the energy consumption was only found for incineration. Estimates for landfill and recycling were approximated from this value assuming recycling glass consumes more energy than transporting it to landfill.

To quantify the burdens due to transportation, a recycling facility, incineration facility and landfill location is selected in NSW, Australia as shown in Fig. 2.

- Recycling facility – Glass Recycling NSW (Ingleburn, NSW) [41]
- Incineration with heat recovery facility – Energy recovery from Waste (West Lithgow precinct) [42]
- Landfill – Greenwood Landfill (Mona Vale) [43]

The assessed glass unit is located in Sydney CBD, and approximate distances from this location to the above locations are shown in the figure below.

Figure 2. Distances between disposal scenario facilities NSW, Australia

6. Results

Impact assessment results using IPCC 2013 GWP 100a are provided for three (3) scenarios, optimistic, neutral, and pessimistic. The optimistic scenario in context of Circular Economy allows analyzing situation where the majority of the glass is recycled. The developed scenarios are outlined below.

Table 2: End of Life Disposal Scenarios

Treatment	Optimistic (%)	Neutral (%)	Pessimistic (%)
Recycling	80	50	20
Landfill	10	25	80
Incineration	10	25	0

Table 3: Results of Scenarios (optimistic, Neutral, Pessimistic) against Impact Categories

Impact Category	Optimistic	Neutral	Pessimistic
Acidification	0.18270 mol H+ eq	0.22022 mol H+ eq	0.23640 mol H+ eq
Climate Change	15.7551 kg CO2 eq	15.9998 kg CO2 eq	16.73456 kg CO2 eq
Ecotoxicity, freshwater	8.481385 CTUe	8.65432CTUe	8.79701 CTUe
Eutrophication, freshwater	0.00098 kg P eq	0.00078 kg P eq	0.00068 kg P eq
Human toxicity (cancer & non-cancer)	4.869e-6 CTUh	3.4532e-6 CTUh	1.00032e-6 CTUh
Land Use	290.09208 Pt	201.06712 Pt	64.773 Pt
Resource Use, fossils	608.39560 MJ	807.42356 MJ	851.46431 MJ

The total transportation distance for the pessimistic scenario is changed because no glass is sent to landfill. Comparing the disposal scenarios against impact categories provides the basis for a circularity assessment. The results are shown in Table 3 for optimistic, neutral, and pessimistic scenarios. Impact categories such as marine eutrophication and ionizing radiation (human health) recorded negligible results and are excluded from table of results. Optimistic, neutral and pessimistic scenarios have cullet proportions set as 80%, 50% and 20%, respectively.

Based on the demonstrated results; the following observations are made:

- Acidification approximately is 30% higher in the pessimistic scenario. This is likely associated with the high emissions from landfills and the low cullet content used in production.
- Climate Change impact category for pessimistic has 1kg more CO2-eq than optimistic case. Subject to further data quality checks, this shows some degree of circularity where the environmental costs of recycling can outweigh alternatives of landfill and incineration.
- Pessimistic Scenario fossils resource use 200MJ more than the optimistic scenario. Subject to further data quality checks, this indicates high recyclability may lead to lower energy consumption overall.
- Land use for the optimistic case (290 Pt) is much greater than the pessimistic case (65 Pt). This category measure soil quality and indicates recycling can lead to poorer soil quality.
- Neutral Scenario provided impact category results that were between optimistic and pessimistic cases.

7. Conclusion and future work

The impact category results show that additional efforts to recycle glass (optimistic scenario) can promote a Circular Economy that is restorative and environmentally benign. To this end, this study uniquely shows under the given assumptions, limitations, and disposal scenarios that additional efforts to recycle do not always lead to further environmental impacts, particular with respect to glass and its favorable recycling properties. However additional data quality checks, system boundaries and scenarios can further interrogate this conclusion. Future work can assess the environmental impact of directly replacing facade systems plus on other systems and identify possible unintended consequences of such replacement [44]. Though this scenario may be challenging to specify in industry as direct replacement of glazing systems remains an uncommon practice. Further, more advanced glazing system can be assessed. These systems result in lower operational energy during their usage phase. It would be insightful to examine whether extra production costs of these advanced systems outweigh energy savings during its lifetime [45, 46].

Appendix

The appendix should be placed before References section. Headings should have the style used above.

References

[1] C. Sassanelli, P. Rosa, R. Rocca, and S. Terzi, "Circular economy performance assessment methods: A systematic literature review," Journal of Cleaner Production, vol. 229, pp. 440-453, 2019.

[2] G. Kamateros and S. Abdoli, "Automated Disassembly of Lithium Batteries; Methods, Challenges, and a Roadmap," Procedia CIRP, vol. 119, pp. 1216-1221, 2023/01/01/ 2023.

[3] D. D. F. Del Rio et al., "Decarbonizing the glass industry: A critical and systematic review of developments, sociotechnical systems and policy options," vol. 155, p. 111885, 2022.

[4] S. Abdoli and Decisions, "A framework for analysing the environmental impact and support decision making in sustainable development context," Environment Systems and Decisions, vol. 43, no. 2, pp. 281-297, 2023.

[5] P. Allan, "Assessment of Australian recycling infrastructure-Glass packaging update," Department of environment energy Policy, 2019.

[6] S. Victoria. Market summary–recycled glass. 2014 [Online]. Available: https://assets.sustainability.vic.gov.au/susvic/Report-Market-Analysis-Glass-Sept-2014.pdf

[7] C. Filippín and S. F. Larsen, "ENERGY EFFICIENCY IN BUILDINGS."

[8] I. B. E. E. Taskgroup, "Building Energy Performance Gap Issues: An International Review," ed: International Partnership for Energy Efficiency Cooperation, IPEEC., 2019.

[9] U. Programme, "2020 Global Status Report For Buildings and Construction: Towards a Zero-Emission, Efficient and Resilient Buildings and Construction Sector. United Nations Environment Programme Nairobi, Kenya."

[10] A. B. o. Statistics, "Building Activity, Australia. ABS," 2021, December, Available: https://www.abs.gov.au/statistics/industry/building-and-construction/building-activity-australia/dec-2021.

[11] T. Chen, J. Burnett, and C. K. Chau, "Analysis of embodied energy use in the residential building of Hong Kong," Energy, vol. 26, no. 4, pp. 323-340, 2001.

[12] N. Mithraratne and B. Vale, "Life cycle analysis model for New Zealand houses," Building environment, vol. 39, no. 4, pp. 483-492, 2004.

[13] N. Huberman and D. Pearlmutter, "A life-cycle energy analysis of building materials in the Negev desert," Energy Buildings, vol. 40, no. 5, pp. 837-848, 2008.

[14] Australian Government, "NATIONAL WASTE POLICY, ACTION PLAN," 2019, Available: https://www.agriculture.gov.au/sites/default/files/documents/national-waste-policy-action-plan-2019.pdf.

[15] H. Schandl, S. King, A. Walton, A. Kaksonen, S. Tapsuwan, and T. Baynes, "National circular economy roadmap for plastics, glass, paper and tyres," ed: CSIRO: Canberra, Australia, 2020.

[16] S. Abdoli, "A modelling framework to support integrated design of production systems at early design stages," nternational Journal on Interactive Design Manufacturing, vol. 17, no. 1, pp. 353-370, 2023.

[17] X. Ji and S. Abdoli, "Challenges and Opportunities in Product Life Cycle Management in the Context of Industry 4.0," Procedia CIRP, vol. 119, pp. 29-34, 2023/01/01/ 2023.

[18] S. Abdoli and B. Bahramimianrood, "A target-driven framework for assessing the effectiveness of product-service-system development approaches at System of Systems level," Procedia CIRP, vol. 119, pp. 229-234, 2023/01/01/ 2023.

[19] M. W. Tait and W. M. Cheung, "A comparative cradle-to-gate life cycle assessment of three concrete mix designs," The International Journal of Life Cycle Assessment, vol. 21, pp. 847-860, 2016.

[20] H. Dullah, M. Malek, and M. M. Hanafiah, "Life cycle assessment of nile tilapia (Oreochromis niloticus) farming in Kenyir Lake, Terengganu," Sustainability, vol. 12, no. 6, p. 2268, 2020.

[21] A. A. M. M. Ali, A. M. Negm, M. F. Bady, and M. G. Ibrahim, "Environmental life cycle assessment of a residential building in Egypt: a case study," Procedia Technology, vol. 19, pp. 349-356, 2015.

[22] A. Arena and C. De Rosa, "Life cycle assessment of energy and environmental implications of the implementation of conservation technologies in school buildings in Mendoza—Argentina," Building Environment, vol. 38, no. 2, pp. 359-368, 2003.

[23] M. U. Siddiqi et al., "Low cost three-dimensional virtual model construction for remanufacturing industry," Journal of Remanufacturing, vol. 9, pp. 129-139, 2019.

[24] J. K. Daljit Singh, G. Molinari, J. Bui, B. Soltani, G. P. Rajarathnam, and A. Abbas, "Life cycle assessment of disposed and recycled end-of-life photovoltaic panels in Australia," Sustainability, vol. 13, no. 19, p. 11025, 2021.

[25] Department of Climate Change and Energy Efficiency, "Baseline Energy Consumption and GHG Emissions in Commercial Buildings In Australia Part 1," November 2021, Available: https://www.energy.gov.au/sites/default/files/baseline-energy-consumption-part_1-report-2012.pdf.

[26] R. Hartwell and M. Overend, "Unlocking the re-use potential of glass Façade systems," Glass Performance Days, vol. 2019, pp. 273-280, 2019.

[27] J. Giesekam, J. R. Barrett, and P. Taylor, "Construction sector views on low carbon building materials," Building research information, vol. 44, no. 4, pp. 423-444, 2016.

[28] C. F. Dunant, M. P. Drewniok, M. Sansom, S. Corbey, J. M. Allwood, and J. M. Cullen, "Real and perceived barriers to steel reuse across the UK construction value chain," Resources, Conservation Recycling, vol. 126, pp. 118-131, 2017.

[29] J. Kirchherr, D. Reike, and M. Hekkert, "Conceptualizing the circular economy: An analysis of 114 definitions," Resources, conservation recycling, vol. 127, pp. 221-232, 2017.

[30] J. Walzberg, G. Lonca, R. J. Hanes, A. L. Eberle, A. Carpenter, and G. A. Heath, "Do we need a new sustainability assessment method for the circular economy? A critical literature review," Frontiers in Sustainability, vol. 1, p. 620047, 2021.

[31] Y. Yu, D. M. Yazan, V. Junjan, and M.-E. Iacob, "Circular economy in the construction industry: A review of decision support tools based on Information & Communication Technologies," Journal of cleaner production, vol. 349, p. 131335, 2022.

[32] M. R. Munaro, S. F. Tavares, and L. Bragança, "Towards circular and more sustainable buildings: A systematic literature review on the circular economy in the built environment," Journal of cleaner production, vol. 260, p. 121134, 2020.

[33] E. M. Foundation, "An approach to Measuring Circularity" Cirularity Indicators Methodology. ," 2019, Available: https://emf.thirdlight.com/link/3jtevhlkbukz-9of4s4/@/preview/1?o.

[34] T. B. Consul and J. M. F. de Paiva, "MATERIAL CIRCULARITY INDICATOR APPLIED TO RECYCLED HIPS AND CLAY COMPOSITES."

[35] F. Krausmann, H. Schandl, N. Eisenmenger, S. Giljum, and T. Jackson, "Material flow accounting: measuring global material use for sustainable development," Annual Review of Environment Resources, vol. 42, pp. 647-675, 2017.

[36] I. M. Voskamp, S. Stremke, M. Spiller, D. Perrotti, J. P. van der Hoek, and H. H. Rijnaarts, "Enhanced performance of the Eurostat method for comprehensive assessment of urban metabolism: A material flow analysis of Amsterdam," Journal of Industrial Ecology, vol. 21, no. 4, pp. 887-902, 2017.

[37] A. W. Larsen, H. Merrild, and T. H. Christensen, "Recycling of glass: accounting of greenhouse gases and global warming contributions," Waste Management Research, vol. 27, no. 8, pp. 754-762, 2009.

[38] S. Manfredi, D. Tonini, T. H. Christensen, and H. Scharff, "Landfilling of waste: accounting of greenhouse gases and global warming contributions," Waste Management Research, vol. 27, no. 8, pp. 825-836, 2009.

[39] B. Johnke, "Emissions from waste incineration," Good Practice Guidance Uncertainty Management in National Greenhouse Gas Inventories, pp. 455-468, 2000.

[40] UK WIN, "Evaluation of the climate change impacts of waste incineration in the United Kingdom," October 2018, Available: UKWIN-2018-Incineration-Climate-Change-Report.pdf.

[41] Glass Recycling NSW. Available: https://glassrecyclingnsw.com.au/

[42] NSW EPA. Energy Recovery Facilities. Available: https://www.epa.nsw.gov.au/error-pages/404?item=%2fyou+environment%2fwaste%2fwaste-facilities%2fenergy-recovery&user=extranet%5cAnonymous&site=website

[43] Kimbriki. Kimbriki Recycling and Resource Centre, Mova Vale. Available: https://kimbriki.com.au/

[44] S. Abdoli, S. Kara, and M. Hauschild, "System interaction, System of Systems, and environmental impact of products," CIRP Annals, vol. 68, no. 1, pp. 17-20, 2019.

[45] S. Abdoli, S. Kara, and M. Hauschild, "Green paradox and the role of life cycle engineering," Procedia CIRP, vol. 90, pp. 159-164, 2020.

[46] S. Abdoli, S. Kara, and M. Hauschild, "An investigation into environmental impact of system of systems," Procedia CIRP, vol. 80, pp. 584-589, 2019.

Biography

Brian Smith is an undergraduate student in School of Mechanical and Manufacturing Engineering, UNSW. He works in the built environment, performing building science studies.

Shiva Abdoli (*1970) 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.

5th Conference on Production Systems and Logistics

Comparative Life Cycle Assessment Of Conventionally Manufactured And Additive Remanufactured Electric Bicycle Motors

Julian Grosse Erdmann[1], Alexander Mahr[1], Patrick Derr[2], Philipp Walczak[3], Jan Koller[1]

[1]Fraunhofer Institute for Manufacturing Engineering and Automation, Bayreuth, Germany
[2]Chair Manufacturing and Remanufacturing Technology, Bayreuth, Germany
[3]Electric Bike Solutions GmbH, Heidelberg, Germany

Abstract

In a circular economy, remanufacturing is crucial in reducing the use of primary raw materials and energy compared to new production. However, poor availability of non-standardized wear components can impede remanufacturing. Additive manufacturing is a promising alternative to conventional manufacturing or spare part purchase for those wear components required for remanufacturing. However, there is uncertainty regarding the environmental impact of using additive manufacturing for remanufacturing. This paper compares conventional and additive spare parts manufacturing to evaluate the potential environmental savings using the example of remanufacturing electric bicycle motors. Therefore, a reference motor was selected, and its manufacturing processes were modeled in SimaPro using the ecoinvent 3.8 Life Cycle Assessment database and the latest knowledge on processing and manufacturing processes. The results show that conventional production of electric bicycle motors has a climate warming potential of around 28 kg CO2-eq. Additive remanufacturing of electric bicycle motors at the end of their life cycle offers significant environmental savings potential. The extent of savings depends on the condition of the used electric bicycle motor and, accordingly, the number of components that need to be replaced. According to the IPCC method for the electric bicycle motor investigated, the study estimates that approximately 90.4 % savings potential can be achieved in terms of Global Warming Potential.

Keywords

Remanufacturing; Life Cycle Assessment; Additive Manufacturing; Electric Bicycle Motors; Circular Economy

1. Introduction

In light of the growing global awareness of the urgent challenges associated with climate change, nations have adopted proactive measures to tackle greenhouse gas (GHG) emissions and strive towards achieving carbon neutrality. For instance, Germany enacted the Federal Climate Protection Act in June 2021, intending to reduce GHG emissions by 65% by 2030, relative to the levels observed in 1990 [1].

The Circular Economy (CE) presents a viable solution that promotes sustainable practices while stimulating economic growth by minimizing GHG emissions through optimized resource utilization and waste reduction [2]. At its core, CE seeks to decouple economic growth from the consumption of resources, thereby preventing resource depletion and the disposal of waste and recyclable materials. Hence, CE aims to maintain resources within the economic system for as long as possible. Therefore, End-of-Life (EoL) strategies are

DOI: https://doi.org/10.15488/15293
ISSN: 2701-6277
publish-Ing.

implemented, prolonging the lifespan of products and unlocking new value by preserving the resources invested in their manufacture [3].

Within this framework, remanufacturing emerges as a crucial solution for CE, offering a highly promising EoL strategy. By enabling a new life cycle for products and components, remanufacturing reduces the consumption of natural resources and mitigates waste generation [4,5].

However, the success of remanufacturing depends upon the availability of used parts and components, as well as spare parts [6]. Since the production and sale of used products can span several years, individual parts may not be readily obtainable due to production halts, expiration of the obligation to supply spare parts, or changes in the product portfolio.

In this specific context, Additive Manufacturing (AM) presents opportunities for remanufacturing components, including producing spare parts. The combination of AM and remanufacturing, known as additive remanufacturing (AdRem), represents a forward-thinking approach to supply chain management that ensures the availability of spare parts through AM techniques [7]. AdRem leverages the advantages of AM and remanufacturing, wherein AM either substitutes or complements traditional manufacturing methods [8,9]. However, no studies have yet been conducted using life cycle methodology to assess the environmental impact of AdRem. Therefore, this paper discusses quantifying the environmental benefits of remanufacturing with additive manufacturing compared to new production.

2. State of the Art

Over the past decades, LCAs (Life Cycle Assessment) have been conducted to evaluate the environmental impact of remanufactured products [10,11]. Several studies have investigated the environmental benefits of remanufacturing compared to newly manufactured automotive components [12–20]. Lee et al. and Gao et al. compared the energy consumption and pollutant emissions of newly manufactured and remanufactured turbochargers, demonstrating that remanufacturing significantly reduces various environmental impacts [13,15]. Schau et al. conducted a sustainability assessment of alternator remanufacturing and concluded that it could reduce emissions compared to producing new parts [17]. Studies also focused on remanufacturing automotive engines, revealing significant reductions in energy consumption and various environmental impacts [16,18]. Warsen et al. compared the environmental performance of newly manufactured and remanufactured transmissions, finding that the remanufactured product outperformed the newly manufactured one in all environmental impact categories [19]. Furthermore, due to the increasing number of electric vehicles in the automotive industry, the ecological footprint of remanufactured lithium-ion batteries is increasingly being analyzed in research [12,14,20].

In addition to automotive components, the ecological impact of remanufactured products in other sectors, such as construction, medical, and electrical equipment, is already being evaluated using LCA. The research consistently demonstrated the environmental benefits of remanufacturing regarding reduced resource consumption, greenhouse gas emissions, and various environmental impacts. [21–25]

Regarding advanced technologies, Zheng et al. assessed the environmental benefits of engine remanufacturing, comparing different restoring technologies, such as brush electroplating, arc spraying, and laser cladding, to new manufacturing. The study employed an LCA to analyze resource and energy consumption and evaluate environmental impact. The results reveal that advanced restoration technologies in engine remanufacturing can restore more damaged components and minimize environmental impacts by reducing raw material consumption. [26]

While environmental studies examining the cumulative impacts of remanufactured products through LCA exist, there remains uncertainty regarding the environmental impact of utilizing AM for remanufacturing purposes. Therefore, to our knowledge, this is the first work that compares conventional and additive spare parts manufacturing to evaluate the potential environmental savings of AdRem.

3. Methodology

For the evaluation of the environmental impacts based on a life cycle approach, an LCA was carried out. According to the definition of ISO 14044, an LCA is divided into four phases: Goal and scope definition, inventory analysis, impact assessment, and interpretation of results. [27]

3.1 Goal and scope definition

The LCA is intended to investigate and compare the environmental impacts of conventional manufacturing and remanufacturing of electric bicycle motors, focusing on AdRem of planetary wheels as spare parts in a cradle-to-gate approach. As a functional unit of the study, the EBS SGI-G V2 motor was selected as a representative example of electric bicycle hub motors, see Figure 1. The motor is a central component of an electric bicycle with a rated power of 250 watts.

Figure 1: Image of the EBS SGI-G V2 motor in closed (left) and open (right) state

The system boundary of the LCA regarding conventional manufacturing considers raw material extraction, material processing, component manufacturing, motor assembly, and necessary transportation to the customer. The remanufacturing process includes the transportation of the motor to the remanufacturing facility and back to the customer. Within the remanufacturing process, the steps of disassembly, cleaning, quality control, procurement of new parts, AdRem of spare parts, and reassembly are taken into account.

Since the primary goal of the LCA is to examine and compare the manufacturing processes, the use phase and disposal of electric bicycle motors are not included. According to the definition of remanufacturing, the remanufactured product should have at least the same performance and quality as a new product [28,29]. Therefore, ideally, no differences in environmental impacts should be observed during the use phase. The cutoff approach is chosen for recycling, and the environmental impacts of these processes are attributed to the new product, thus not considered in the LCA. Figure 2 illustrates the defined system boundaries in the process flow diagram of an electric bicycle motor.

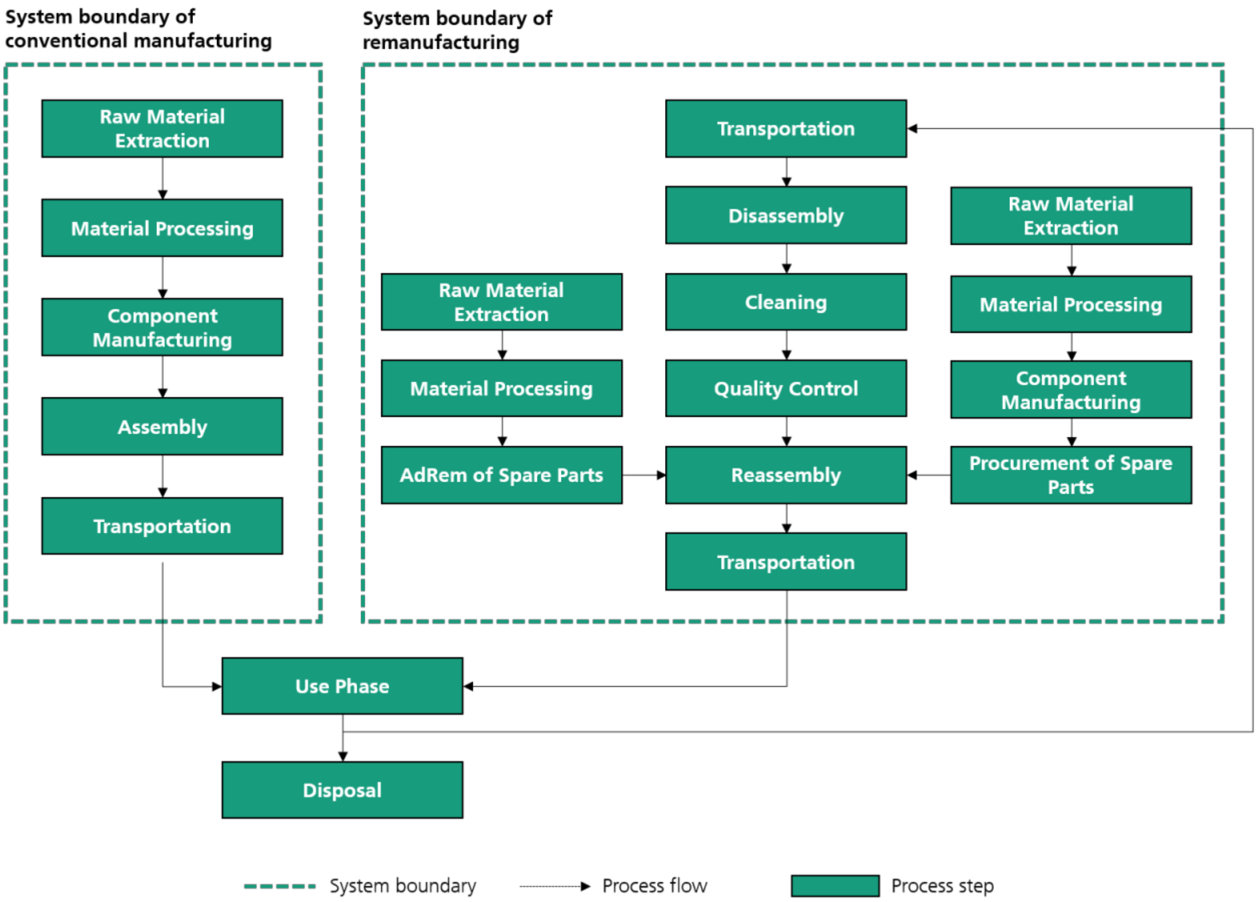


Figure 2: System boundary of conventionally manufactured and remanufactured electric bicycle motor

The LCA was modeled in SimaPro using the ecoinvent 3.8 Life Cycle Assessment database and the latest processing and manufacturing processes knowledge. The data for the LCA were obtained from experts, technical literature and journal entries, manufacturer information on machines, and analysis of electric bicycle motors.

3.2 Inventory analysis

During the disassembly process, the electric bicycle motor was separated into 28 components, and some parts were further destructed to enable a detailed weight analysis of the individual materials. Table 1 presents the components' names, quantities, weights, materials, and scrap rates. According to expert knowledge, the scrap rate column represents the estimated likelihood that the component will not be reused and will require replacement at the end of its lifespan.

Components with negligible environmental impacts due to their size, energy consumption, or weight can be cut off and excluded from consideration [27]. Hence, all components and materials weighing one gram or less were excluded. The bearings used in both motors partially contain a small proportion of plastic covers. The LCA does not consider this proportion, and the weight is assigned to the material steel.

Table 1: Component overview of the EBS SGI-G V2 motor

No.	Component	Quantity	Weight [grams]	Materials	Scrap rate
1	Shaft nut	2	8	Steel	5 %
2	Washer	2	8	Steel	100 %
3	Motor housing with ring gear	1	579	Aluminum (463 g) / Steel (116 g)	5 %

4	Bearing 6001RS	1	19	Steel	100 %
5	Washer	1	1	Steel	100 %
6	Circlip for planetary wheels	3	1	Steel	100 %
7	Planetary carrier	1	420	Steel	30 %
8	Bearing 6903RS	1	17	Steel	100 %
9	Bearing 6901RS	1	11	Steel	100 %
10	Cassette with freewheel	1	235	Steel	10 %
11	Case cover	1	101	Aluminum	5 %
12	Plastic cover winding package	1	10	PVC	< 5 %
13	Cover of circuit board	1	2	PVC	< 5 %
14	Sun gear	1	50	Steel	< 5 %
15	Circlip	1	< 1	Steel	100 %
16	Slot nut	1	1	Steel	0 %
17	Bearing 6902RS	2	18	Steels	100 %
18	Rotor (with magnets)	1	517	Steel (368 g) / Neodymium (149 g)	< 5 %
19	Plastic cover	1	1	PVC	< 5 %
20	Shaft seal	3	< 1	Rubber	100 %
21	Screw	30	28	Steel	100 %
22	Cover for nut	6	20	PVC	< 5 %
23	Nut	6	33	Steel	100 %
A	Planetary wheel*	3	70	Steel (37 g) / PVC (33 g)	10 %
B	Shaft with motor cable	1	210	Steel (176 g) /Copper (13 g) / PVC (21 g)	20 %
C	Stator with circuit board	1	796	Electrical Sheet (446 g) / Copper (186 g) / Aluminum (149 g) / Nylon (16 g)	< 5 %

* Process of AdRem used for manufacturing spare parts

The total weight of the components amounts to 3186 grams. The control unit required for the electric bicycle motor's operation is not integrated into the motor but exists as a separate module and is, therefore, not considered in the analysis.

3.3 Impact assessment

This LCA focuses on the Global Warming Potential (GWP), generally considered the most relevant impact category in the transportation sector [30]. The calculation method used is the IPCC 2021 GWP100 (including CO2 uptake), which quantifies the Global Temperature Potential (GTP) climate change factors of IPCC with a timeframe of 100 years, where carbon dioxide uptake and biogenic carbon dioxide emissions are explicitly included [31]. The life cycle inventory is based on the weight and material analysis of the components. Based on the material data, technical literature, company inquiries, and project data, conventional manufacturing, transportation, and remanufacturing processes were modeled in the LCA software SimaPro.

Conventional manufacturing includes producing all the components of the electric bicycle motor following the modeled processes of the electrical sheet, copper, steel, aluminum, magnets, and plastics (PVC and Nylon). In addition to these processes, transportation of the finished electric bicycle motor from China to Germany and the transport within Germany was also considered. Both transport activities are modeled with the ecoinvent processes “transport, freight, lorry >32 metric tons, EURO6 and transport, freight, sea, container ship based”.

For the remanufacturing process, the steps of disassembly, cleaning, quality control, procurement of new parts, AdRem of spare parts, and reassembly were considered. Disassembly and reassembly are performed manually by trained personnel. These processes were divided into 22 steps for the EBS SGI-G V2. Since the process involves purely manual operations and, according to Klöpffer, the manufacture of the production machines can be ignored, disassembly and reassembly are not considered in the LCA [32]. Also, the quality control process is not considered as no data was available, and no significant environmental impacts are expected. The cleaning process was modeled with the Pero R1 cleaning system. [33] The average energy consumption, solvent replacement, and batch size per electric bicycle motor were considered for modeling. The assumptions result in an energy consumption of 0.95 kWh and 6.2 ml of solvent per cleaned electric bicycle motor. Since ecoinvent does not offer a large variance of solvents, ethanol is used for modeling. For the production of AdRem spare parts, using the example of planetary gears, the UltiMaker 5S printer was used. [34] Due to the high requirements for production costs, elongation at break, and noise emissions of the planetary gears, nylon was selected as the printing material. In addition to the environmental impacts during the raw material extraction and material processing, energy consumption during printing was taken into account. The scrap rates of the individual components are used to model the average procurement of new parts and the associated average environmental impact. As with conventional manufacturing, transportation of the components from China to Germany and the transport within Germany was considered. In addition, for the transportation of the used and remanufactured electric bicycle motor, an average transport route of 400 km within Germany to the remanufacturing site and back to the customer is assumed. The transport activity was modeled with the ecoinvent process “transport, freight, lorry >32 metric tons, EURO6”.

Table 2 shows the LCA results of the EBS SGI-G V2 electric bicycle motor according to the IPCC 2021 GWP100 (incl. CO2 uptake) method. The environmental impact is given as the CO2-equivalent value for each component.

Table 2: IPCC results of the EBS SGI-G V2

		Conventional Manufacturing		**Remanufacturing**		
No.	**Component**	**kg CO2-eq**	**Percentage**	**Scrap rate**	**kg CO2-eq**	**Percentage**
1	Shaft nut	0.060	0.1 %	5 %	0.004	0.1 %
2	Washer	0.064	0.1 %	100 %	0.064	2.4 %
3	Motor housing with ring gear	5.841	20.8 %	5 %	0.292	10.9 %
4	Bearing 6001RS	0.077	0.3 %	100 %	0.077	2.9 %
5	Washer	-	-	-	-	-
6	Circlip for planetary wheels	-	-	-	-	-
7	Planetary carrier	1.693	6.0 %	30 %	0.508	18.9 %
8	Bearing 6903RS	0.069	0.2 %	100 %	0.069	2.6 %
9	Bearing 6901RS	0.044	0.2 %	100 %	0.044	1.6 %
10	Cassette with freewheel	0.947	3.4 %	10 %	0.095	3.5 %
11	Case cover	1.172	4.2 %	5 %	0.059	2.2 %
12	Plastic cover winding package	0.038	0.1 %	0 %	0.000	0.0 %
13	Cover of circuit board	0.008	0.0 %	0 %	0.000	0.0 %

14	Sun gear	0.202	0.7 %	0 %	0.000	0.0 %
15	Circlip	-	-	-	-	-
16	Slot nut	-	-	-	-	-
17	Bearing 6902RS	0.145	0.5 %	100 %	0.145	5.4 %
18	Rotor (with magnets)	9.386	33.5 %	0 %	0.000	0.0 %
19	Plastic cover	-	-	-	-	-
20	Shaft seal	0.030	0.1 %	0 %	0.000	0.0 %
21	Screw	0.113	0.4 %	100 %	0.113	4.2 %
22	Cover for nut	0.212	0.8 %	0 %	0.000	0.0 %
23	Nut	0.133	0.5 %	100 %	0.113	4.2 %
A	Planetary wheel*	0.498	1.8 %	10 %	0.069	2.6 %
B	Shaft with motor cable	0.857	3.1 %	20 %	0.171	6.4 %
C	Stator with circuit board	5.733	20.5 %	0 %	0.000	0.0 %
	Transport, truck	0.111	0.4 %	-	0.221	8.2 %
	Transport, ship	0.628	2.2 %	-	0.062	2.3 %
	Remanufacturing process	-	0.0 %	-	0.577	21.5 %
	Total	**28.030**	**100 %**		**2.683**	**100 %**

* Process of AdRem used for manufacturing spare parts

3.4 Interpretation of results

Compared to conventional manufacturing, assuming the given assumptions, remanufacturing the EBS SGI-G V2 electric bicycle motor can save 90.4 % on average of the GWP according to the IPCC 2021 GWP100 (incl. CO2 uptake) method. Depending on the material, e.g., magnets or electrical sheet, up to 100 % of the materials can be reused. The material savings from remanufacturing the electric bicycle motor is shown in Figure 3. The component, weight, and scrap rate significantly influence this scenario's impacts. In the remanufacturing scenario, producing new parts accounts for 63.7 % of the total environmental impact. However, only cleaning and AdRem were considered within the manufacturing process, as the remaining work was carried out manually.

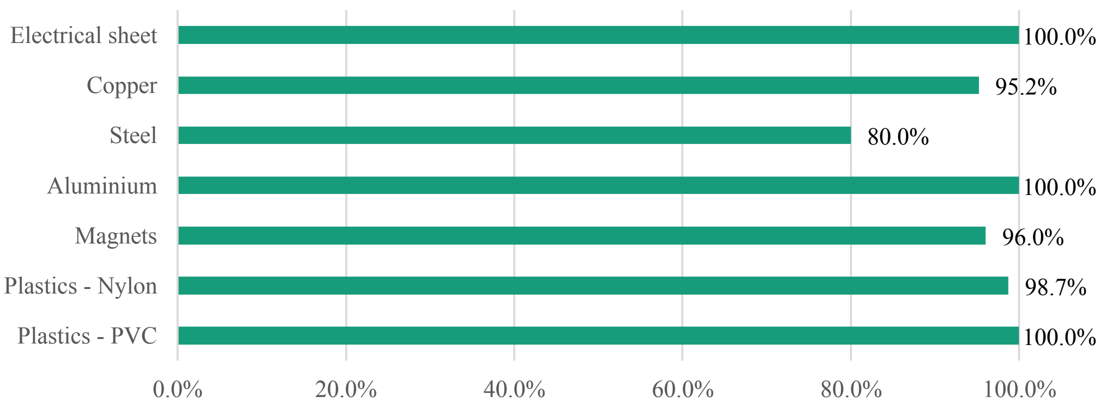


Figure 3: Material savings of the EBS SGI-G V2 through remanufacturing

The distinction between the magnet and other materials is evident when considering its significant environmental impact per gram. Figure 4 compares the proportion of materials in electric bicycle motors' weight and their corresponding contribution to GWP, as determined by the IPCC 2021 GWP100 (incl. CO2 uptake) method.

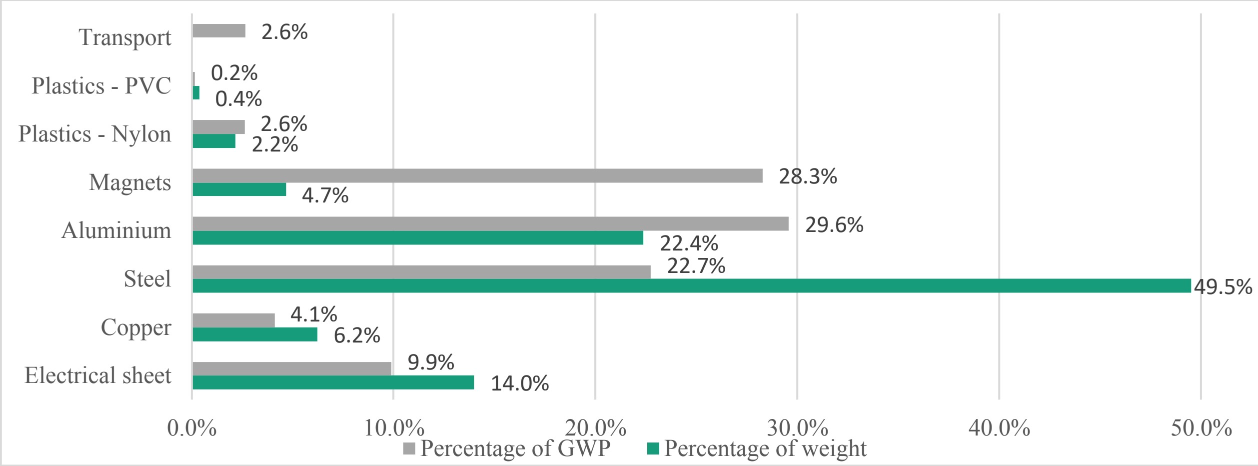


Figure 4: Comparison of the share of weight and GWP of the materials for new component manufacturing

Considering the LCA of AdRem of the planetary wheels, it is noticeable that the process with 0.694 kg CO2-eq. has a higher impact than conventional manufacturing with 0.498 kg CO2-eq. However, since only 10 % of the planetary wheels are scrapped, their CO2 impact, with 2.6 % of the total emissions of the electric bicycle motor, only plays a subordinate role in the overall process.

4. Conclusion

The paper aims to assess the environmental impacts associated with the conventional manufacturing of the EBS SGI-G V2 electric bicycle motor, estimating it to be around 29 kg CO2-eq. The findings of the manufacturing comparison validate the earlier assumptions that remanufacturing not only offers potential material savings but also reduces environmental impacts. However, quantifying these savings is challenging due to various factors, e.g., variation of quality of used products and materials, company-specific manufacturing and remanufacturing processes, and reverse logistics activities that come into play. In this context, the proportion of procuring new parts due to different quality levels of used products, for example, influences the overall result and leads to possible deviations even with identical remanufacturing processes. Hence, further analyses could focus on considering the influences mentioned above. Based on the assumptions made in this study, the potential reduction in GWP, according to the IPCC 2021 GWP100 (incl. CO2 uptake) method, is approximately 90.4 %.

Although AdRem of the planetary wheels has a higher carbon footprint than conventional manufacturing, remanufacturing used products with AdRem components has a significantly lower impact than new production. Therefore, despite the poorer environmental performance at the component level, AdRem can be reasonable if it allows delivery times to be met or spare parts to be made available to enable remanufacturing. The impact of the AdRem process on the overall process must be assessed on a case-by-case basis, depending on the product. Thereby, the proposed procedure can be applied to other products or components.

Similar to previous LCAs, this study faces challenges due to limited data availability, especially primary data, and the need to establish clear system boundaries for a comprehensive and realistic evaluation. To enhance the robustness of the results, additional (primary) data on the environmental impacts and energy consumption of the production facilities, along with a detailed examination of the electronic components used, could be incorporated alongside the findings of this study.

Acknowledgments

This paper evolved from the research project AddRE-Mo and was funded by the Federal Ministry of Education and Research with Grant No 033R234A.

References

[1] Bundesministerium für Wirtschaft und Klimaschutz, 2021. Deutsche Klimaschutzpolitik : Verbindlicher Klimaschutz durch das Bundes-Klimaschutzgesetz. https://www.bmwk.de/Redaktion/DE/Artikel/Industrie/klimaschutz-deutsche-klimaschutzpolitik.html. Accessed 7 June 2023.

[2] Haas, W., Krausmann, F., Wiedenhofer, D., Heinz, M., 2015. How Circular is the Global Economy?: An Assessment of Material Flows, Waste Production, and Recycling in the European Union and the World in 2005. Journal of Industrial Ecology 19 (5), 765–777.

[3] Russell, J., Nasr, N., 2019. Value-Retention Processes within the Circular Economy, in: Nasr, N. (Ed.), Remanufacturing in the circular economy. Operations, engineering and logistics. Wiley; Scrivener Publishing, Hoboken, Beverly, pp. 1–29.

[4] Häfner C., Koller J., Koop C., Klein V., 2021. Zukunftstrend nachhaltige Elektrofahrräder?: Erhebung zur Kreislaufwirtschaft in der Elektrofahrradbranche, Bayreuth.

[5] Sundin E., Tomohiko S., Lindahl M., Kao C-C., Joungerious B., 2016. Map of remanufacturing business model landscape.

[6] Schlesinger, L., Koller, J., Oechsle, O., Molenda, P. Remanufacturing of E-mobility Components - Five-Step Implementation Strategy to increase Sustainability within Circular Economy, in: IEEE (Ed.), 2021 11th International Electric Drives Production Conference (EDPC), pp. 1–8.

[7] Kleylein-Feuerstein J., 2019. Autarkie der Langzeitverfügbarkeit technischer Produkte mittels Addtiver Fertigung. Dissertation, Bayreuth.

[8] Lahrour, Y., Brissaud, D., 2018. A Technical Assessment of Product/Component Re-manufacturability for Additive Remanufacturing. Procedia CIRP 69, 142–147.

[9] van Le, T., Paris, H., Mandil, G., 2018. Extracting features for manufacture of parts from existing components based on combining additive and subtractive technologies. International Journal on Interactive Design and Manufacturing 12 (2), 525–536.

[10] Peng, S., Ping, J., Li, T., Wang, F., Zhang, H., Liu, C., 2022. Environmental benefits of remanufacturing mechanical products: a harmonized meta-analysis of comparative life cycle assessment studies. Journal of environmental management 306, 114479.

[11] Zhang, X., Zhang, M., Zhang, H., Jiang, Z., Liu, C., Cai, W., 2020. A review on energy, environment and economic assessment in remanufacturing based on life cycle assessment method. Journal of Cleaner Production 255, 120160.

[12] Chen, Q., Lai, X., Gu, H., Tang, X., Gao, F., Han, X., Zheng, Y., 2022. Investigating carbon footprint and carbon reduction potential using a cradle-to-cradle LCA approach on lithium-ion batteries for electric vehicles in China. Journal of Cleaner Production 369, 133342.

[13] Gao, W., Li, T., Tang, Z., Peng, S., Zhang, H., 2017. Investigation on the Comparative Life Cycle Assessment between Newly Manufacturing and Remanufacturing Turbochargers. Procedia CIRP 61, 750–755.

[14] Kamath, D., Moore, S., Arsenault, R., Anctil, A., 2023. A system dynamics model for end-of-life management of electric vehicle batteries in the US: Comparing the cost, carbon, and material requirements of remanufacturing and recycling. Resources, Conservation and Recycling 196, 107061.

[15] Lee, J.-H., Kang, H.-Y., Kim, Y.-W., Hwang, Y.W., Kwon, S.-G., Park, H.-W., Choi, J.-W., Choi, H.-H., 2023. Analysis of the life cycle environmental impact reductions of remanufactured turbochargers. Jnl Remanufactur 13 (2), 187–206.

[16] Liu, Z., Li, T., Jiang, Q., Zhang, H., 2014. Life Cycle Assessment-based Comparative Evaluation of Originally Manufactured and Remanufactured Diesel Engines. Journal of Industrial Ecology 18 (4), 567–576.

[17] Schau, E.M., Traverso, M., Finkbeiner, M., 2012. Life cycle approach to sustainability assessment: a case study of remanufactured alternators. Jnl Remanufactur 2 (1).

[18] Smith, V.M., Keoleian, G.A., 2004. The Value of Remanufactured Engines: Life-Cycle Environmental and Economic Perspectives. Journal of Industrial Ecology 8 (1-2), 193–221.

[19] Warsen, J., Laumer, M., Momberg, W., 2011. Comparative Life Cycle Assessment of Remanufacturing and New Manufacturing of a Manual Transmission, in: Hesselbach, J., Herrmann, C. (Eds.), Glocalized solutions for sustainability in manufacturing. Proceedings of the 18th CIRP International Conference on Life Cycle Engineering, Technische Universität Braunschweig, Braunschweig, Germany, May 2nd - 4th, 2011. Springer, Berlin, Heidelberg, pp. 67–72.

[20] Wrålsen, B., O'Born, R., 2023. Use of life cycle assessment to evaluate circular economy business models in the case of Li-ion battery remanufacturing. Int J Life Cycle Assess 28 (5), 554–565.

[21] Jun, Y.-S., Kang, H.-Y., Jo, H.-J., Baek, C.-Y., Kim, Y.-C., 2019. Evaluation of environmental impact and benefits for remanufactured construction equipment parts using Life Cycle Assessment. Procedia Manufacturing 33, 288–295.

[22] Kanazawa, T., Matsumoto, M., Yoshimoto, M., Tahara, K., 2022. Environmental Impact of Remanufacturing Mining Machinery. Sustainability 14 (13), 8118.

[23] Mann, A., Saxena, P., Almanei, M., Okorie, O., Salonitis, K., 2022. Environmental Impact Assessment of Different Strategies for the Remanufacturing of User Electronics. Energies 15 (7), 2376.

[24] Meister, J.A., Sharp, J., Wang, Y., Nguyen, K. an, 2023. Assessing Long-Term Medical Remanufacturing Emissions with Life Cycle Analysis. Processes 11 (1), 36.

[25] Schulte, A., Maga, D., Thonemann, N., 2021. Combining Life Cycle Assessment and Circularity Assessment to Analyze Environmental Impacts of the Medical Remanufacturing of Electrophysiology Catheters. Sustainability 13 (2), 898.

[26] Zheng, H., Li, E., Wang, Y., Shi, P., Xu, B., Yang, S., 2019. Environmental life cycle assessment of remanufactured engines with advanced restoring technologies. Robotics and Computer-Integrated Manufacturing 59, 213–221.

[27] DIN EN ISO 14044:2018-05, Umweltmanagement_- Ökobilanz_- Anforderungen und Anleitungen (ISO_14044:2006_+ Amd_1:2017); Deutsche Fassung EN_ISO_14044:2006_+ A1:2018. Beuth Verlag GmbH, Berlin. doi:10.31030/2761237.

[28] BSI - British Standards Institution, 2009. BS 8887–2:2009 Design for manufacture, assembly, disassembly and end- of-life processing (MADE): Terms and definitions.

[29] Steinhilper, R., 1998. Remanufacturing: The ultimate form of recycling. Fraunhofer-IRB-Verl., Stuttgart, 108 pp.

[30] Moritz Mottschall, 2012. Entwicklung der Vergabekriterien für ein klimaschutzbezogenes Umweltzeichen: Kurzstudie im Rahmen des Projekts "Top 100 – Umweltzeichen für klimarelevante Produkte", Berlin. https://www.oeko.de/oekodoc/1720/2012-341-de.pdf.

[31] Database & Support team at PRé Sustainability, 2023. SimaPro database manual: Methods library.

[32] Klöpffer, W., Grahl, B., 2014. Life Cycle Assessment (LCA): A guide to best practice. Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, Germany, 396 pp.

[33] Pero AG. Solvent Cleaning Plants: R1. https://en.pero.ag/cleaning_plants/r1/. Accessed 7 July 2023.

[34] Ultimaker B.V. UltiMaker S5: Expand your 3D printing ambitions. https://ultimaker.com/3d-printers/s-series/ultimaker-s5/. Accessed 7 July 2023.

Biography

Julian Große Erdmann (*1994) has been a research associate at Fraunhofer IPA since 2020, focusing on the Circular Economy and resource-efficient optimization in production. He focuses on business field development in remanufacturing, optimizing business and production processes, strategy development, and business case creation.

Alexander Mahr (*1991) studied mechanical engineering at the Friedrich-Alexander University Erlangen-Nuremberg in 2017. Since then, he has worked as a research associate at the Chair Manufacturing and Remanufacturing Technology of the University of Bayreuth and, since 2021, as a project manager at the Fraunhofer IPA on industrialization and resource efficiency of additive manufacturing processes.

Patrick Derr (*1998) studied engineering management at the University of Bayreuth in 2022. His bachelor thesis at the Chair Manufacturing and Remanufacturing Technology focused on the LCA of electric bicycle motors. Besides his master's studies, he works as a research assistant at Fraunhofer FIT.

Philipp Walczak (*1982) studied chemistry in Heidelberg. He co-founded the Heidelberg-based company Electric Bike Solutions GmbH (EBS) in 2009 and acts as managing director. EBS sells and develops components and drives systems for small electric mobility used in e-bikes and similar vehicles.

Jan Koller (*1992) is a group manager at the Fraunhofer IPA Project Group Sustainable Manufacturing in Bayreuth. His work focuses on Circular Economy with particular emphasis on remanufacturing. In national and international research and industrial projects, he addresses the challenges of remanufacturing and develops efficient, innovative, and sustainable solutions.

CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
CPSL 2023-2

5th Conference on Production Systems and Logistics

Developing A Key Performance Indicator System To Integrate Sustainable Corporate Objectives Into Maintenance Using The Analytic Hierarchy Process

Christina Bredebach[1]

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

Abstract

Maintenance in a manufacturing company is a key function for maintaining or restoring the functional condition of the production equipment and machinery and thus for maintaining the overall efficiency of the company. Because of this role, maintenance is often considered "sustainable". As a result of regulatory requirements as well as stakeholder demands, companies are under pressure to specify their sustainability strategies. However, due to a lack of knowledge about the sustainability potential of this function, the identification of clear objectives for sustainable maintenance is often neglected. Therefore, this paper presents a performance indicator system. 133 performance indicators in the three dimensions of sustainability (economic, environmental and social) were identified in a systematic literature review. In a qualitative content analysis and inductive category building, these were then assigned to 20 different categories. The hierarchical arrangement as well as the derivation of sustainable maintenance objectives from the corporate strategy enables companies to rank the performance indicators with the help of AHP (Analytic Hierarchy Process), a tool of MCDM (Multi Criteria Decision Making). This leads to a system of performance indicators based on a company's sustainability strategy, which strengthens the focus on sustainability in maintenance functions.

Keywords

Sustainable Maintenance; Sustainability Strategy; Corporate Objectives; Multi Criteria Decision Making; Analytic Hierarchy Process

1. Introduction

Companies are facing more and more challenges, such as a lack of resources, changing customer requirements, especially in the direction of sustainability, stricter laws and regulations regarding the use of non-renewable resources, emissions or occupational health and safety [1]. The protection of people and the environment, which is the focus of the above challenges, is also called sustainability [2].

Sustainability traditionally consists of three dimensions economy, ecology and social [3,4] and is also referred to as the triple bottom line [5], as it is supposed to form the basis of entrepreneurial action. Due to the interconnectedness of the three dimensions, it is essential to consider all three in an integrative manner. Sustainability in companies is a top-down process, as the requirements for sustainable action are specified by the corporate strategy and then passed on to the individual departments [6]. Sustainability is incorporated into the corporate strategy based on stakeholder requirements [6].

DOI: https://doi.org/10.15488/15323
ISSN: 2701-6277
publish-Ing.

The specialist area of maintenance combines the administrative and technical measures as well as management measures to maintain and restore the functional condition of machinery and equipment. This includes measures in the area of maintenance, inspection, repair and improvement. [7] Maintenance therefore affects the productivity of companies, and their efficient and effective actions have an effect on profitability [8]. While it used to be seen only as a reactive function and cost driver, maintenance has evolved into a technologically advanced area that is an important driver of Industry 4.0 [9] but also of sustainability, as maintenance can save resources, for example [10].

Sustainable maintenance differs from traditional maintenance by considering the triple bottom line in all decisions, the inclusion of stakeholder requirements, improved process quality and the application of new technologies to increase efficiency [11]. A theoretical definition of sustainable maintenance is therefore already available, but there is a lack of methods and tools for actual implementation [10]. A group discussion conducted in January 2023 with maintenance experts from the process industry revealed that the topic is in focus for companies but is perceived as very abstract. There is a lack of concrete measures or strategies to achieve sustainability, and companies need assistance in formulating goals.

Strategies are measures to achieve goals [12]. Strategy development in companies follows four steps according to [13]. At the beginning the target picture of the company is formed. This is followed by competitive and environmental analysis, then strategy formulation and evaluation. In the last step, the strategy is implemented. During these steps, strategy controlling is also carried out to check its effectiveness and adjust it if necessary.

During strategy formulation, both overarching and functional strategies are formulated. For this paper, the focus is on the formulation of measures for sustainable maintenance, i.e. a functional strategy. To check the success of the individual measures, performance indicators can be used that are derived from the strategy development. Therefore, this paper presents key indicators that exist in the three dimensions of sustainability in maintenance. These are sorted and categorized, and then a tool is presented that enables companies to derive key figures for their functional area strategy from their corporate strategy.

2. Methods

This chapter presents the methods used, with systematic literature review in 2.1, qualitative content analysis and inductive category building in 2.2, and the Analytic Hierarchy Process in 2.3.

2.1 Systematic Literature Review

To begin, a systematic literature search was conducted to identify the existing metrics that exist on sustainable maintenance. A systematic literature search follows a transparent, reproducible, and scientific process, minimizing subjective bias through extensive searches and detailed descriptions of the procedure. This allows for the identification of high quality articles and the evaluation of existing literature on a selected topic. [14]

A literature review is conducted in three steps. At the beginning, the research is planned, although a specific research question is not necessary, however a description of the significance of the problem needs to be considered. The goal is to create a research protocol that does not limit the researcher, but minimizes bias. The second step is to conduct the literature review. In this case, the search was conducted in Web of Science and Elsevier. The search string "Maintenance AND Sustainab* AND Industr' AND (KPI OR "Performance Indicato*" was derived from the question “what are the areas of influence in maintenance with respect to sustainability”. During this systematic literature search, articles containing performance indicators of sustainable maintenance were included. The search was conducted until all performance indicators found could be assigned to an existing category through inductive category building (see also 2.2) and no new category had to be formed.

2.2 Qualitative Content Analysis and Inductive Category Building

Qualitative content analysis has the goal of analyzing documented communication, whereby in this case, as well as in the preceding literature research, a systematic, i.e. theory- and rule-guided, approach is taken. The source material, their formal characteristics as well as the concrete research question are determined in advance. [15] The used source material was selected by the systematic literature research (see also 2.1).

According to [15] the inductive category formation, which was carried out subsequently, consists of four steps. In the first step, the source material is sighted and paraphrased. This includes deleting content that is not relevant to the research question. In the following, sentence statements are generalized in the same way, although here the sentences are maintenance performance indicators. Mathematical formulas were abstracted to literal descriptions. In the next step, the first reduction, sentences with the same meaning are deleted. In this case, identical performance indicators were combined, but all sources were noted. In the fourth step, or the second reduction, paraphrases with similar meaning are combined into one. Performance Indicators with the same or similar sphere of influence are combined into one category. For clarity, these categories were then assigned to one of the three sustainability dimensions. This resulted in a category system for ordering performance indicators in maintenance to areas of influence in sustainability. When forming categories, care was taken to ensure that a category consists of a maximum of nine performance indicators, as this enables pairwise comparisons [16], that are described in the following.

2.3 Analytic Hierarchy Process

The Analytic Hierarchy Process (AHP) is a method of Multi Criteria Decision Making (MCDM). MCDM is the general term for formal approaches to help individuals or groups make decisions involving more than one decision criterion. [17,18] AHP is a method for representing and modeling problems with hierarchical structures [19]. An alternative to AHP is the Analytic Network Process (ANP), which, in addition to hierarchical structures, also incorporates interactions and dependencies of elements of a higher level with elements of a lower level. This provides a better representation of real-world problems, while increasing the complexity and scope of pairwise comparisons. [19] To keep the complexity lower and allow easy implementation in companies, AHP is selected for this paper.

AHP is particularly valuable for decisions involving qualitative, abstract, or subjective criteria. The decisions do not require the decision maker (DM) to break down a complex problem. Certain inconsistencies in the pairwise comparisons that make up the AHP are acceptable. AHP consists of three steps, beginning with identifying and organizing objectives, constraints, alternatives, and criteria. In the second step, the pairwise comparisons are performed at each level of the hierarchy, and finally the algorithm for calculating the most suitable alternative is applied. [19]

For this paper, the goal of the AHP is to make the best decision. The criteria are "economy", "ecology" and "social" are placed on the first level, the individual categories (see also 3.1) on the second level. The alternatives that are evaluated are, for example, "Reduce resource consumption" and "Reduce maintenance costs". The result of the AHP as well as an illustrative example is presented in chapter 3.2.

3. Results

The results of this research will be presented in the following chapters.

3.1 Categories and Performance Indicators

By means of qualitative content analysis and inductive category formation, various categories of sustainable maintenance could be presented. This made the areas of influence of maintenance on sustainability clear.

The categories identified are shown in Figure 1, and the performance indicators they contain are shown in tables 5-7 (Appendix).

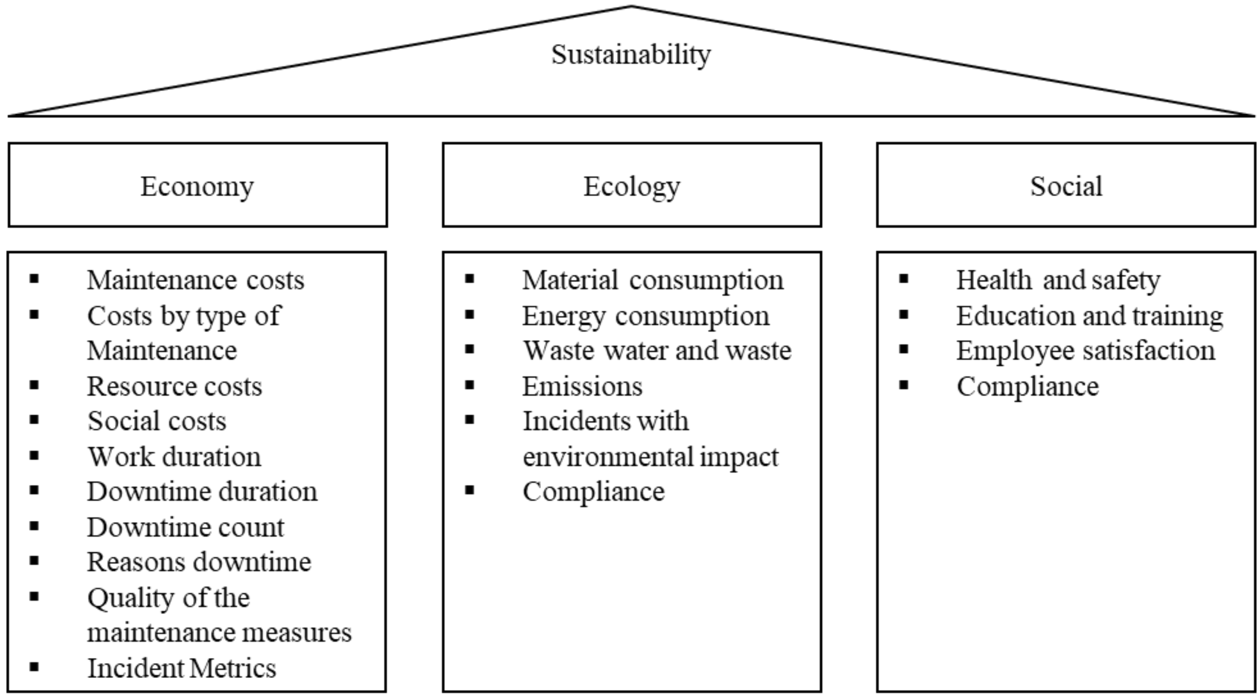


Figure 1: Categories of Sustainability in Maintenance

3.2 Analytic Hierarchy Process

Following the development of the category system for sustainability metrics in maintenance, an AHP process was developed for selecting the most important metrics for the selected sustainability strategy.

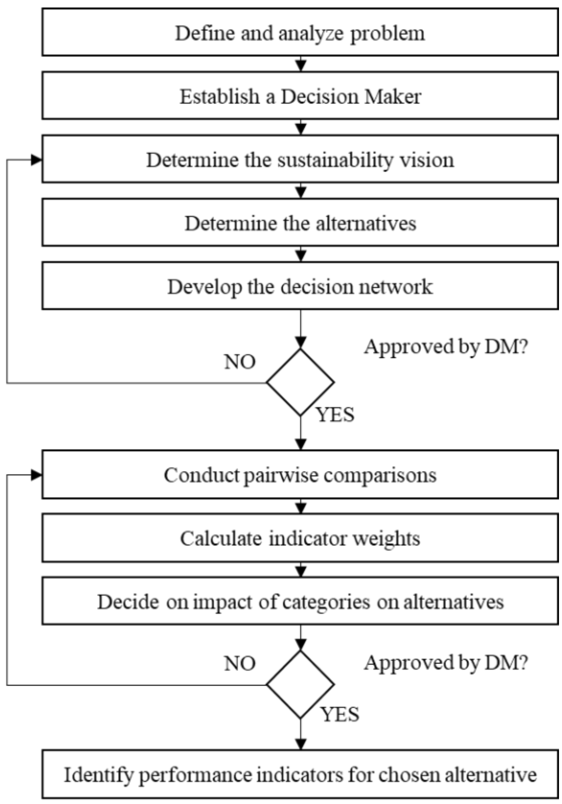


Figure 2: Process for conducting AHP following [20]

For decision making on the use of metrics, a decision model was first developed that corresponds to the categories in Figure 1. First, pairwise comparisons are conducted to determine the importance of the three dimensions: economic, environmental and social. Then, the importance of each category within the dimensions is determined by pairwise comparisons. Finally, the alternatives are evaluated with respect to the individual categories. The result shows the alternative that best fits the goal of making the best decision in terms of the categories and their importance. The procedure is illustrated in Figure 2.

As an exemplary case, this process was carried out using the "Superdecisions" software [21]. In this process, a Decision Maker (DM) was able to perform the evaluations first for the three dimensions, then for the individual dimensions. The evaluation is shown in Tables 1-3. Subsequently, possible alternatives for the decision had to be determined. In this fictitious example, the company must prioritize the set goals for sustainability and decides by means of AHP between the alternatives "reduce resource consumption" and "reduce maintenance costs". For this purpose, the alternatives were evaluated with respect to categories, for example, maintenance costs have a very large influence on the alternative "Reduce maintenance costs". The individual ratings are shown in tables 1-3.

Table 1: Normalized Ranking of Economical Criteria

Economical Criteria	**Normalized Rating**
Cost by Maintenance Strategy	0.085
Downtime Duration	0.151
Downtime Reasons	0.081
Maintenance Costs	0.223
Maintenance Metrics	0.136
Number of Downtime	0.050
Quality of Maintenance	0.054
Resource Costs	0.145
Social Costs	0.046
Working Hours	0.027

Table 2: Normalized Ranking of Ecological Criteria

Ecological Criteria	**Normalized Rating**
Incidents with environmental concerns	0.064
Compliance	0.063
Emissions	0.166
Energy used	0.270
Materials used	0.321
Sewage and Waste	0.115

Table 3: Normalized Ranking of Social Criteria

Social Criteria	**Normalized Ranking**
Employee Satisfaction	0.159
Health and Safety	0.046
Social Compliance	0.285
Training	0.51

As a result, based on the evaluation of the importance and the assignment of the correlation between categories and alternative, the company is recommended to pursue "Reduce resource consumption", as shown in table 4.

Table 4: Result of AHP

	Totals	**Priorities**
Resource Consumption	0.617	**0.614**
Reduce Maintenance costs	0.388	**0.386**

4. Conclusion

The aim of this work was to collect key performance indicators on sustainable maintenance through a systematic literature review, to sort these by inductive category building and to identify areas of influence of sustainability, and then to use AHP, a method of MCDM, to select suitable key performance indicators for a goal set by a company.

A total of 133 performance indicators were identified in the categories of economy, ecology and social, which could be classified into 20 different categories. The application of AHP is theoretically target-guiding; thus, it enables companies to identify a suitable target. The selection of the appropriate indicators through an AHP process is not directly possible as there is no overall performance indicator ranking based on the chosen alternative, however, the importance of the criteria and the evaluation of the influence of criteria on the alternatives can be used to determine which performance indicators could be considered more closely.

This study is limited by the fact that it was not tested in a real case, but only in a fictitious case. Therefore, it is recommended that the AHP process be tested in a case study and the result re-evaluated afterwards. Furthermore, the study is limited by the fact that the evaluation of the criteria should be derived from the company's mission statement, which implies that sustainability is integrated there.

For further research, it is recommended to identify a method to further improve the selection of metrics for companies, for example through the analytical network process (ANP). It is as well recommended to empirically test this model in order to allow adaptions to real-world cases, to prevent academic over-simplification or abstraction.

Appendix

Table 5: Economic Performance Indicators [22–30]

Economic criteria	**Performance Indicator**
Maintenance costs	Total maintenance cost/replacement value

	Return on Maintenance Invest Return on eco friendly Invest Average inventory value of maintenance material/replacement value Maintenance costs per unit Maintenance costs/sales (maintenance costs + cost of unavailability) / quantity Output Improvement in maintenance costs / Total maintenance costs Outage costs Shutdown maintenance costs / Total maintenance costs
Costs by maintenance type	Costs of planned maintenance activities Costs of unplanned maintenance activities Corrective maintenance costs / Total maintenance costs Preventive maintenance costs / Total maintenance costs Condition-based maintenance costs / total maintenance costs Predetermined maintenance costs / Total maintenance costs Expected PM costs / actual PM costs
Resource costs	Maintenance material costs / average inventory value Costs for processing maintenance waste Energy costs Maintenance measures Energy costs maintained systems
Social costs	Penalties for EHS violations during maintenance activities Penalties for EHS violations on maintained systems due to lack of maintenance activities. Labor costs Training costs
Downtime duration	Duration of planned maintenance activities Duration of unplanned maintenance activities Downtime due to short stops Downtime due to long stops Setup time between stop and start Total operating time/(total operating time + downtime due to planned maintenance)
Downtime count	Number of short stops Number of stops Number of long stops Number of planned maintenance activities Number of unplanned maintenance activities
Reasons downtime	Downtime due to preventive maintenance / total downtime due to maintenance Downtime due to predestined maintenance / total downtime due to maintenance Downtime due to condition-based maintenance / total downtime due to maintenance Downtime Downtime due to maintenance errors Downtime due to waiting for spare parts Downtime due to lack of training
Quality of the maintenance measures	Rework time due to lack of training Actual operation time/required operation time Percentage of maintenance tasks requiring rework

	Backlog (number of overdue tasks/number of tasks)
	Number of work orders after PM inspections
Incident Metrics	Failure rate
	Availability
	Reliability
	OEE
	MTTR
	MTBF
	MDT
	MOTBF
	MTTF
Operating time	Time required for preventive maintenance/total time for maintenance
	Time required for critical corrective maintenance/total time for maintenance
	Planned and predictive time for maintenance/total time for maintenance
	Labor hours for unplanned maintenance activities / available labor hours
	Labor hours for planned maintenance activities / available labor hours
	Planned working hours / available working hours

Table 6: Ecological Performance Indicators [23, 29-31]

Ecological criteria	Performance Indicators
Material consumption	biodegradable components
	recycled/reused/remanufactured materials
	direct material intensity
	Indirect material intensity
	Consumption of lubricants and cleaning agents
	biodegradable lubricants and cleaning agents
	Amount of PBT (persistent, bioaccumulative, toxic) chemicals in maintenance processes
	Amount of water needed for maintenance activities
Energy consumption	direct energy intensity ratio (within)
	Indirect energy intensity
	Reduction of energy consumption through maintenance measures
	Reduction of energy consumption of maintenance activities due to initiatives to reduce energy consumption.
	Energy emitted (heat, vibration) by maintenance processes
	Renewable energies
Waste water and waste	Maintenance waste
	Influence of maintenance waste on soil
	Soil area for maintenance activities, divided into fertile and infertile soils.
	Waste from maintained systems
	Amount of waste due to maintenance activities
	Amount of waste caused by defective maintained systems due to faulty maintenance procedures.
	Amount of liquid spilled due to maintenance activities
	Quantity of spilled liquid due to maintained systems

	Waste rate Hazardous material
Emissions	Internal GHG emissions External GHG emissions GHG Emissions Intensity Ratio Reduction of GHG emissions Emissions of ozone-depleting substances (ODS) from maintenance activities Emissions ODS due to maintained systems Emissions of (NOX, SOX, Persistent Organic Pollutants, Volatile organic compounds, hazardous air pollutants, particulate matter) due to maintenance activities Emissions of (NOX, SOX, Persistent Organic Pollutants, Volatile organic compounds, hazardous air pollutants, particulate matter) from maintained systems
Accidents with environmental impact	Noise, odor, dust, mist due to maintenance activities Number of failures due to environmental degradation caused by maintenance activities.
Compliance	Number of failures with possible impact on the environment Number of complaints, lawsuits, fines, and sanctions for non-compliance of maintenance activities with environmental laws and regulations. Number of complaints, lawsuits, fines, and penalties for non-compliance of maintained systems with environmental laws and regulations due to lack of maintenance activities. Implementation of an environmental management system Number of suppliers audited for environmental criteria

Table 7: Social Performance Indicators [23,26,27,29-31]

Social criteria	**Performance Indicators**
Health and safety	Occupational accidents Days lost due to maintenance accidents Implementation of an Occupational Health and Safety Management System Occupational accidents due to neglected maintenance Number of maintenance workers at high risk of illness or accidents due to their work Implementation of a program of continuing education for risk control to reduce the risk of occupational accidents. Personal protective equipment for maintenance activities Availability of first aid facilities Improve security performance because of security measures
Education and training	Average hours of maintenance education and training per maintainer Percentage of maintenance staff by gender receiving regular performance appraisals Percentage of maintenance staff trained in sustainability Number of training and continuing education courses conducted
Employee satisfaction	Days lost Number of complaints from employees

	Motivation level of employees Employee retention Employee satisfaction Number of suggestions for improvement from maintenance staff
Compliance	Number of complaints, lawsuits, fines, and sanctions for non-compliance of maintenance activities with social laws and regulations Number of complaints, lawsuits, fines and sanctions for non-compliance of maintained systems with social laws and regulations Number of customer complaints Number of new customers Number of returning customers Number of suppliers audited according to social criteria Stakeholder satisfaction

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] Enquete-Kommission "Schutz des Menschen und der Umwelt" des 13. Deutschen Bundestages. Konzept Nachhaltigkeit, Fundamente für die Gesellschaft von morgen, 252 pp.

[3] Brundtland, G.H., 1987. Our Common Future: Report of the World Commission on Environment and Development. World Commission on Environment and Development, Oslo, 300 pp.

[4] Meadows, D.L., Meadows, D.H., Randers, J., Behrens III, W.W., 1972. The limits to growth: A report for the Club of Rome's Project on the Predicament of Mankind, 2. ed. ed. Universe Books, New York, 205 pp.

[5] Buchmüller, M., 2019. Nachhaltigkeit und Produktmodularisierung. Springer Fachmedien Wiesbaden, Wiesbaden, 383 pp.

[6] Schaltegger, S., Kleiber, O., Müller, J., 2003. Die „Werkzeuge“ des Nachhaltigkeitsmanagements. Konzepte und Instrumente zur Umsetzung unternehmerischer Nachhaltigkeit, in: Linne, G. (Ed.), Handbuch Nachhaltige Entwicklung. Wie Ist Nachhaltiges Wirtschaften Machbar? VS Verlag fur Sozialwissenschaften GmbH, Wiesbaden, pp. 331–342.

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

[8] 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.

[9] Pawellek, G., 2016. Integrierte Instandhaltung und Ersatzteillogistik. Springer Berlin Heidelberg, Berlin, Heidelberg, 440 pp.

[10] 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.

[11] Bredebach, C., 2023. Is Sustainable Maintenance a Support- or Standalone Function? A Definition.

[12] Bea, F.X., Haas, J., 2019. Strategisches Management, 10., überarbeitete Auflage ed. UTB GmbH; UVK Verlag, Stuttgart, München, 623 pp.

[13] Welge, M.K., Al-Laham, A., Eulerich, M., 2017. Strategisches Management. Springer Fachmedien Wiesbaden, Wiesbaden.

[14] Tranfield, D., Denyer, D., Smart, P., 2003. Towards a Methodology for Developing Evidence-Informed Management Knowledge by M eans of Systematic Review. British Journal of Management 14, 207–222.

[15] Mayring, P., 2015. Qualitative Inhaltsanalyse: Grundlagen und Techniken, 12., vollständig überarbeitete und aktualisierte Aufl. ed. Beltz, Weinheim, 152 pp.

[16] Saaty, T.L., 2012. Decision making for leaders: The analytic hierarchy process for decisions in a complex world, 3. ed., 5. print ed. RWS Publ, Pittsburgh, Pa., 343 pp.

[17] Belton, V., 2002. Multiple Criteria Decision Analysis: An Integrated Approach, 1st ed. ed. Springer, Boston, 380 pp.

[18] Korhonen, P., Moskowitz, H., Wallenius, J., 1992. Multiple criteria decision support - A review. European Journal of Operational Research 63 (3), 361–375.

[19] Saaty, T.L. The Analytic Network Process.

[20] Rösner, T., Bredebach, C., 2022. Integrating the United Nations sustainable development goals into organizational strategy: A sustainability balanced scorecard approach using ANP and TOPSIS. J Sustainability Outreach 3 (1), 1–18.

[21] Saaty, T.L., 2023. Super Decisions. Creative Decisions Foundation. https://superdecisions.com/. Accessed 26 August 2023.

[22] Ferreira, S., Silva, F.J.G., Casais, R.B., Pereira, M.T., Ferreira, L.P., 2019. KPI development and obsolescence management in industrial maintenance. Procedia Manufacturing 38, 1427–1435.

[23] Lundgren, C., Bokrantz, J., Skoogh, A., 2021. Performance indicators for measuring the effects of Smart Maintenance. IJPPM 70 (6), 1291–1316.

[24] Muchiri, P.N., Pintelon, L., Martin, H., Meyer, A.-M. de, 2010. Empirical analysis of maintenance performance measurement in Belgian industries. International Journal of Production Research 48 (20), 5905–5924.

[25] Oliveira, M., Lopes, I., Rodrigues, C., 2016. Use of Maintenance Performance Indicators by Companies of the Industrial Hub of Manaus. Procedia CIRP 52, 157–160.

[26] Peach, R., Ellis, H., Visser, J.K., 2016. A MAINTENANCE PERFORMANCE MEASUREMENT FRAMEWORK THAT INCLUDES MAINTENANCE HUMAN FACTORS: A CASE STUDY FROM THE ELECTRICITY TRANSMISSION INDUSTRY. SAJIE 27 (2).

[27] Pfaffel, S., Faulstich, S., Sheng, S., 2019. Recommended key performance indicators for operational management of wind turbines. J. Phys.: Conf. Ser. 1356 (1), 12040.

[28] Rødseth, H., Strandhagen, J.O., Schjølberg, P. Key Performance Indicators for Integrating Maintenance Management and Manufacturing Planning and Control 459, 70–77.

[29] Saihi, A., Ben-Daya, M., As'ad, R.A., 2022. Maintenance and sustainability: a systematic review of modeling-based literature. JQME.

[30] Sari, E., Ma'aram, A., Shaharoun, A.M., Chofreh, A.G., Goni, F.A., Klemeš, J.J., Marie, I.A., Saraswati, D., 2021. Measuring sustainable cleaner maintenance hierarchical contributions of the car manufacturing industry. Journal of Cleaner Production 312, 127717.

[31] Franciosi, C., Roda, I., Voisin, A., Miranda, S., Macchi, M., Iung, B., 2021. Sustainable Maintenance Performances and EN 15341:2019: An Integration Proposal, in: Dolgui, A., Bernard, A., Lemoine, D., Cieminski, G. von, Romero, D. (Eds.), Advances in Production Management Systems. Artificial Intelligence for Sustainable and Resilient Production Systems, vol. 633. Springer International Publishing, Cham, pp. 401–409.

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.

5[th] Conference on Production Systems and Logistics

Enhancing Decision-Making In SCM: Investigating The Status-Quo And Obstacles Of Advanced Analytics In Austrian Companies

Patrick Brandtner[1,2]

[1]Josef Ressel Centre PREVAIL, Steyr, Austria

[2]Department for Logistics, University of Applied Sciences, Steyr, Austria

Abstract

Over the past few years, the stability and predictability of logistics and supply chain networks have significantly decreased. This has led to higher risks and increased uncertainty in decision-making within supply chain management (SCM). Fortunately, the abundance of available data presents a tremendous opportunity to alleviate this uncertainty. However, realizing the full potential of advanced analytics, such as predictive and prescriptive analytics, is hindered by a lack of knowledge regarding their practical applications and performance benefits, as well as a deficiency in implementation expertise. This research paper examines the current state of advanced analytics applications and the primary challenges faced by Austrian companies in this domain. The findings reveal a distinct pattern: although the literature highlights numerous performance advantages, the practical utilization of advanced analytics remains at a rudimentary stage and is primarily confined to isolated departments. While demand management, procurement, and transport planning have shown some initial success in their implementation, other areas like production planning and, particularly, warehouse management lag. The primary challenges observed in practice include a limited understanding of the potential of advanced analytics, lack of transparency and data quality issues, difficulties in internal marketing, and inadequate organizational integration. These challenges, along with potential courses of action, serve as a starting point for other companies aiming to address similar issues. The significance of this work lies not only in its theoretical contribution to existing research on advanced analytics in SCM but also as one of the few studies that delve into the practical implementation and specific application domains of advanced analytics in Austria.

Keywords

Supply Chain Management; Advanced Analytics; Data Analytics; Logistics Networks; Decision Support.

1. Introduction

Over the past few years, the stability and predictability of logistics and supply chain (SC) networks have significantly decreased. This has led to higher risks and increased uncertainty in decision-making within supply chain management (SCM) [1]. At the same time, new technologies, such as advanced analytics, offer pivotal approaches for enhancing decision-making processes, optimizing operations, and ultimately improving the overall performance of supply chains [2]. Advanced analytics in SCM involves the use of sophisticated algorithms and models to extract valuable insights from large volumes of data, enabling companies to anticipate future developments, identify potential risks, and make corresponding decisions [3]. This is particularly crucial in today's volatile and competitive business environment, where the ability to quickly adapt to changes and make informed decisions can significantly impact a company's success.

DOI: https://doi.org/10.15488/15258
ISSN: 2701-6277

Fortunately, the abundance of available data presents a tremendous opportunity to alleviate this uncertainty. However, realizing the full potential of advanced analytics, such as predictive and prescriptive analytics, is hindered by a lack of knowledge regarding their practical applications and performance benefits, as well as a deficiency in implementation expertise [4]. Especially for smaller companies like SMEs or for smaller countries with limited labor force, the implementation of advanced analytics represents a significant challenge. In the case of Austria, a country characterized by a strong presence of small and medium-sized enterprises (SMEs), the application of advanced analytics in SCM is still in its early stages. Despite the recognized potential of these technologies, their actual implementation remains limited, and research in this area is often confined to analyzing theoretical potentials [6,5,4]. This presents a significant research gap, as understanding the specific challenges and opportunities associated with the implementation of advanced analytics in SCM in the Austrian context can provide valuable insights for both practitioners and researchers and can be transferred to comparably small countries. Hence, this paper aims to explore the application of advanced analytics in SCM in Austria, focusing on current implementations and the challenges associated with them. By doing so, it seeks to contribute to the existing body of knowledge and provide practical recommendations for companies seeking to leverage advanced analytics in their SCM processes.

Considering the above, this study poses the following research questions:

- RQ1: What are the current implementations of advanced analytics in SCM in Austria?
- RQ2: What challenges hinder the implementation of advanced analytics in SCM in Austria?

The answers to these questions will not only provide a snapshot of the current state of advanced analytics in SCM in Austria but also identify the barriers that need to be addressed to further its adoption. This, in turn, can guide future research and practice in this area, contributing to the advancement of SCM in Austria and beyond. The remainder of the paper is structured as follows: section 2 introduces the theoretical background of the study. Section three discusses the research methodology applied. In section 4 the results of the study are presented. Subsequently, section 5 concludes the paper, also providing limitations and outlook.

2. Background

Subsequently, the two concepts underlying the paper, i.e., SCM and Advanced Analytics (AA) are explained.

2.1 Supply Chain Management

A supply chain is a network of companies that work together to create and deliver a good (product) and its information (e.g., price, delivery window) to an end customer. A SC thus covers all companies involved in the value creation in the context of product creation and service provision and includes the totality of all activities and processes that are applied to a good from the beginning to completion and provision. In concrete terms, an SC begins with the producer of a raw material and ends with the provision or delivery of a product to the end customer. SCM - as defined by Mentzer et al. (2001) - is the "*systematic, strategic coordination of the traditional business functions and the tactics across these business functions within a particular company and across businesses within the supply chain, for the purposes of improving the long-term performance of the individual companies and the supply chain as a whole*." [7], p. 1.

The goal of SCM is to meet customer needs as efficiently as possible. This requires the optimization of numerous processes within and outside the company that are involved in the creation of value. Along with the development of the term SCM, the understanding of the tasks and activities in SCM has also changed. In the 1990s, the focus was still very much on the optimization and functional integration of internal supply chains. This purely internal view expanded in the 2000s to include the components of increased information exchange and collaborative management of complex value creation processes. Increasingly, the synchronization of internal and external supply chains also became a central goal of SCM [8]. Accordingly, there are many studies that deal with the specific tasks and processes in SCM. Lambert et al. [9] speak of eight key activities in SCM, Chopra and Meindl [10] summarize 15 activities in three central SC macro-processes, the well-known SCOR model defines six core processes and numerous sub-processes in SCM [11] and Porter's value chain [12] names six primary activities. From the perspective of the present work, a categorization is selected that serves as a solid framework in the context of data analytics in SCM and can be used as a basis for the expert interviews. For this reason, we build on the work of Nguyen et al. (2018), in which fields of application and potentials at the interface between data analytics and SCM were elaborated. Thus, SCM in this paper comprises the following main activities [14,13]: i) procurement, ii) production planning, iii) warehouse management, iv) logistics and transport planning, and v) demand management.

2.2 Advanced Analytics

The term "Advanced Analytics" (AA) covers various aspects of the four categories of data analytics, i.e., descriptive, diagnostic, predictive and prescriptive analytics. In the following table, exemplary definitions from the literature are given and the term is delimited from the perspective of the work:

Table 1: Exemplary definitions of the term advanced analytics in the literature

Source	Definition
[15], p. 1388	*"Advanced Data Analytics is [...] examination of data [...] using sophisticated techniques [...] to discover [...] insights, make predictions or generate recommendations."*
[16], p. 12	*"Compared with conventional statistical methods, advanced machine learning algorithms are more capable of capturing complicated nonlinear relationships."*
[17], p. 1	*„Advanced analytics is a mixture of machine learning, artificial intelligence, graphs, text mining, data mining, semantic analysis. [...] Beyond the traditional business intelligence, it is a semi and autonomous analysis of data by using different techniques and tools."*
[18], p. 266	*"ADA refers to the information systems and analytics applications used to collect, analyze, and extract insights from data to be used in organizational decision making."*
[19], p. 249	*"We started to use advanced data analytics (ADA) to describe the paradigm shift (i.e., from statistical hypothesis testing to automatically gathered data)."*
[20], p. 2	*"[...] advanced data analytics (ADA), as all the technologies that are part of it are related to the processing and analysis of data that goes beyond traditional [...] procedures."*

In summary, and in contrast to conventional analyses and approaches of traditional business intelligence, which are limited to describing and summarizing data, advanced analytics uses advanced technologies and algorithms of machine learning and deep learning to recognize patterns in data, make predictions and provide recommendations for action as a basis for decision-making. Advanced analytics thus clearly focuses on predictive and prescriptive analysis, but also includes the identification of complex patterns in past data in the sense of descriptive and diagnostic analysis. Advanced Analytics hence primarily refers to models from the field of machine learning and deep learning. There are numerous works in the literature that deal with the categorization of machine learning models. Many roughly divide them into the areas of regression analyses, classification analyses and cluster analyses [23,22,21]. In addition, the categories of association and time series analyses, anomaly detection and reinforcement learning are frequently mentioned [25,24].

3. Research Methodology

The address the defined research questions, qualitative expert interviews are used as a suitable method. The aim of the expert interviews is to ascertain the current use and challenges in the context of advanced data analytics in Austrian SCM practices. Specifically, the aim is to identify i) how and in which SCM activities advanced analytics is already used in corporate practice and ii) where challenges lie in their implementation, Expert interviews are particularly suitable if the aim of the survey is to analyze tacit knowledge in a defined knowledge field and among corresponding knowledge holders [28,27,26]. This is clearly the case in the present work. Expert interviews consist of the following essential steps: 1) identification and selection of experts, 2) data collection and 3) data analysis. In the context of expert identification and selection, an information-based selection approach is followed in the work. Based on defined characteristics, experts are identified and selected to participate in the survey [30,29]. Specifically, the selection criteria include: i) several years of experience in SCM in practice (> 5 years), ii) current involvement or leadership in SCM analysis tasks, and iii) overall management-level understanding of the use of advanced analytics in the respective SCM area through several years of experience (> 3 years) in the company. The search for suitable candidates was based on contacts at the Logistikum at the Upper Austrian University of Applied Sciences. The Logistikum is the largest research institution in the field of logistics and SCM in Austria and accordingly a broad network of corporate partners could be accessed (cf. www.logistikum.at). A total of 9 experts were interviewed, all from large companies. The details were anonymized at the request of the experts:

Table 2: Overview of expert participants

ID	Company / Industry	Expert status
1	Building industry	SCM process designer analyst; 8 years experience.
2	Automotive industry	Logistics and SC manager; 10 years experience.
3	Manufacturing industry	Head of Demand Chain for several years; 11 years experience.
4	Metal industry	Head of Data Analytics; 6 years experience.
5	Mechanical engineering	Head of Global Operations Excellence; several years experience.
6	Food retail company	Head of SCM Monitoring & Analytics; 10 years experience.
7	Mechanical engineering	Head of SCM with focus on production logistics; 10 years experience.
8	Paper industry	Purchasing manager, including all SCM tasks; several years experience.
9	Manufacturing industry	Manager in SCM Operations & Performance, 13 years experience.

Data collection is based on a semi-structured interview guide, allowing for a natural setting of the interview and at the same time ensuring that consistent questions in each interview - albeit possibly in a different order [31]. The interview guide was sent to the participants by email at least one week before the interview. The interviews were conducted face-to-face or by video conference via MS Teams. Each interview was recorded and analysed directly after the interview by analyzing recordings [33,32,34].

4. Results

Subsequently, the results of the paper are presented, focusing on current applications of advanced analytics in Austrian SCM practice (4.1) and the challenges occurring during their implementation (4.2.).

4.1 Current Applications of Advanced Analytics in SCM

4.1.1 Current Applications in Procurement

According to experts, advanced analytics is already finding first applications in procurement. In more than half of the companies surveyed, corresponding approaches are already being used successfully. Specifically, this includes the prediction of material requirements based on regression and time series analyses, building on parts lists (or also for checking parts lists) and decision trees, building on past orders. The optimization of central order variables such as order quantities, times and the prediction of material prices is also a component of current applications of advanced analytics in procurement. Another use case is the analysis and prediction of supplier default risks based on pattern recognition and predictive analysis. In two of these companies, advanced analytics is not used independently, but in the form of AI-based standard solutions that include numerous optimization heuristics or machine learning models. The way this software functions is a black box for the respective company. The other half of the companies surveyed do not use any advanced analytics methods in procurement - apart from the use of classic ERP and MRP systems. However, all in all, from a practical point of view, there is still high potential in this area, which is not yet being exploited.

4.1.2 Current Application in Production Planning

The experts interviewed only apply advanced analytics to a small degree in production planning. The examples given include the implementation of image recognition to identify production errors or the use of regression and correlation analyses to identify unusually long machine downtimes and set-up times. One company uses optimization methods for production planning but relies on a purchased standard tool and does not know the details of the algorithms. In one company, initial trials have been carried out regarding predictive maintenance of production machines, but operational and actual use has not yet taken place. In the other companies, production is either planned manually based on parts lists and adjusted in the medium or short term, is rule-based, or plays no role (because it is a trading company).

4.1.3 Current Applications in Warehouse Management

The current use of advanced analytics in warehouse management is also limited in practice. Only one company uses such methods to derive central warehouse parameters (i.e., safety stocks and order points) and to identify inventory drivers. The company's goal is to predictively identify out-of-stock situations and subsequently avoid them while still maintaining efficient inventory management. In the other companies, inventory management is in conflict between production planning, procurement and demand management and is not dealt with separately in the form of advanced data analysis. Specifically, inventory management is usually driven by procurement, which in turn is driven by production, which is driven by predicted customer demand. A company flexibly rents warehouses or storage space from suppliers to deal with uncertainty in procurement. However, in terms of efficient inventory management, this is not really a sensible SCM tactic. Thus, warehouse management has not yet really been dealt with in Austrian practice.

4.1.4 Current Applications in Logistics and Transportation Planning

In logistics and transport planning - as in procurement - there are already first applications of advanced analytics in practice. At two companies, these include the optimizations of transport routes and the use of resources in this area through optimization processes. One company uses machine learning in the context of geospatial analyses to determine the optimal positioning of transport and distribution infrastructure, such as distribution centers and cross-docking stations. The same company also analyses patterns from past transport data in terms of determining optimal transport lot sizes and derives the future resource-optimal quantities accordingly. A fourth company uses artificial neural networks and regression analyses to predict and control future incoming and outgoing goods transports in the distribution center - here there is a direct connection to warehouse management. Other companies mostly use classic, rule-based transport management systems, plan transport manually or leave the transport planning to a logistics service provider. Thus, there is still unused performance potential of advanced analytics in logistics and transport planning.

4.1.5 Current Applications in Demand Management

In practice, demand management is the SCM area most intensively supported by advanced analytics. The experts name numerous successful fields of application here. In six companies, these include the use of regression models or AI-based software to predict future customer demand. One of these companies also uses advanced analytics to predict the probability of certain BOM combinations, another already uses Explainable AI (to assess feature relevance) to make forecasts more understandable. In one of the companies, the demand forecast can also be adapted by manipulating selected parameters (e.g., inflation rate, market data, etc.) in the form of what-if analyses. The same company also uses machine learning and deep learning to determine or predict the ideal discount for individual customers. According to order and customer data, the probabilities of order completion and the corresponding contribution margin are predicted here depending on discount levels. In addition to these six companies, a seventh company does not use advanced analytics methods in the actual demand forecast but does use image recognition with customers to identify future repair needs and to point this out to the customer in the sense of demand management.

4.1.6 Summary of Current Applications

In summary, first solid applications of advanced analytics in basically all areas of SCM can already be seen in corporate practice. In particular, demand management, the area most intensively supported by advanced data analysis, procurement, logistics and transport planning already have concrete applications in most companies. In the area of warehouse management, advanced analytics is currently used the least, which is also in line with the literature. Interestingly, this also applies to production planning, which is one of the most researched areas in the literature. The following chart shows the current advanced analytics applications in the respective SCM areas named by the experts (in brackets the number of mentions):

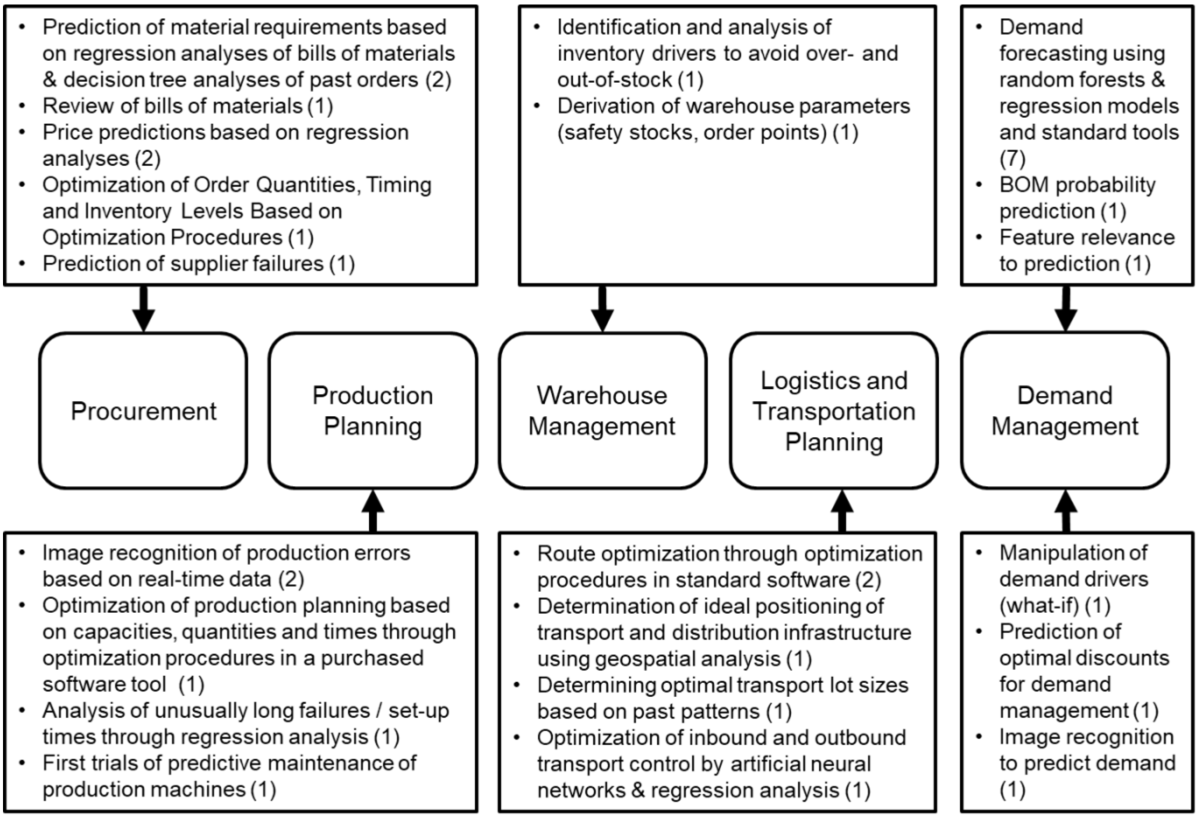


Figure 1: Summary of current Advanced Analytics applications in SCM

4.2 Challenges hindering the implementation of Advanced Analytics in Austrian Companies

From the experts' point of view, there are numerous challenges that need to be considered in the context of implementing advanced analytics in practice. Advanced analytics procedures are often perceived as black boxes. The results of such analyses are therefore difficult or impossible to comprehend and are viewed critically accordingly. If the results do not correspond to what is usually assumed or regarded as normal, acceptance among decision-makers in the company drops significantly as a result.

Another challenge is that the added value of complex analyses can often only be made visible and comprehensible afterwards, i.e., after their implementation. In practice, this means that investments in advanced analytics projects are often postponed, or such projects must be carried out without additional budget and with existing resources in addition to day-to-day business. The internal marketing of ideas or the creation of awareness in the company is therefore often laborious and it needs a strong and motivated driver with appropriate connections to management or - ideally - a direct supporter from top management. Often, successful applications fail because they are not sufficiently automated and integrated into operational systems. If a large amount of working time must be invested in the operational use of such solutions in order to carry out the analyses and use the results, the willingness to use them quickly decreases.

A lack of sufficiently qualified employees who can select, use and sustainably maintain complex models from the field of advanced analytics is also a challenge in practice. This goes hand in hand with the automation and integration of advanced analytics into company processes. If this does not take place, a high level of ongoing effort will be necessary in addition to the initial effort. From the point of view of SCM, the competence here usually lies in the market-side areas such as sales and marketing. Experts are therefore needed at the interface between data analytics and SCM who understand the use case and the technology.

Interface problems due to heterogeneous systems and infrastructure were also mentioned as major challenges in practice. Since isolated applications in individual areas do not enable the full potential of advanced analytics, many different systems must be integrated here, and their data processed or linked accordingly. This applies not only at the level of data extraction and preparation, but also in the context of result implementation in decision support. A directly resulting problem is that in some companies there is a lack of data understanding. There is transparency in one's own area, but across the board it is difficult to assess the data basis and draw conclusions about the data quality. There are also challenges at the level of the IT infrastructure. Infrastructures are still implemented locally for the most part, and cloud approaches are currently only used to a limited extent - both in terms of data storage and processing as well as analysis.

The organisational integration of advanced analytics is another challenge. In particular, the connection or distinction to classic reporting and the corresponding tasks must be well thought out in terms of acceptance. The same applies to the required roles and responsibilities. Here, the often still strongly anchored thinking in areas and silos or in operational and strategic activity profiles also represents a challenge that stands in the way of a cross-area SCM approach and optimization. A similar issue is that the scope or authority to engage in advanced analytics is often anchored in the parent company and little is possible nationally. This forces the emergence of central solutions that are as broadly applicable as possible, but which are often not applicable in specific local decision-making situations.

5. Conclusion, Limitations and Outlook

In this paper, a detailed analysis of the current application of advanced analytics in Austrian SCM practice and the challenges in this context has been conducted. The findings reveal a distinct pattern: although the literature highlights numerous performance advantages, the practical utilization of advanced analytics remains at a rudimentary stage and is primarily confined to isolated departments. While demand management, procurement, and transport planning have shown some initial success in their implementation, other areas like production planning and, particularly, warehouse management lag. The primary challenges observed in practice include a limited understanding of the potential of advanced analytics, lack of transparency and data quality issues, difficulties in internal marketing, and inadequate organizational integration. These challenges, along with potential courses of action, serve as a starting point for other companies aiming to address similar issues. Overall, advanced analytics is hence only applied to a limited degree, and there are several challenges that currently hinder further application.

From a practical point of view, the present work contributes to the identification of application and performance potentials of advanced analytics in SCM practice of small countries. The discussion of the implementation challenges enables other companies in similar settings to identify the central areas of action more quickly and to address them accordingly in terms of the recommendations for action derived. From a theoretical point of view, the work is one of the few studies that deals with the concrete design or the actual fields of application of advanced analytics in Austria. Possible limitations of this study are that only nine experts representing SCM practice were interviewed. In this context, however, the scientifically based procedure described in Chapter 4.1. for the selection of experts ensured that they were actual knowledge carriers from the SCM sector. The companies represented also come from numerous different sectors, so a very broad diversity of sectors was also considered. Nevertheless, the experts interviewed were only representatives from Austria, so a general picture of the use of advanced analytics in SCM at an international level cannot be provided. Building on the present work, similar surveys could be conducted in other countries and with a larger number of experts in future studies and their results discussed against the background of the current findings.

Acknowledgements

This research has been funded by the Christian Doppler Research Association as part of the Josef Ressel Centre for Predictive Value Network Intelligence (PREVAIL).

References

[1] Brandtner, P., 2023. Predictive Analytics and Intelligent Decision Support Systems in Supply Chain Risk Management—Research Directions for Future Studies, in: Yang, X.-S., Sherratt, S., Dey, N., Joshi, A. (Eds.), Proceedings of Seventh International Congress on Information and Communication Technology, vol. 464. Springer Nature Singapore, Singapore, pp. 549–558.

[2] Saravanan, N., Olivares-Aguila, J., Vital-Soto, A., 2022. Bibliometric and Text Analytics Approaches to Review COVID-19 Impacts on Supply Chains. Sustainability 14 (23), 15943.

[3] Udokwu, C., Brandtner, P., Darbanian, F., Falatouri, T., 2022. Proposals for Addressing Research Gaps at the Intersection of Data Analytics and Supply Chain Management. JAIT 13 (4).

[4] Brandtner, P., Udokwu, C., Darbanian, F., Falatouri, T., 2021. Applications of Big Data Analytics in Supply Chain Management: Findings from Expert Interviews, in: 2021 The 4th International Conference on Computers in Management and Business. ICCMB 2021: 2021 The 4th International Conference on Computers in Management and Business, Singapore Singapore. 30 01 2021 01 02 2021. ACM, New York, NY, USA, pp. 77–82.

[5] Brandtner, P., Schober, S., Zimmermann, R., Staberhofer, F., 2023. Status-Quo of IoT in Supply Chain Management - Applications, Potentials and Challenges in Austria, in: Proceedings of the 2023 6th International Conference on Computers in Management and Business. ICCMB 2023: 2023 The 6th International Conference on Computers in Management and Business, Macau China. 13 01 2023 15 01 2023. ACM, New York, NY, USA, pp. 133–138.

[6] Al., R.M.E., Gilkey, J., 2021. The challenges and realities of retailing in a COVID-19 world: Identifying trending and Vital During Crisis keywords during Covid-19 using Machine Learning (Austria as a case study).

[7] Mentzer, J.T., DeWitt, W., Keebler, J.S., Min, S., Nix, N.W., Smith, C.D., Zacharia, Z.G., 2001. Defining Supply Chain Management. J Bus Logist 22 (2), 1–25.

[8] Leicht, U., 2022. Erfolgsfaktoren des Supply-Chain-Risikomanagements in der Krise. Springer Fachmedien Wiesbaden, Wiesbaden.

[9] Lambert, D.M., Cooper, M.C., Pagh, J.D., 1998. Supply chain management: implementation issues and research opportunities. IJLM 9 (2), 1–20.

[10] Chopra, S., Meindl, P., 2016. Supply chain management: Strategy, planning, and operation / Sunil Chopra, Kellogg School of Management, Peter Meindl, Kepos Capital, Sixth edition, Global edition ed. Pearson, Boston.

[11] APICS, 2017. Supply Chain Operations Reference Model SCOR. Version 12.0. APICS. http://www.apics.org/docs/default-source/scor-training/scor-v12-0-framework-introduction.pdf?sfvrsn=2.

[12] Porter, M.E., 2007. Wettbewerbsvorteile. Spitzenleistungen erreichen und behaupten. Springer.

[13] Werner, H., 2017. Supply Chain Management. Springer Fachmedien Wiesbaden, Wiesbaden.

[14] Nguyen, T., Li, Z., Spiegler, V., Ieromonachou, P., Lin, Y., 2018. Big data analytics in supply chain management: A state-of-the-art literature review. Computers & Operations Research 98, 254–264.

[15] Agatic, A., Tijan, E., Hess, S., Jugovic, T.P., 2021. Advanced Data Analytics in Logistics Demand Forecasting, in: 2021 44th International Convention on Information, Communication and Electronic Technology (MIPRO). 2021 44th International Convention on Information, Communication and Electronic Technology (MIPRO), Opatija, Croatia. 27.09.2021 - 01.10.2021. IEEE, pp. 1387–1392.

[16] Fan, C., Da Yan, Xiao, F., Li, A., An, J., Kang, X., 2021. Advanced data analytics for enhancing building performances: From data-driven to big data-driven approaches. Build. Simul. 14 (1), 3–24.

[17] Mire, A., Malik, S., Tyagi, A.K., 2022. Advanced analytics and deep learning models. Wiley-Scrivener, Hoboken.

[18] Ginger Korsten, Banu Aysolmaz, Oktay Türetken, Diederick Edel, Barış Özkan, 2022. ADA-CMM: A Capability Maturity Model for Advanced Data Analytics, in: Hawaii International Conference on System Sciences.

[19] Marttila-Kontio, M., Kontio, M., Hotti, V., 2014. Advanced data analytics education for students and companies, in: Proceedings of the 2014 conference on Innovation & technology in computer science education - ITiCSE '14. the 2014 conference, Uppsala, Sweden. 21.06.2014 - 25.06.2014. ACM Press, New York, New York, USA, pp. 249–254.

[20] Krieger, F., Drews, P., Velte, P., 2021. Explaining the (non-) adoption of advanced data analytics in auditing: A process theory. International Journal of Accounting Information Systems 41, 100511.

[21] Kersting, K., Lampert, C., Rothkopf, C., 2019. Wie Maschinen lernen. Springer Fachmedien Wiesbaden, Wiesbaden.

[22] Annansingh, F., Sesay, J.B., 2022. Data Analytics for Business. Routledge, London.

[23] Adamov, A.Z., 2019. Machine learning and advanced analytics in tax fraud detection, in: 2019 IEEE 13th International Conference on Application of Information and Communication Technologies (AICT), pp. 1–5.

[24] Sharda, R., 2020. Analytics, data science, & artificial intelligence, Eleventh edition ed. Pearson, Hoboken NJ, xxxv, 795 pages.

[25] Sarker, I.H., 2021. Data Science and Analytics: An Overview from Data-Driven Smart Computing, Decision-Making and Applications Perspective. SN computer science 2 (5), 377.

[26] van Audenhove, L., Donders, K., 2019. Talking to People III: Expert Interviews and Elite Interviews, in: van den Bulck, H., Puppis, M., Donders, K., van Audenhove, L. (Eds.), The Palgrave Handbook of Methods for Media Policy Research. Springer International Publishing, Cham, pp. 179–197.

[27] Döringer, S., 2020. 'The problem-centred expert interview'. Combining qualitative interviewing approaches for investigating implicit expert knowledge. International Journal of Social Research Methodology 1 (4), 1–14.

[28] Brandtner, P., Mates, M., 2021. Artificial Intelligence in Strategic Foresight – Current Practices and Future Application Potentials, in: Proceedings of the 2021 12th International Conference on E-business, Management and Economics (ICEME 2021). International Conference on E-business, Management and Economics (ICEME 2021), pp. 75–81.

[29] Flyvbjerg, B., 2006. Five Misunderstandings About Case-Study Research. Qualitative Inquiry 12 (2), 219–245.

[30] Brandtner, P., Zimmermann, R., Allmendinger, J., 2023. Implications of 3D Printing on Physical Distribution in Logistics and Supply Chain Management, in: Yang, X.-S., Sherratt, R.S., Dey, N., Joshi, A. (Eds.), Proceedings of Eighth International Congress on Information and Communication Technology, vol. 694. Springer Nature Singapore, Singapore, pp. 641–653.

[31] Kallio, H., Pietilä, A.-M., Johnson, M., Kangasniemi, M., 2016. Systematic methodological review: developing a framework for a qualitative semi-structured interview guide. Journal of advanced nursing 72 (12), 2954–2965.

[32] Hill, Z., Tawiah-Agyemang, C., Kirkwood, B., Kendall, C., 2022. Are verbatim transcripts necessary in applied qualitative research: experiences from two community-based intervention trials in Ghana. Emerging themes in epidemiology 19 (1), 5.

[33] Halcomb, E.J., Davidson, P.M., 2006. Is verbatim transcription of interview data always necessary? Applied nursing research: ANR 19 (1), 38–42.

[34] Loubere, N., 2017. Questioning Transcription: The Case for the Systematic and Reflexive Interviewing and Reporting (SRIR) Method. Forum Qualitative Sozialforschung / Forum: Qualitative Social Research, Vol 18, No 2 (2017).

Biography

Patrick Brandtner (*1987) is a professor of Data-Driven Management at the University of Applied Sciences Upper Austria. He has been Head of the research department Data Analytics & Foresight since 2022. Currently he is director of the Josef Ressel Centre for Predictive Value Network Intelligence. He is a member of many academies of technical sciences and other scientific societies.

CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
CPSL 2023-2

5th Conference on Production Systems and Logistics

Sustainable Urban Logistics Model Applied to Food Trucks. Case Study and Descriptive Analysis

Andrea Fernanda Peirano Madrid[1], Arianna Zúñiga Novaro[2]
Yvan Jesus García-López[3] , José Antonio Taquía Gutiérrez[4]
[1,2,3,4]Universidad de Lima, Lima, Peru
Carrera de Ingeniería Industrial

Abstract

The food truck service is growing due to the change in customers' fast food consumption habits. This research aims to test the logic of using urban logistics to improve the optimization of food truck supply. This research proposes a case study where route optimization methods, central location, and the estimation of the environmental impact through the emission of pollutant gases at the time of supplying food trucks are proposed; RStudio and COPERT V software was used to obtain quantitative results. Concerning the results, it was found that the food truck is viable due to the number of potential customers within the case study area. The central location (longitude, latitude) of the food truck within the area where its customers are located was found; in addition, thanks to the optimal supply route, it was possible to calculate the emissions of polluting gases: CO2, PM2.5, PM10, NOX, VOC.

Keywords

Urban Logistics; Food Truck; Environmental Impact; Route Optimization; Optimal Downtown Location

1. Introduction

Today, it is possible to appreciate different changes such as a continuous increase of population within urban areas, citizens' concern about environmental pollution or the same safety within their cities, co-management, and traffic problems, the emergence of new technological opportunities, and policymakers of urban transport [1].

The new challenges cities face due to large concentrations, different stakeholders are affected, and it becomes more challenging to meet the needs of citizens efficiently and effectively [2]. Companies must reevaluate their logistics practices when forced to work with their suppliers and customers in urbanized areas [3].

Urban logistics has been applied within the food supply process as it presents environmental, social, and economic challenges. Different local authorities consider the quality and safety of food and the impact on the environment generated by food supply and transportation systems [2]. Therefore, it is essential to find the best location of distribution centers within cities for interested companies. By achieving this, a change in the cities could be appreciated because transportation routes will be more efficient, bringing less congestion and a lower negative environmental impact. However, to implement urban logistics, transportation, food demand, and distribution must be considered variable.

Nowadays, not only fast-food restaurants have grown, but also the number of food trucks that can be found parked on busy streets that facilitate access to food consumption. A food truck is a truck or trailer equipped with the necessary tools (e.g., kitchen) to produce and sell fast food. However, the mode of distribution of

DOI: https://doi.org/10.15488/15283
ISSN: 2701-6277

these is in fixed points that must be located strategically to reduce transportation costs and have the optimal inventory of raw materials to avoid being out of stock in a day or, on the contrary, having an excess that generates food waste. The warehouses of urban distribution points involve many vehicles for which operational monitoring of the routes must be carried out to limit consumption and excessive emission of polluting gases [4].

This generates transportation costs and raw material waste and leads to environmental impact. Even though urban logistics is a minor part of the total transport time of goods, it comes to represent 28% of transport costs. On the other hand, polluting gases vary between 16- 50% of global pollution due to activities carried out within urban areas [5].

Despite technological advances that include the development of electric powered trucks, such as battery electric heavy-duty trucks cause less emission of Carbon Dioxide (CO_2) than Disel [6], it is rarely done at present due to the require investment and the slow introduction of it in the international market.

However, despite the advances in the different published sources described above, more is needed to know about how urban logistics affects different city services, specifically food trucks. Since few researchers have addressed urban logistics applications in food trucks, it is necessary to explore this modality of fast-food service to align it with the purpose of urban logistics, which is to be sustainable and efficient.

The research question is: Can the urban Logistics model be run to achieve an optimal and sustainable supply of inventory in food trucks in Metropolitan Lima through a simulation to reduce the environmental impact emitted by polluting gases? This work aims to simulate an urban logistics model to achieve an optimal and sustainable inventory supply in Metropolitan Lima food trucks.

This research is to check the logic of using urban logistics to improve the optimization of food truck supply. In this way, the emissions of Carbon Dioxide (CO_2), Nitrogen Oxides (NO_x), Volatile Organic Compounds (VOC) and Particulate Matter (PM) can be estimated for sustainable distribution, and with the knowledge of potential customers and suppliers, the food truck's optimal location and supply route can be found.

Therefore, in this study, we will test the following hypotheses: It is possible to simulate an urban logistics model to achieve an optimal and sustainable supply of inventory in food trucks in Metropolitan Lima.

This paper is organized as follows: the formulation used to simulate the optimization process will be described in the Methods section. Then, in the Results section, the findings obtained from the simulation will be demonstrated. Finally, the Discussion section will analyze the results obtained to test the hypothesis formulated.

2. Literature review

2.1 Urban Logistics

Urban logistics is an inclusive term applied in different ways; for example, after using the Delphi methodology to 19 participants, it was obtained that the biggest perceived problem was congestion and traffic caused in cities [7]. Due to this, they defined the stakeholders' roles in the activities that fall under this heading. This is complemented in the research [8] where the context of urban logistics focuses on the optimal use of resources. Considering the above, simulations can be formulated to optimize distribution processes in urban areas concerning the importance given to stakeholders and resources used in urban logistics.

An essential term in logistics is the last mile, which refers to the delivery to the final customer within a logistics process. This is put into practice in the research [9], where they sought to determine the optimal number and location of product pick-up points in given periods using a Monte Carlo optimization simulation.

In conclusion, it was found that one of the essential points to consider for this last delivery and the efficient number of pickup/sale points is always to consider the uncertainty of the demand for decision-making.

As mentioned above, urban logistics generates an environmental impact as there is a negative impact on low-emission logistics if there is inadequate distribution. To achieve flue gas reduction within the urban logistics distribution process, the research [10] explores a closed-loop logistics distribution route optimization method that positively impacts low-carbon logistics, promoting a low-carbon agenda in logistics network practice. An alternative approach was developed [11]; these studies the emissions and the intensity of these related to trucks according to the purpose of the trip. The results of the work suggest that the design of emissions management measures should consider which factors (population densities, Euclidean distance, and empty weight of vehicles) impact GHG emissions for each trip purpose.

2.2 Logistic distribution simulation models

The formulation developed a mathematical model concerning the vehicle routing problem to test the reduction of total distribution costs and pollutant gas emissions [12]. The variables considered were distribution costs, carbon oxide emissions, total transportation time, number of routes, and distance. The SIMMAG 3D tool was used to implement the mathematical model formulated. The study showed an 8.1% reduction in total distribution costs.

On the other hand, a mathematical model applied to a context more like the problems of vehicular congestion in Bogota, Colombia [5]. In this, two scenarios were compared: collaborative and non-collaborative, where the purpose was the most efficient decision-making for urban distribution. The research also considered a term widely used within urban logistics: routing problems of capable vehicles. The variables used were distance, total number of delivery points, average vehicle transport speed, vehicle capacity, and demand. Finally, an approximate 25% cost reduction was achieved in a collaborative scenario.

Another model applied in Latin America was the research [13] in Santiago, Chile. In this model, an alternative approach was used, aiming at minimizing the environmental impact of air pollution to improve the efficiency of the distribution and commercial supply process. The optimization model was carried out, considering the vehicle routing problem. It was obtained that a reduction of 53 tons of carbon dioxide and a reduction of 1103 hours of annual interruptions in vehicle congestion in the sector can be achieved.

The Traffic and Land Use Simulator for Urban Logistics [14] was developed for Tokyo (metropolitan area). It seeks to evaluate the level of externalities linked to logistics facilities' spatial distribution patterns. It analyzes the different impacts of urban freight transportation through simulations of different scenarios of the locations of urban logistics facilities and chains and truck flow. The paper’s results indicate that the scarcity of facilities in high-demand locations exacerbates negative externalities, while moderate concentration and deconcentration of facilities do not significantly affect them.

The research [15] presented a static deterministic mixed integer linear programming (MILP) model. This solves the two-box capacitated location-routing problem (2E-CLRP) with modal choice in the context of urban logistics services (ULS). It additionally provides an optimal routing cost estimation formula and optimization heuristics. The results demonstrate that the 2E-CLRP model generates high-quality, time-reasonable closed-form approximations for optimal routing costs.

Finally, a coding applied in RStudio software to calculate the optimal location through the center-of-mass approach so that the location is where the highest concentration of random points is. It was used as an assumption that the transport shipping volumes in the distribution truck and the potential customers have similar cost structures and that these depend on the distance traveled. The "x" and "y" coordinates were obtained from the weighting of sales demand in conjunction with the quantity supplied from the suppliers as the point of origin and the demand in costs of the point of arrival represented by the potential customers. Once the coding was run, the optimal location centroid was obtained, which can be visualized in ggplot2 or a ggmap [16].

3. Methodology

The present research has as variables: environmental impact and urban logistics [2] The first is caused due to the emission of gases at the time of making the supply route and subsequently to the point of sale. On the other hand, the dependent variable focuses on the urban logistics used to optimize the distances traveled and achieve a strategic location central for potential customers. The dimensions developed are environmental pollution and the type of delivery used to deliver food orders, in this case, food trucks.

To achieve an optimal location and supply route for food trucks, the following data must be considered: gas emissions, kilometers traveled, location of suppliers, number of potential customers, maximum temperature, minimum temperature, and relative humidity. In this way, it is shown that the research has a quantitative approach based on numerical databases, an experimental type, and pre-experimental scope where the formulas proposed and described in the research design to be carried out are put into practice.

It should be taken into consideration that the research consists of a case study in which a descriptive analysis is developed since a survey is conducted, which provides more accurate data regarding the number of potential customers.

Figure 1 shows the initial and practical phase of the research.

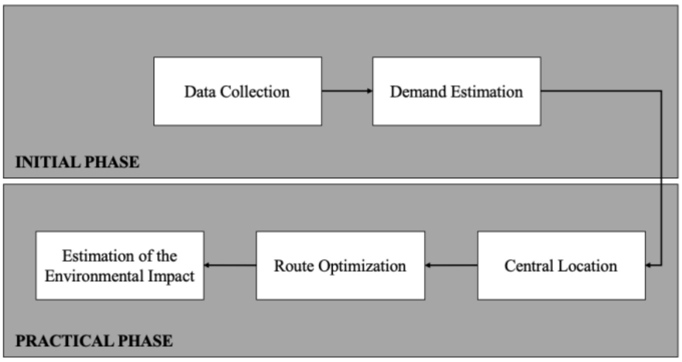


Figure 1: Research design

3.1 Initial phase

First, the initial phase of the research consisted of two stages: data collection and demand estimation. The first stage involved gathering the necessary information to build the following phases. The second stage consisted of estimating the demand of potential customers who will consume the food provided by the food truck.

3.1.1 Data collection

The first stage of the initial phase was collecting data for the proposed models. To estimate the demand and thus obtain potential customers, information was collected through surveys conducted with different customers who consume food provided by food trucks in the area where the case study was conducted. The questionnaire had questions of intention and intensity to estimate the demand of potential customers. The sample was obtained thanks to the "finite population" formula because the size of the total population is known. The survey questions were validated by "Marketing Research" experts.

The sample to be studied was calculated by applying (1):

$$N = \frac{(N \times Z^2 \times p \times q)}{(d^2 \times (N-1) + Z^2 \times p \times q)} \tag{1}$$

Where:

- N: Total population of the case study area
- Z: Taking into consideration a 95% certainty, this value will be 1.96
- p: Expected proportion; this value will be 50%.
- q: Is the complement of p; in this case, it will be 50%.
- d: Accuracy of the investigation; in this case, it will be 5%.

Considering that a spatial approach must be taken to calculate travel distances, the addresses and stops involved in the food truck supply process were collected.

In addition, information on Lima's minimum temperature, maximum temperature, and relative humidity was extracted from the database of the National Meteorological and Hydrological Service of Peru (SENAMHI), an entity attached to the Ministry of Environment of Peru. These data were used for the experimental phase of the environmental impact estimation.

3.2 Demand estimation

The second stage consisted of obtaining the demand for daily orders through the survey, where the intention and intensity of these orders were obtained.

Once the sample was obtained, the survey was conducted among passers-by in the area where the food truck was parked to sell its dishes. The formula applied was (2)

$$Number\ of\ potential\ customers = N_{customers} \times I_1 \times I_2 \tag{2}$$

Where:

- *Number of potential customers:* The number of people surveyed who responded that they would be interested in consuming the dish offered by the food truck; therefore, it is the purchase intention multiplied by the intensity.
- *I1*: Intensity, percentage of people where the degree of interest in the purchase is demonstrated (Interval of 1-10).
- *I2*: Intention, percentage of people willing to consume in the food truck.

3.3 Practical phase

The experimental phase of the research demonstrated what was necessary for the central location of the food truck, route optimization, and estimation of environmental impacts.

First, the central location of the food truck obtained the point where the food truck should be located to stock and deliver the orders of dishes to its potential customers.

Secondly, by finding a central location, it was possible to obtain the optimal supply route for the food truck, covering all the points it needs to reach the warehouse, suppliers, and point of sale.

Thirdly, the environmental impact measured the number of gases emitted by the food truck concerning the distance traveled from the first point to the point of sale of the dishes to be offered.

3.3.1 Central location

Regarding the first stage of this phase, RStudio software was used to implement the coding performed [16]. The objective of the coding is to be able to find the centric location under the principles of the center of mass approach using the formulas of x (longitude) and y (latitude); these use a weight which is the "volume of expenditure per orders."

Having the weighted average coordinates of the center of mass, the location was visualized with a scatter plot with "ggplotz/ggmap". The heat map was plotted in RStudio with the Leaflet package, where the optimal center point can be visualized.

The central point was the food truck's location for the following route optimization calculations and estimation of pollutant gases emitted when traveling the food truck supply distances.

3.3.2 Route optimization

The second stage of the experimental phase of the research consisted of constructing an optimal route for food supply from the food trucks. The distance it takes to go to the different points to the endpoint was considered to spatialize the route. The points can vary between the raw material warehouse, the central location previously found, and that of the suppliers.

To create the optimal route, "Analytics in georeferenced systems" [17] was used, allowing route optimization and analysis of intelligent distribution models. In addition, the tool allowed to obtain the distance traveled in kilometers that the food truck travels to get from the initial point to the final point.

A+" and "Dijkstra" algorithms are used because the algorithm stops when it finds the shortest path leading from the initial point to the rest of the points.

3.3.3 Estimated environmental impact

To estimate the environmental impact, only the direct emissions of exhaust gases from the use of the vehicles were considered. The software estimated the emissions of CO2, NOx, VOC, and PM, as these are the ones involved in the process of supplying food trucks. These gases are a result from the use of Diesel which is a main resource to complete the route of truck supplying. The emission of this gases has consequences that not only contaminants the atmosphere of the cities, as well as the health of its citizens. The COPERT V software (Computer program for calculating emissions from transportation routes) is used (3) to estimate gas emissions:

$$Gas\ emission = f_{emission}(truck\ category\ , speed_{average}) \times\ distance \tag{3}$$

Where:

- $f_{emission}$: This function is extracted from the COPERT V emissions database.

Equation (3) consists of entering primary data on the minimum and maximum temperature and relative humidity of the area where the study was conducted, in this case, Lima, Peru. In addition, the category (model of the vehicle used to travel the route) and the distance traveled in kilometers were entered. The data entered will correspond to 2021 with the history SENAMHI (National Service of Meteorology and Hydrology) reported.

4. Results

4.1 Initial phase

4.1.1 Data collection

In order to collect the data needed to estimate demand and requirements, the inhabitants of the case study area, "Villa Militar Oeste Chorrillos", were surveyed. The total population was approximately 1708 local residents (N=1708); therefore, by applying the "Finite Population" formula, a sample size of 314 people was obtained. The 314 people were surveyed with an 8-question questionnaire with questions of intention “Would you buy food from this food truck? Yes or No” (I1=92.11%) and intensity “From 1 to 10, indicate how likely you are to buy fast food from the food truck” (I2=76.11%). Table 1 and Table 2 reflect the results of these types of questions.

Concerning the addresses and stops to supply the food truck in a day, four points were identified: the warehouse, supplier 01, supplier 02, and the point of sale (primary address).

Table 1: Results of the question "Intension".

Reply	Total	Porcentage
Yes	175	92.11%
No	15	7.89%
Total	**190**	**100%**

Table 2: Results of the question "Intensity".

Intensity	Total	Percentage	Weighted
1	2	1.14%	0.01
2	2	1.14%	0.02
3	1	0.57%	0.02
4	5	2.86%	0.11
5	14	8.00%	0.40
6	16	9.14%	0.55
7	25	14.29%	1.00
8	53	30.29%	2.42
9	32	18.29%	1.65
10	25	14.29%	1.43
Total	**175**	**100.00%**	**7.611**

Concerning the data obtained from the National Meteorological and Hydrological Service of Peru (SENAMHI), the history of temperature reports recorded in previous years was obtained. The data from the station closest to the district of Chorrillos (Lima, Peru) was used, in this case, the Campo de Marte station. These data will be used in the experimental phase to calculate the emission of polluting gases and apply the optimization based on the reduction of these gases for a route with sustainable impact.

Table 3 shows the data collected based on historical data for the year 2021.

Table 3: Minimum Temperature, Maximum Temperature, and Humidity in 2021

Month	Tmín	Tmáx	H %
Jan-21	18.80	28.00	80.06
Feb-21	18.20	28.60	76.74
Mar-21	18.60	29.10	76.66
Apr-21	16.30	27.80	82.46
May-21	15.00	24.40	86.91

Jun-21	14.90	21.50	86.17
Jul-21	14.50	19.90	86.52
Aug-21	13.40	19.60	87.68
Set-21	13.40	19.40	88.01
Oct-21	14.00	20.50	85.85
Nov-21	15.60	21.50	83.55
Dec-21	16.60	25.10	81.88

4.1.2 Demand estimation

To calculate the demand, we used the data obtained from the survey on the intensity and intensity of the respondents.

$$Number\ of\ potential\ customers = 1708 \times 92.11\% \times 76.11\% \tag{4}$$

Using the formula described in the methodology chapter, we obtained the number of potential customers of 1198 people in the case study area.

4.2 Practical Phase

4.2.1 Central Location

First, random data were used for potential customers, longitude and latitude, and volume of spending per order (PEN 50.00-PEN 100.00); to program the coding in the RStudio software and obtain the central location of the food truck. Figure 2 shows the result obtained. By randomly locating the distribution of potential customers, it is possible to visualize in the heat map the concentration of them within the case study area.

In addition, the figure shows the center of mass, representing the food truck's optimal location. Thus, the sales coordinates are:

- Longitude: x = -77.02059
- Latitude: y = -12.15889

Once the central location is obtained, the routing tool "Analytics in georeferenced systems", [17] is used. In this way, the optimal supply route the food truck should follow for its supply and, finally, the point of sale is calculated.

The route shown in Figure 3 is obtained using the tool, where the optimal minimum distance between the food truck's supply and sales points is given.

Thanks to the optimal route, the distances from point to point were obtained, and the results can be seen in Table 4.

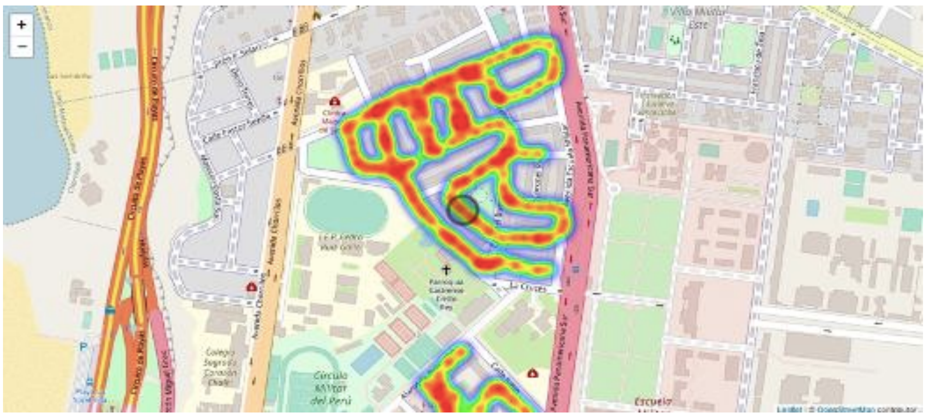


Figure 2: Load distribution and central location

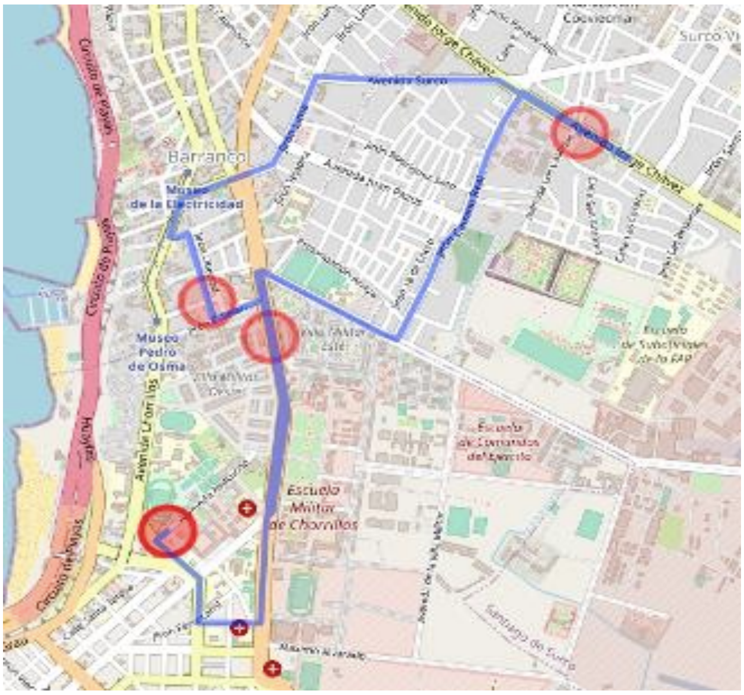


Figure 3: Load Distribution and Central Location

Table 4: Distances in Km

Points	Distance (km)
Warehouse	0.362487
Supplier 01	0.554349
Supplier 02	1.485415
Point of Sale	0.461031

4.2.2 Estimated environmental impact

Finally, once the optimal route was obtained, the total distance traveled by the food truck was calculated and entered into the pollutant gas emission simulation in the Copert V software with the data collected on minimum and maximum temperature and relative humidity in the study area.

Table 5 shows the amount of pollutant gas emissions during the route.

Table 5: Pollutant Gases Emissions

Emission	kg/km
Carbon dioxide (CO_2)	100.0847
Particulate Matter PM $_{2.5}$	0.00049
Particulate Matter PM $_{10}$	0.00902
Nitrogen Dioxide (NOX)	0.03367
Volatile organic compounds (VOC)	0.13582

Table 5 shows the amount of pollutant gas emissions during the route.

5. Discussion

It was possible to prove that using the center of mass theory and, subsequently, the calculation of the routing optimization based on Dijkstra's algorithm were fundamental tools to achieve an optimal route model. Thus, because of the shorter distance traveled, it was possible to reduce the environmental impact emitted by polluting gases when the food truck had to travel through the streets of Metropolitan Lima to supply raw materials and reach the final point of sale.

The data collection method was obtained as needed for each of the stages. Intensity and intensity data, the addresses of the points involved in the food truck supply, and temperature and humidity data were collected.

Thanks to the survey, we collected the intensity (I1 =92.11%) and intensity (I2 =76.11%), which helped to find the number of potential customers. The number of potential customers for the food truck within the case study area is 1198, which indicates that there is a demand to be met within the case study area and is profitable.

To obtain the optimal location, through the simulation performed in RStudio, longitude and latitude (-77.02059; -12.15889) were obtained for the location of the food truck according to the estimated volume of spending by potential customers. The purpose of obtaining these coordinates was that the food truck is not only placed by default in a location but also has a relationship with the estimated income from the location of its potential customers.

For this stage, the four points involved in the food truck supply process were identified: the warehouse, supplier 01, supplier 02, and the point of sale (main address obtained in the previous point).

Once the food truck was located at the coordinates obtained, the optimal routing was made, considering the suppliers' locations of inputs for preparing the dishes to be offered at the point of sale. With the optimal route, we obtained the total mileage that the food truck travels daily to stock up and then position itself to prepare and sell dishes. The total distance traveled by the food truck is 1030.03 kilometers/year. With this distance, the environmental impact was calculated in the gas emission simulation based on the distance the vehicle travels in the Copert V software.

To complete the last stage of the research, information was collected on the maximum temperature, minimum temperature, and relative humidity of the nearest station in the case study area. In addition, the type of vehicle used by the food truck for fueling was also considered. Having the necessary data for COPERT V, the annual gas emissions of the food truck supply route were obtained. These were as follows: CO_2 100.0847 kg/km, PM2.5 0.00049 kg/km, PM10 0.00902 kg/km, NOX 0.03367 kg/km, VOC 0.13582 kg/km.

As could be seen, the findings presented are consistent with the results reported [16]; thanks to its coding in RStudio software, it was possible to obtain the optimal location of the food truck, taking into account the volume of sales that the food truck would have and the random location of potential customers, thanks to the center of mass principle. Additionally, as shown in the research, the coordinates of the optimal location were displayed and could be visualized in a heat map using a leaflet.

Unlike the research [2], it can be noted that the distribution center of the case study is an established point. However, the two research find the optimal routes for minor pollutant gas emissions during the supply process. COPERT V software was used to estimate these annual emissions for the proposed scenarios. Thus, finding the amount of CO_2, PM2.5, PM10, NOX, and VOC emissions.

6. Conclusion

The results show the feasibility of applying the quantitative approach using simulation software used in RStudio and Copert V, where the optimal location and routes were obtained to reach the environmental impact caused by the emission of gases from the food truck at the time of supply. Based on these numerical results, the minimization of gas emissions can be sought for sustainable routing.

References

[1] Lagorio, A., & Pinto, R. 2016. Research in urban logistics: a systematic literature review, International Journal of Physical Distribution & Logistics Management, 46 (10), 908-931. DOI 10.1108/IJPDLM-01-2016-0008

[2] Palacios-Argüello, L., & et al. 2018. Assessing the economic and environmental impacts of urban food systems for public school canteens: a case study of Great Lyon region, European Transport Research Review, 10 (37). https://doi.org/10.1186/s12544-018-0306-8

[3] Rose, W., & et al. 2015. Exploring urban institutional pressures on logistics service providers, International Journal of Physical Distribution & Logistics Management, 46 (2), 153-176. DOI 10.1108/IJPDLM-03-2015-0068

[4] Raicu, S., et al. 2020. Distribution system with flow consolidation at the boundary of congested urban areas, Sustainability (Switzerland), 12 (3), art. no. 990. https://doi.org/10.3390/su12030990

[5] Muñoz-Villamizar, A., et al. 2015. Non-collaborative versus collaborative last-mile delivery in urban systems with stochastic demands, Procedia CIRP, 30, pp. 263-268. https://doi.org/10.1016/j.procir.2015.02.147

[6] Moll, C., et al. Are battery-electric trucks for 24-hour delivery the future of city logistics? -A German case study", World Electric Vehicle Journal, 11 (1), art. no. 16. DOI: 10.3390/WEVJ11010016

[7] Rześny-Cieplińska, J., & Szmelter-Jarosz, A. 2020. Environmental sustainability in city logistics measures, Energies, 13 (6), art. no. en13061303. https://doi.org/10.3390/en13061303

[8] Szmelter-Jarosz, A., & et al. 2020. Assessing resources management for sharing economy in urban logistics, Resources, 9 (9), art. no. 113. https://doi.org/10.3390/RESOURCES9090113

[9] Rabe, M., et al. 2021. Simulation-optimization approach for multi-period facility location problems with forecasted and random demands in a last-mile logistics application, Algorithms, 14 (2), art. no. 41.https://doi.org/10.3390/a14020041

[10] Wang, J., & et al. 2018. Promoting low carbon agenda in the urban logistics network distribution system, Journal of Cleaner Production. 211, 146-160. https://doi.org/10.1016/j.jclepro.2018.11.123.

[11] Gann M., & et al. 2018. Identifying truck-related greenhouse gas emissions and critical impact factors in an urban logistics network, Journal of Cleaner Production, 178, 561-571. https://doi.org/10.1016/j.jclepro.2018.01.047.

[12] Wasiak, M., et al. 2017.The method for evaluation of the efficiency of the concept of centrally managed distribution in cities, Transport, 32 (4), pp. 348-357. https://doi.org/10.3846/16484142.2017.1345005

[13] Urzúa-Morales, J.G., et al. 2020. Logistic modeling of the last mile: Case study Santiago, Chile, Sustainability (Switzerland), 12 (2), art. no. 648.https://doi.org/10.3390/su12020648

[14] Sakai, T., & et al. 2018. Evaluation of the spatial pattern of logistics facilities using urban logistics land-use and traffic simulator, Journal of Transport Geography, 74, 145-160. https://doi.org/10.1016/j.jtrangeo.2018.10.011.

[15] Winkenbach, M., & et al. 2016. Enabling Urban Logistics Services at La Poste through Multi-Echelon Location- Routing, Transportation Science, 50 (2), 520-540. http://dx.doi.org/10.1287/trsc.2015.0624

[16] Linnart, M.SC. 2022. Monte Carlo simulation in R applied risk assessment for warehouse location.

[17] Taquía, J. 2022. Analytics in Georeferenced Systems, https://joseantoniotaquia.shinyapps.io/Planning_Gis//

Biography

Andrea Fernanda Peirano Madrid bachelor's degree in industrial engineering from Universidad de Lima with a major in Commercial Engineering.

Arianna Zúñiga Novaro bachelor's degree in industrial engineering from Universidad de Lima with a major in Commercial Engineering.

Garcia-Lopez Yvan Jesus is a Ph.D (c) in Engineering and Environmental Science, UNALM, MBA in Maastricht School of Management, Holland, MSc in Computer Science, Aerospace Technical Center - ITA, Brazil. He has over 25 years of extensive experience managing investment projects, execution, and commissioning in Peru, Colombia, USA, Brazil, and China.

José Antonio Taquía, is a Doctoral engineer from Universidad Nacional Mayor de San Marcos and holds a Master of Science degree in Industrial Engineering from Universidad de Lima. He is a member of the School of Engineering teaching courses on quantitative methods, predictive analytics, and research methodology. Mr. Taquía has a strong background in supply chain analytics and operations modeling applied in different industry sectors. He leads an Industry 4.0 and predictive analytics research group using quantitative methods.

CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
CPSL 2023-2

5th Conference on Production Systems and Logistics

Resilience Maturity Assessment in Manufacturing Supply Chains

Maria Thomassen[1], Bjørnar Henriksen[2]

[1]SINTEF Digital, Oslo, Norway
[2]SINTEF Digital, Arendal, Norway

Abstract

Industry 5.0 is a new vision for European industry with focus on human centricity, sustainability, and resilience. Due to that most research on Industry 5.0 concentrates on digital technologies, mainly because its relation to Industry 4.0, there is still limited and one-sided understanding of the concept. To enhance the competitiveness of manufacturing industries in Europe, companies need to develop their capabilities not only in digitalization, but also of human centricity, sustainability and resilience. Resilience, the capacity to withstand or to recover quickly from difficulties, is an important aspect due to war, pandemic, energy crisis and climate change crisis. Many manufacturing companies face major challenges in their supply chains, with limited availability of components, lack of critical virgin materials, high-cost growth, and high supply risk exposure. This research seeks to bring further understanding of the resilience dimension of the Industry 5.0 concept. It adds to the limited amount of research available on Industry 5.0. Also, manufacturing companies need to better understand how they can strengthen their resilience in the supply chains. This paper presents a tool that companies may use to evaluate their maturity, and identify improvement areas. The tool is assessed in three companies.

Keywords

Maturity assessment; Industry 5.0; Digitalization; Supply chain resilience; Tool development

1. Introduction

European industry is a main driver in the currently undergoing economic and societal transitions, and plays a key role in providing solutions to several major societal challenges including preservation of resources, climate change and social stability [1]. Industry 5.0 is a new concept launched by the European Union, which implies a novel approach for future industry that brings benefits for industry, for workers and for society [1]. The concept provides a vison that stretches beyond single goals of efficiency and productivity, and reinforces the role and the contribution of industry to society. The vision involves the transition to a sustainable, human-centric, and resilient European industry. It also complements the techno-economic vision of the Industry 4.0 concept, with emphasis on digitalization, including the transition towards a digital, data-driven, and interconnected industry [1]. While Industry 4.0 is technology driven, Industry 5.0 is assumed to be value driven, providing positive benefits to many stakeholders [2]. The twin transition involves a combined approach for achieving the green transition and the digital transition in society and industry, and for these two transitions to reinforce each other [3]. The aim is to achieve sustainability, combat climate change and environmental degradation, and future digital technologies may be key enablers for the green transition [3].

Recent multiple crises such as the climate change and environmental degradation crises, the covid-19 pandemic and the economic crisis have led to major challenges for the European industry [1]. Companies

DOI: https://doi.org/10.15488/15294
ISSN: 2701-6277

thus seek to create resilient organizations that can withstand or recover quickly from difficulties, and need to enhance their resilience capabilities [11]. Resilience in an Industry 5.0 setting may also involve aspects of sustainability and human centricity [1]. Companies need to be resilient to deal with not only unexpected environmental or climate change events, but also related to new environmental regulations, for instance. Moreover, humans are typically affected by the environmental and climate change impacts, and constitute important enabling resources to ensure resilience in companies by their creativity and flexible abilities.

To ensure systematic resilience management and improvement in manufacturing companies, powerful tools, and methods for measuring and evaluating the performance in terms of resilience are needed. These tools should also be ambitious regarding meeting future requirements, meaning that they should be aligned with the broad vision of industry transformation based on Industry 5.0 as well as of the narrower Industry 4.0 vision expressing ambitions for digital transformation.

Resilience has been a topic of high interest to researchers for several decades, which has resulted in a significant amount of research literature proposing resilience assessment frameworks and tools [19, 20]. Also, there is a rapidly growing body of research seeking to measure digital and Industry 4.0 maturity, see for instance literature reviews by [4–7]. However, there is a research gap on methods and models for resilience maturity measurement in Industry 5.0 including the enabling the role of digital technology. This is due to several reasons. First, Industry 5.0 is still a new concept in both European industry and academia. Therefore, there is limited general research on this new concept and thus also lack of research on resilience in an Industry 5.0 context. Second, despite a large body of research, the role of digital technology is rarely included in previous research on resilience. Third, the recently developed maturity models are concentrated to Industry 4.0 and digital technology, paying little attention to its importance for the Industry 5.0 dimensions. It is therefore suggested to extend existing digital maturity models in these areas [8]. In addition, self-assessment methods for small and medium sized companies (SMEs) to support their digital transformation are lacking, since current digital maturity models available in literature are developed for large companies and thus fail to meet specific requirements of SMEs [9].

With a starting point in the shortcomings of existing literature on resilience and maturity models described above, this research is expected to contribute with a better understanding of resilience maturity in manufacturing supply chains in an Industry 5.0 context. The manufacturing sector is an important industry in Europe. The aim is to support manufacturing companies, especially SMEs, to enhance their resilience capabilities in line with the Industry 5.0 vision and ambitions of digital transformation that are fundamental for the future of European industry. More specifically, this paper presents the outline of a new tool for assessing Industry 5.0 resilience maturity, which may be used to measure the maturity level of supply chain resilience in manufacturing SMEs. This includes a set of critical resilience maturity aspects in an Industry 5.0 context identified in literature, and the development of a resilience maturity assessment (RMA) tool that is assessed in three manufacturing SMEs.

2. Theoretical considerations

Industry 5.0 is a new vision for European industry with focus on human centricity, sustainability, and resilience [1]. The resilience concept is closely related with the capability and ability of a company to return to a stable state after a disruption [20]. In a business context, resilience can be defined as the capacity for an enterprise to survive, adapt, and grow in the face of change and uncertainty [18]. To improve in terms of resilience, companies may strengthen their capabilities related to resilience and resilience may be measured by a company's ability to deal with risk and reduce vulnerability [11].

Readiness and maturity can measure a company's status and progress towards a future state of resilience. Supply chain resilience (SCRES) is the adaptive capability of a supply chain to prepare for and/or respond to disruptions, to make a timely and cost effective recovery, and progress to a better state of operations, and can be assessed in view of the preparation for a disruptive event, response to an event, recovery from the event, and growth/competitive advantage after the event [10].

The tool is based upon a set of relevant categories and factors identified in literature that are listed in Table 1. Supply chain resilience maturity [11] is characterized by a collection of capabilities and vulnerabilities. Current potential global risks are identified based on the recent report published by the World Economic Forum [12]. A set of factors reflecting resilience aspects of human workers are identified based on [13]. A considerable number of models for measuring digital and Industry 4.0 maturity are identified, see [6, 14, 8]. Maturity models are concerned with measuring adoption of advanced digital technologies in firms and relevant items for enabling resilience capabilities and vulnerabilities are identified based on [14] and [15].

Table 1: Identified resilience maturity assessment factors

Category	Factors/sub-factors	Ref.
Vulnera-bilities	Turbulence; Environment characterized by frequent changes in external factors beyond your control Deliberate threats; Intentional attacks aimed at disrupting operations or causing human or financial harm External pressures; Influences, not specifically targeting the firm, which create business constraints or barriers Resource limits; Constraints on output based on availability of the factors of production Sensitivity; Importance of carefully controlled conditions for product and process integrity Connectivity; Degree of interdependence and reliance on outside entities Supplier/customer disruptions; Susceptibility of suppliers and customers to external forces or disruptions	[11]
Global risks	Economic, Environmental, Geopolitical, Societal, Technological	[12]
Capa-bilities	Flexibility in Sourcing; Ability to quickly change inputs or the mode of receiving inputs Flexibility in Order Fulfilment; Ability to quickly change outputs or the mode of delivery Capacity; Availability of assets to enable sustained production levels Efficiency; Capability to produce outputs with minimum resource requirements Visibility; Knowledge of the status of operating assets and the environment Adaptability; Ability to modify operations in response to challenges or opportunities Anticipation; Ability to discern potential future events or situations Recovery; Ability to return to normal operational state rapidly Dispersion; Broad distribution or decentralization of assets Collaboration; Ability to work effectively with other entities for mutual benefit Organization; Human resource structures, policies, skills, and culture Human workers; Ability of operators to use human creativity, ingenuity, and innovation, and their interaction with machines Market Position; Status of a company or its products in specific markets Security; Defence against deliberate intrusion or attack Financial Strength; Capacity to absorb fluctuations in cash flow	[11]
	Human workers; Ability of workers to use human creativity, ingenuity, and innovation, and their interaction with machines	[13]
Enabling digital technologies	Additive Manufacturing (AM), Artificial Intelligence (AI), Augmented Reality (AR) or virtualization, Automation and collaborative robots, Big data and Analytics, Blockchain, Cloud computing, Cyber-Physical Systems, Cybersecurity, Horizontal and Vertical systems integration, Internet of Things (IoT), Simulation and Modelling, Visualization Technology	[14], [15]

3. Methodology

The resilience maturity assessment (RMA) tool is based on a brief literature review. The objective was to establish a starting point for tool development rather than conducting a comprehensive review. It was concentrated to identifying relevant existing maturity assessment tools related to resilience, digital maturity and Industry 4.0. The review also included searches for literature within the field of Industry 5.0. Approaches by [16] and [17] were used, adopting a stepwise iterative approach with planning and formulating the problem and literature search.

A set of previous maturity assessment tools were identified. The SCRAM tool developed by [18] was selected as a starting point for the RMA tool. This tool includes an exhaustive list of vulnerability and capability parameters, is well defined and described and validated in seven companies. The tool was extended to also include specific aspects related to human centricity based on the concept of Resilient Operator 5.0 [13], global risks defined by the World Economic Forum [12] and enabling digital technologies see [15] and [14].

The RMA tool is developed in MS Excel and is still in a prototype stage. It includes a set of statements and questions in a survey type of format, where respondents are asked to indicate the extent of agreement or disagreement based on personal knowledge of products, organization, and operations. We believe that the survey or prototype constitutes the starting point of the development of a new tool, but that it should be further developed to become a complete web tool with practical guidelines that companies may use to measure and improve their maturity in terms of resilience.

For the statements related to vulnerabilities and capabilities, ratings are conducted by a 5-point Likert scale ranging from Strongly disagree (1) to Strongly agree (5). The severity of global risks is assessed by a 5-point Likert scale ranging from Low severity (1) to High severity (5). In addition, the alternative Do not know was included. Ratings of the importance of vulnerabilities and capabilities are conducted by a three-level scale, Critical, Important and Minor importance, also with the alternative Not relevant/Don't know.

Regarding the enabling digital technologies, respondents are asked to rate (the same scale 1-5 of degree of agreement as for vulnerabilities and capabilities) the use of advanced digital technologies to enable or enhance the company's preparedness to withstand vulnerabilities (factors 1-7), as well as to enable or enhance capabilities (factors 1-15). Also, respondents are asked to specify the type of technology (technology types 1-13) for each statement that is marked (strongly) agree (rate 4 or 5).

The RMA tool was first assessed among researchers at SINTEF before it was distributed by e-mail to three SMEs. The companies were selected due to their participation in ongoing research projects involving the development of manufacturing excellence in Europe, and their strong interest in the Industry 5.0 concept. Two of the companies manufacture agricultural equipment, with production facilities in Norway. Company A delivers products primarily to domestic customers, while the markets of Company B are outside Norway. The third company (Company C) is a recently established company in the renewable energy sector, with high export potential, planning to set up manufacturing facilities in Norway. All three companies are exposed to risks, experience vulnerabilities and are thus concerned with ensuring resilience in their operations and supply chains. The tool was sent to the main contact person of the research projects in respective company. All three companies filled out the tool and returned answers to all questions and parameters. The tool was filled out by one person at each company.

4. Examples of test results

This chapter presents a selection of results from assessing the RMA tool in the SMEs.

4.1 Company A

The results of the assessment of Company A regarding the vulnerabilities that currently challenge operations are shown in Figure 1 and results regarding to the severity of future global risks in Figure 2.

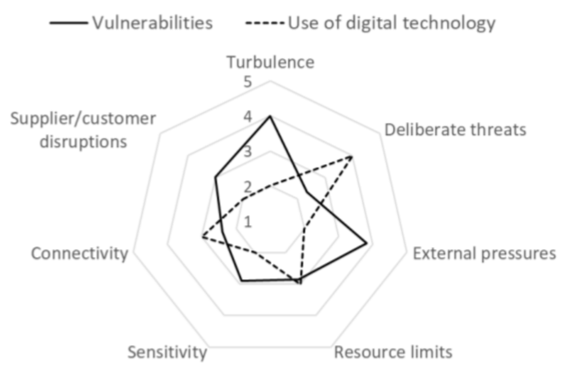


Figure 1: Vulnerabilities of Company A

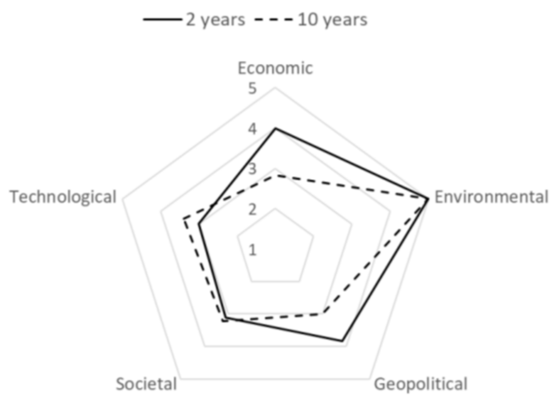


Figure 2: Severity of future global risks of Company A

Turbulence is the most challenging category, followed by external pressures (solid line, Figure 1). The use of advanced digital technology in the company to enable or enhance preparedness to withstand vulnerabilities seems to be low in general, except for the use of cyber physical systems that are used to withstand deliberate threats (dotted line, Figure 1). Turbulence and deliberate threats are critical. The company expects to be exposed to major environmental risks both on a short term (solid line, Figure 2) and long term (dotted line, Figure 2), as well as geopolitical and economic risks, especially in a short term. The company expects both economic and geopolitical risks to be reduced in the long-term.

Results regarding the rating of capabilities are shown in Figure 3.

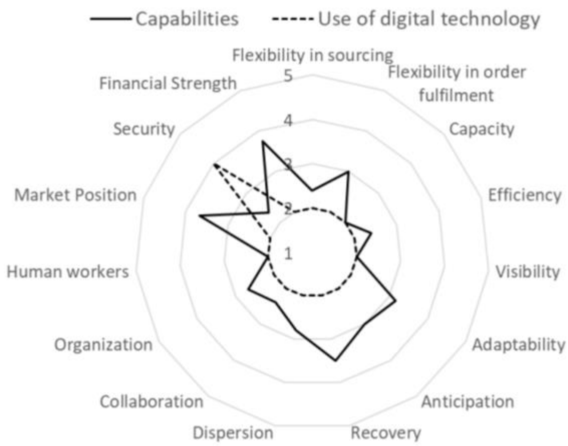


Figure 3: Capabilities of Company A

The capabilities with highest score are financial strength, market position, recovery and adaptability (solid line, Figure 3). However, most capabilities have low ratings indicating a weak resilience capability. Regarding the use of digital technology (dotted line, Figure 3), the score is low overall, except for security, where again cyber physical systems are used. Capacity is considered a critical capability.

4.2 Company B

Results of the assessment of Company B regarding the vulnerabilities that currently challenge operations and severity of future global risks are shown in Figure 4 and Figure 5.

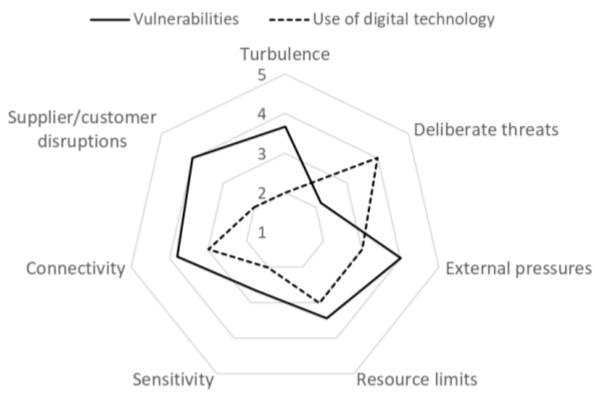


Figure 4: Vulnerabilities Company B

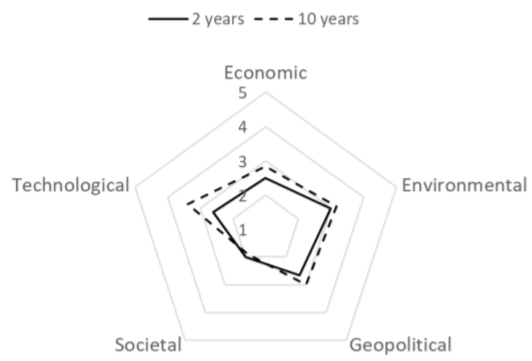


Figure 5: Severity of future global risks Company B

The categories supplier/customer disruptions and external pressures constitute the most challenging categories, followed by the connectivity category (solid line, Figure 4). The use of advanced digital technology to enable or enhance preparedness to withstand vulnerabilities seems to be low in general, except for the use of cybersecurity technology that is used to withstand deliberate threats (dotted line, Figure 4). None of the categories are critical to the company, and several categories are of minor importance. The company expects to be exposed to medium severe environmental risks on a short term (solid line, Figure 5) and long term, as well as increased geopolitical, economic and technological risks on a long term (dotted line, Figure 5). The company expects societal risks to be low, both on short and long-term. Results regarding the rating of capabilities are shown in Figure 6.

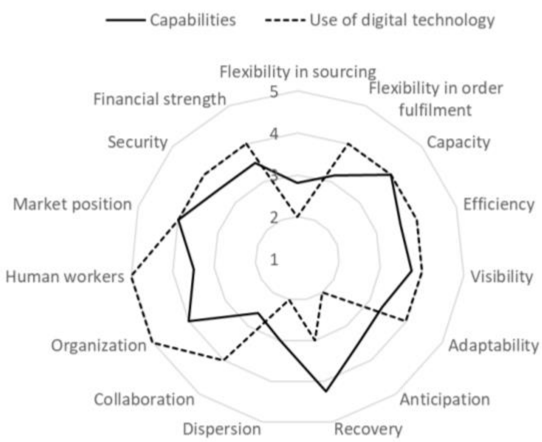


Figure 6: Capabilities Company B

The capabilities with highest score involve capacity, recovery, organization and market position (solid line, Figure 6). Most capabilities are scored between 3 and 4, which indicates a good general resilience capability. Regarding the use of digital technology, several capabilities are also enhanced by advanced technologies such as automation and collaborative robots, cyber-physical systems, and Internet of things (dotted line, Figure 6). Digital technologies are especially used to support the company's capabilities related to human workers and organization. Regarding the rating of importance, flexibility in sourcing, organization, human workers and market position are considered especially critical capabilities to the company.

4.3 Company C

The results of the assessment of Company C regarding vulnerabilities that currently challenge operations are shown in Figure 7 and results regarding severity of future global risks in Figure 8.

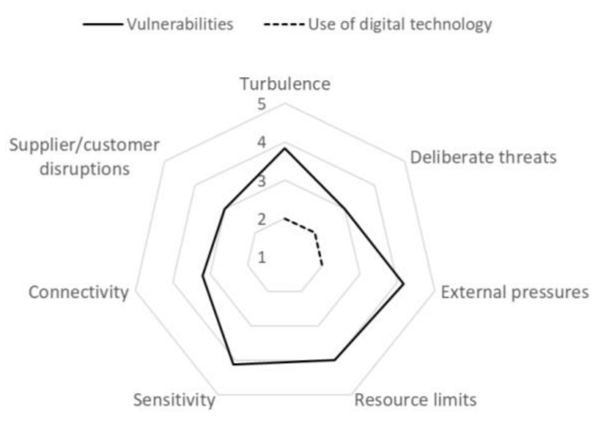


Figure 7: Vulnerabilities Company C

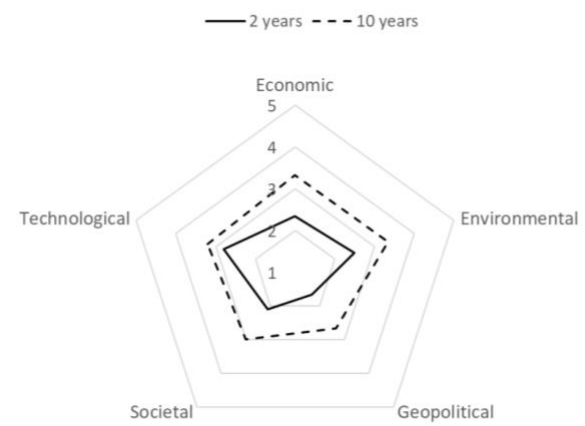


Figure 8: Severity of future global risks Company C

The categories external pressures, resource limits, and sensitivity are the most challenging, followed by turbulence (solid line, Figure 7). The company does not use advanced digital technology to enhance preparedness to withstand vulnerabilities (dotted line, Figure 7). None of the vulnerability categories are critical. Regarding the severity of future global risks, the company expects to be exposed to an overall insignificant risk on a short term (solid line, Figure 8). On a long term (dotted line, Figure 8), risks are expected to increase, especially economic, environmental and technological risks. Geopolitical risks are low on short and long term. The ratings of capabilities are shown in Figure 9.

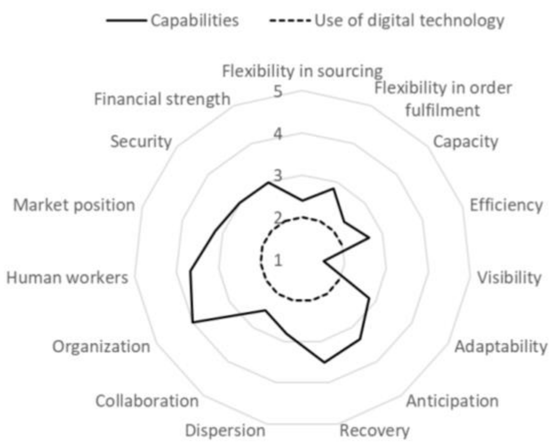


Figure 9: Capabilities of Company C

Capabilities related to flexibility in sourcing and flexibility in order fulfilment considered critical. However, capabilities related to organization, human workers and recovery have the highest score (solid line, Figure 9). The company does not use digital technology to enhance its resilience capabilities (dotted line, Figure 9).

4.4 Summary of test results

The results of the RMA tool tests in the three companies are summarised in Table 2.

Table 2: Summary of test results (DT = use of digital technology)

Category	Item	Company A	Company B	Company C
Vulnera-bilities	Ave. score	3,05	3,25	3,73
	Ave. score DT	2,57	2,71	2,00
	Critical categories	Turbulence, deliberate threats	-	-
	Categories highest score	Turbulence, external pressures	External pressures, supplier/ customer disruptions, connectivity	External pressures, resource limits, sensitivity

Global risks	Categories high severity 2 years	Economic, environmental, geopolitical	-	-
	Categories high severity 10 years	Environmental, technological	Technological, environmental	Economic, environmental, technological
Capa-bilities	Ave. score	2,73	3,48	2,91
	Ave. score DT	2,13	3,67	2,00
	Critical categories	Capacity	Flexibility in sourcing, organization, human workers, market position	Flexibility in sourcing, flexibility in order fulfilment
	Categories highest score	Financial strength, market position, recovery, adaptability	Capacity, recovery, organization, market position	Organization, human workers, recovery

5. Discussion and conclusion

The test of the RMA tool shows how it may be used to measure vulnerabilities, analyse current and expected future challenges and risks and assess resilience capabilities and the use of digital technology to build resilience and preparedness to deal with vulnerabilities and risks. Such tools are important to create a resilient European industry in line with Industry 5.0. While previous approaches are conceptual or concerned with traditional views of supply chain resilience only, the RMA tool extends the resilience concept by including elements from Industry 5.0, reflecting human centricity, sustainability and digital technology.

By conducting tests in three companies, the tool can be used to identify key areas of improvement for companies that seek to enhance resilience. It is expected that resilience is a key issue for many European companies, proposing that many companies may find the tool useful. The tool is primarily developed to provide support to manufacturing SMEs that typically have scarce resources and limited expertise available to conduct such assessments. The tool may also be further developed and adapted to specific settings of various manufacturing sectors. Variants of the tool can be developed, for example based on prioritization and selection of critical items or for specific industries.

The tool is intended to help companies identifying critical aspects for building resilience in their supply chains. It presents a set of criteria for assessment of a company perspective and should be used for developing capabilities by identifying the current situation (AS IS) and analysing improvement areas in view of a wanted future state (TO BE). Even though the tool is primarily developed to support individual companies, it can serve as a starting point for the development of more comprehensive maturity surveys including a larger sample of companies in manufacturing or in specific segments within the manufacturing sector. Also, further research is needed to better understand company specific circumstances explaining maturity results. This can be done by conducting multiple case studies, where test results can be compared, and similarities and differences can be explained. Such insight may constitute valuable input to the development of industry or sector specific RMA tools.

This paper presents a first version of the RMA tool and results of a first test round in three companies. A limitation of the tool at this stage is that it is based on few literature sources. A thorough literature review is thus needed to ensure that the new tool version includes a wider range of literature. Results of this first round of tests can be discussed in the companies to get better insights to underlying contextual factors and feedback on improvements. To ensure validity, the tool can be tested in companies representing a variety of industries.

Acknowledgements

This research is part of an innovation project that is partly funded by the Research Council of Norway. We are grateful for the feedback from the anonymous reviewers that have helped to improve the paper.

References

[1] European Commission, Directorate-General for Research and Innovation, Renda, A., Schwaag Serger, S., Tataj, D., Morlet, A., Isaksson, D., Martins, F., Mir Roca, M., Hidalgo, C., Huang, A., Dixson-Declève, S., Balland, P.,

Bria, F., Charveriat, C., Dunlop, K., and Giovannini, E., 2022. Industry 5.0, a Transformative Vision for Europe: Governing Systemic Transformations towards a Sustainable Industry. Publications Office of the European Union.

[2] Xu, X., Lu, Y., Vogel-Heuser, B., and Wang, L., 2021. Industry 4.0 and Industry 5.0—Inception, Conception and Perception. Journal of Manufacturing Systems, 61, pp. 530–535.

[3] Muench, S., Stoermer, E., Jensen, K., Asikainen, T., Salvi, M., and Scapolo, F., 2022. Towards a Green & Digital Future. JRC Publications Repository [Online]. Available: https://publications.jrc.ec.europa.eu/repository/handle/JRC129319. [Accessed: 22-Jun-2023].

[4] Sony, M., and Naik, S., 2019. Key Ingredients for Evaluating Industry 4.0 Readiness for Organizations: A Literature Review. Benchmarking: An International Journal.

[5] Felch, V., Asdecker, B., and Sucky, E., 2019. Maturity Models in the Age of Industry 4.0 - Do the Available Models Correspond to the Needs of Business Practice? In Proceedings of the 52nd Annual Hawaii International Conference on System Sciences (HICSS), pp. 5165-5174.

[6] Mittal, S., Khan, M. A., Romero, D., and Wuest, T., 2018. A Critical Review of Smart Manufacturing & Industry 4.0 Maturity Models: Implications for Small and Medium-Sized Enterprises (SMEs). Journal of manufacturing systems, 49, pp. 194–214.

[7] Schumacher, A., Erol, S., and Sihn, W., 2016. A Maturity Model for Assessing Industry 4.0 Readiness and Maturity of Manufacturing Enterprises. Procedia CIRP, 52, pp. 161–166.

[8] Hein-Pensel, F., Winkler, H., Brückner, A., Wölke, M., Jabs, I., Mayan, I. J., Kirschenbaum, A., Friedrich, J., and Zinke-Wehlmann, C., 2023. Maturity Assessment for Industry 5.0: A Review of Existing Maturity Models. Journal of Manufacturing Systems, 66, pp. 200–210.

[9] Mittal, S., Romero, D., and Wuest, T., 2018. Towards a Smart Manufacturing Maturity Model for SMEs (SM3E). Advances in Production Management Systems. Smart Manufacturing for Industry 4.0, I. Moon, G.M. Lee, J. Park, D. Kiritsis, and G. von Cieminski, eds., Springer International Publishing, Cham, pp. 155–163.

[10] Tukamuhabwa, B. R., Stevenson, M., Busby, J., and Zorzini, M., 2015. Supply Chain Resilience: Definition, Review and Theoretical Foundations for Further Study. International Journal of Production Research, 53(18), pp. 5592–5623.

[11] Pettit, T. J., Fiksel, J., and Croxton, K. L., 2010. Ensuring Supply Chain Resilience: Development of a Conceptual Framework. Journal of business logistics, 31(1), pp. 1–21.

[12] WEF, 2023, Global Risks Report 2023, 18th edition, World Economic Forum.

[13] Romero, D., and Stahre, J., 2021. Towards The Resilient Operator 5.0: The Future of Work in Smart Resilient Manufacturing Systems. Procedia CIRP, 104, pp. 1089–1094.

[14] Pacchini, A. P. T., Lucato, W. C., Facchini, F., and Mummolo, G., 2019. The Degree of Readiness for the Implementation of Industry 4.0. Computers in Industry, 113.

[15] Maddikunta, P. K. R., Pham, Q.-V., B, P., Deepa, N., Dev, K., Gadekallu, T. R., Ruby, R., and Liyanage, M., 2022. Industry 5.0: A Survey on Enabling Technologies and Potential Applications. Journal of Industrial Information Integration, 26.

[16] Thomé, A. M. T., Scavarda, L. F., and Scavarda, A. J., 2016. Conducting Systematic Literature Review in Operations Management. Production Planning & Control, 27(5), pp. 408–420.

[17] Brocke, J. vom, Simons, A., Niehaves, B., Niehaves, B., Reimer, K., Plattfaut, R., and Cleven, A., 2009. Reconstructing the Giant: On the Importance of Rigour in Documenting the Literature Search Process.

[18] Pettit, T. J., Croxton, K. L., and Fiksel, J., 2013. Ensuring Supply Chain Resilience: Development and Implementation of an Assessment Tool. Journal of business logistics, 34(1), pp. 46–76.

[19] Cheng, Y., Elsayed, E. A., and Huang, Z., 2022. Systems Resilience Assessments: A Review, Framework and Metrics. International Journal of Production Research, 60(2), pp. 595–622.

[20] Bhamra, R., Dani, S., and Burnard, K., 2011. Resilience: The Concept, a Literature Review and Future Directions. International Journal of Production Research, 49(18), pp. 5375–5393.

Biography

Maria Thomassen is a senior research scientist at SINTEF Digital, Norway, with experience from applied research projects in research fields including operations and production management, logistics and supply chain management, involving industry collaboration. Thomassen holds a PhD in production management and control from the Norwegian University of Science and Technology in Trondheim.

Bjørnar Henriksen is a senior research scientist at SINTEF Digital, Norway. He is an experienced applied research scientist within manufacturing strategy, process improvement, DFX and digitalisation. Henriksen holds a PhD in operations management from the Norwegian University of Science and Technology in Trondheim.

CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
CPSL 2023-2

5th Conference on Production Systems and Logistics

Demand Forecast Model and Route Optimization to Improve the Supply of an SME in the Bakery Sector

Emory Pablo Bazan Flores[1], Candice Maria Fe Gamarra Villanueva[1],
José Antonio Taquía Gutiérrez[1], Yvan Jesus Garcia Lopez[1*]
[1]*Facultad de Ingeniería, Carrera de Ingeniería Industrial, Universidad de Lima, Perú.*
**Corresponding Author: ygarcia@ulima.edu.pe*

Abstract

This research employs the Lean Six Sigma DMAIC methodology to address enhancing product distribution efficiency in a bakery chain. Following the diagnostic phase, demand forecasting models were developed using ARIMA and Holt Winter methods, with ARIMA demonstrating higher prediction accuracy. Furthermore, route mapping was conducted using the Clark-Wright algorithm. Key performance indicators (KPIs) such as delivery time, distance traveled, and MAPE (Mean Absolute Percentage Error) will be established for process control. Implementing these improvements aims to achieve more efficient product distribution management within the bakery chain.

Keywords

Supply Management Improvement, Demand Forecasting, Clark-Wright, Route Optimization, ARIMA

1. Introduction

In recent years, the implementation of Industry 4.0 has transformed and improved the connection systems between different entities. The digital transformation of the supply chain arises to communicate and coordinate situations in real time to increase the organization's competencies. These technological advances have a positive impact on the economy of organizations since the management of the supply chain is optimized, and demand has exponential growth due to globalization [1]. At the same time, supply chains have developed with greater complexity among their processes, which now consider the diversification of their portfolios, customer preferences, internal demand situations, multiple collaborations of suppliers, different geographical areas to be served, and a variety of intermediaries [2]. Interruptions in the distribution processes of SMEs happen very often, often due to a lack of production control according to the most inefficient and traditional supply method: supply to order. Since this strategy is not standardized, it is very likely to incur a production error, which generates unnecessary costs [1].

Having good transportation logistics and final delivery of finished products generates great value in the customer experience; however, this can be affected by high transportation costs such as gasoline. In 2022, gas prices have become 28% more expensive in Peru [3]. On the other hand, if you do not have good routing, this can delay established delivery times. In Peru, the increase in cars has a continuously growing trend of 6.49% yearly [4].

For the most part, small and medium-sized enterprises (SMEs) usually try to satisfy specific and focused needs of society and industry, which is why their distribution systems are generally based on small quantities, exact frequencies to supply their customers, and unique transport conditions. Considering those markets in

DOI: https://doi.org/10.15488/15321
ISSN: 2701-6277
publish-Ing.

which SMEs supply and their billing levels, they limit their investment in the necessary resources to plan and keep distribution activities under control; the situation is repeated if we talk about their levels of innovation, which directly affects their competitiveness and profitability in the long term [5].

Ensuring the availability of a product by satisfying consumer demand in a set period has proven to be a competitive advantage for retail chains. However, the inefficiency in the programming of routes of the distribution center vehicles causes delays in deliveries and many times culminates in shortages, so optimizing routes in the product distribution process can be considered a fundamental factor in customer demand satisfaction [6]. In addition, the planning of delivery routes through traditional methods needs to be improved since they only focus on reducing transportation costs between two locations. Therefore, Tsang includes in his investigation other factors such as food quality, arrival time windows, and even incidents or violations of driving requirements during delivery [7].

For all these reasons, the purpose of this research is the joint application of the projection of the demand of an SME in the bakery sector through triple exponential smoothing (Holt-Winters) and the Arima model and the optimization of routes for optimal replenishment. of their stores.

2. State of art

2.1 Forecast Models

The demand forecast is independent of the sector where you want to apply. It is an essential component for good management of your resources. It can be used in any industry that has a demand. We have Time series, regression, and machine learning models among the main demand forecast models [8]. Within the time series models, we have the ARIMA Model and Exponential Smoothing [8]. The ARIMA model is a derivative of the ARMA model, a moving average autoregressive model used to understand and predict future points in a time series, and the integration variable is added [8]. On the other hand, the Exponential Smoothing method is a more focused method for data with seasonal trends [8].

Among the most used techniques for demand forecasting is the Monte-Carlo Method, which consists of generating random events through sampling and thus calculating the probability of an event occurring. The value "0" is assigned to the event that did not happen, and the value "1" to the event that does occur. Finally, the accumulated frequencies are recorded; the more significant the simulation, the there is the probability that the event will occur. In 2021, Cui et al. applied the Monte-Carlo Method to estimate the required demand for the replacement of aircraft parts subject to different guarantees, correctly achieving control and planned replacement of inventories [9].

2.2 Impact of the application of demand forecast models in perishable products

Each demand projection model has its particularities. For a demand for baked goods in a supermarket, the ARIMAX model was applied, combining the ARIMA model with exogenous variables; they are not related to the time series but can influence the prediction [10]. For this case, both methods were compared, surpassing ARIMAX in terms of MAPE, thereby achieving greater precision in predicting and detecting replaceable items [10].

In another research for a German bakery that makes bread, they benchmarked their performance using various forecasting models, including S-Naïve, S-Mean, S-Median, ETS, and LSTM. The evaluation was based on several indicators: the target service level, fill rate, surplus rate, and loss. The results revealed that the LSTM model consistently showed higher precision than the other models. A significant difference was also observed between the ETS model and the baseline methods. Furthermore, it was concluded that operational performance is closely related to the accuracy of the forecasts provided. In summary, the results highlighted the superior performance of the LSTM model and its positive impact on the quality of operational decision-making [11].

2.3 Programming models for the optimization of distribution routes

Vehicle Routing Problems (VRPs) maintain simple structures, so they often appear to be basic optimization problems through discrete combinatorics. In the real world, the practicality of VRPs is significant, which is why they are used to validate the optimization performance of different algorithms, which ultimately helps develop efficient algorithms (Li et al., 2022). On the other hand, other authors mention that the VRP is naturally a complicated problem, and its modeling demands a statistical analysis of the speed and congestion of vehicles on different routes. In addition, travel time measurement strategies are fundamental and consist of several aspects, including simple, discrete, continuous, and stochastic [12].

In the study by Lugo, an algorithm model was used in a real case for the distribution of beauty products in 2 areas of Metropolitan Lima. This study used models such as Savings Algorithms, Petal Algorithms, and Insertion Algorithms. Managing to reduce 10.90 km of travel on the newly designed route and S/196.20 per year in each district [13].

The research carried out in previous years about product distribution management indicates that it is required to transport perishable foods through a refrigeration system. Therefore, an infrastructure suitable for long-term trips is required. Added to this is the importance of accelerating the distribution process to maximize the useful life of the products and not impair their quality and freshness. This situation can be achieved through adequate temperature control and the application of IoT technology for optimal route selection [14].

On the other hand, it highlights that the route optimization models that are given through IoT not only reduce the distribution and transportation time but also lead to a reduction in costs and an increase in the level of satisfaction for the client part [15]. His research tested the model's validity for optimizing vehicular routes through simulation, starting from a distribution center to 15 different customer destinations.

3. Methodology

The Lean Six Sigma DMAIC methodology will be employed to manage this project in Table 1. This methodology will assist us in identifying the root causes of the case study. Throughout each phase of the DMAIC process, we will gather crucial information essential for developing the proposed solutions.

Table 1: **Project Phases**

Project Phases	Tools
Define	Data Analysis
Measure	Pareto Analysis
Analyse	Ishikawa Diagram
Improve	Demand Forecasting Models and Route Distribution Model
Control	KPIS

a. Define

As a case study, we will focus on small and medium-sized enterprises (SMEs) in the food sector. This SME operates a chain of bakeries and has established itself as one of the leading traditional bakeries in the northern area of Lima and Callao. Their value proposition is based on improving the quality of their products and services and continuously innovating their facilities to meet the needs of their customers.

Currently, the distribution center and manufacturing plant are located at the Covida premises, and they have nine stores (8 legal entities) that sell their products. The process that will be improved within the bakery is product distribution to the branches. This process involves forecasting the demand, confirming the orders, and having the store managers sign an acknowledgment stating the reception of the products.

Objective: To improve the efficiency of product distribution to the stores, reducing transportation costs and ensuring that products arrive fresh and in line with the projected demand.

b. Measure

A virtual interview was conducted with the current engineer who supervises the factory at Covida SME. The interview aimed to gather general information about the distribution process and identify the main problems. The interview lasted for 1 hour, and the following data was collected regarding the initial situation:

- Average time spent on product dispatch: 1 hour and 30 minutes.
- Departure times from the factory to the stores: 10 am and 3:30 pm.
- Distribution cycle time to stores: 3 hours per vehicle.
- Number of transports: 2 non-refrigerated cars and one refrigerated car.
- Maximum number of stores per transport: 3.
- Monthly fuel expenses: No information available.
- Shifts per day: 2.
- Days per week: 7.
- Quantity of products to distribute: an average of 620.
- Quantity of containers to distribute: an average of 260.
- Staff: 3 Drivers,2 Dispatchers., 3 Product packing and sorting, 1 Supervisor

Additionally, a visit was scheduled for Saturday, November 19, 2022, during which evidence was collected from the SME's dispatch areas and shipping vehicles, Table 2.

Table 2: **Distribution Locations of the Company under Study**

Business Name	Locations	Address
Industria Alimentaria D'Julia S.A.C.	Vivanco	Av. General Manuel Vivanco N°400 - Pueblo Libre
Inversiones Tipequi E.I.R.L.	Megaplaza	Av. Alfredo Mendiola N°3698, Interior M4 - Independencia
Inversiones Maricela Peralta E.I.R.L.	Centro Cívico	Av. Inca Garcilazo de la Vega N°1337 Int. 1102 - Cercado de Lima
Inversiones Yuri Peralta E.I.R.L.	Covida	Urb. Covida Av. Antúnez de Mayolo N°1223 - Los Olivos
Maricela Peralta E.I.R.L.	Covida Snack	Urb. Covida Av. Antúnez de Mayolo N°1217 - Los Olivos
Maricela Peralta Quintanilla	Sucre	Jr. Cusco 400 - Magdalena del Mar
Inversiones Cariza E.I.R.L	Bolívar	Av. Simón Bolivar N°1097 - Pueblo Libre
Ysmael Peralta Quintanilla	Palmera	Av. Carlos A. Izaguirre N°948 - Urb. Las Palmeras - Los Olivos

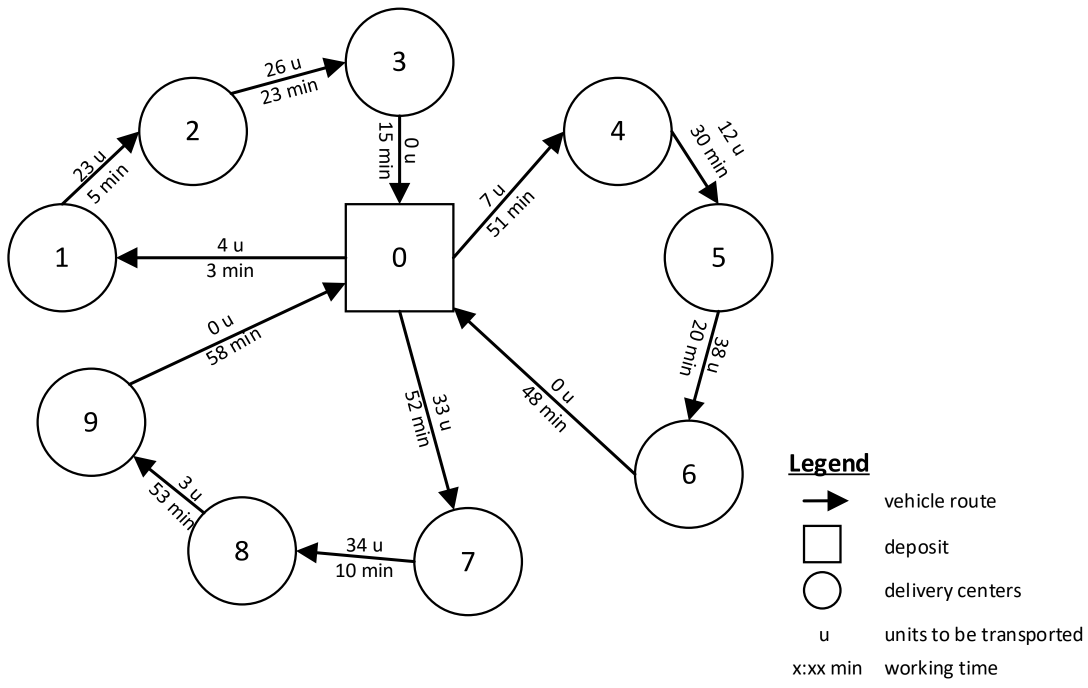


Figure 1: Initial Routing Diagram of 1 vehicle

c. Analyse

A Pareto diagram in Figure 2 y Table 3 will be developed to identify the main problems in the product distribution process based on the drivers' interviews, visits, and tracking of distribution trips over 30 days.

Table 3: **Problems Found in the Diagnosis**

Problems	Frequency	Percentage	Percentage Accumulated
Percentage Accumulated	14	82.4	82.4
Percentage Accumulated	2	11.8	94.1
Poor cargo organization	1	5.9	100

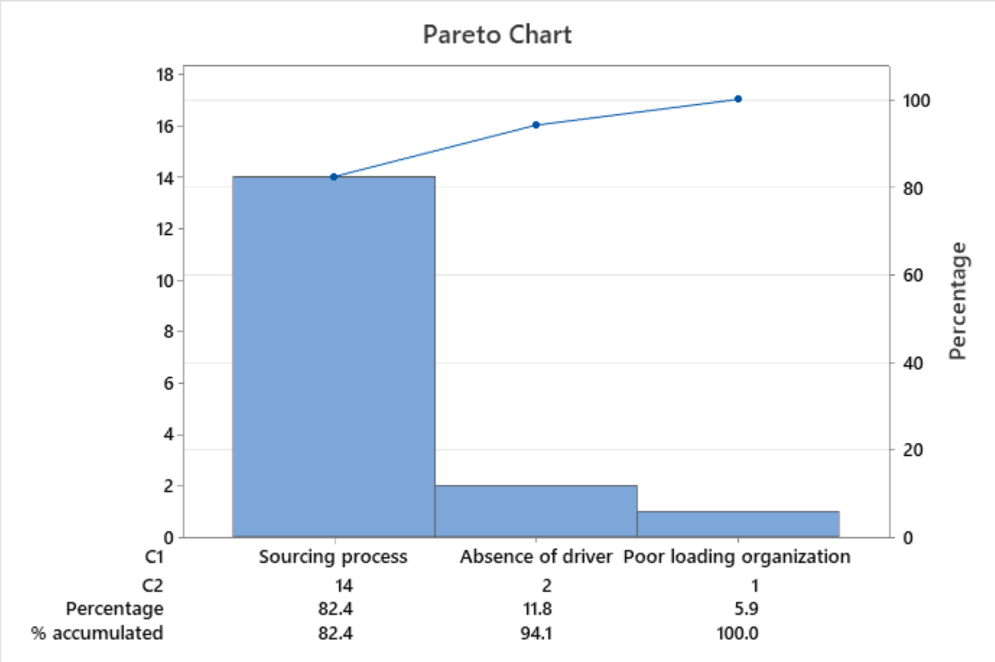


Figure 2: Pareto Chart

Considering the accumulated percentage of 94.1%, the main problems in the studied process are the delay in product delivery and driver absence.

Next, the Ishikawa diagram in Figure 3 will be developed for the main problem identified in the Pareto diagram to determine the root causes.

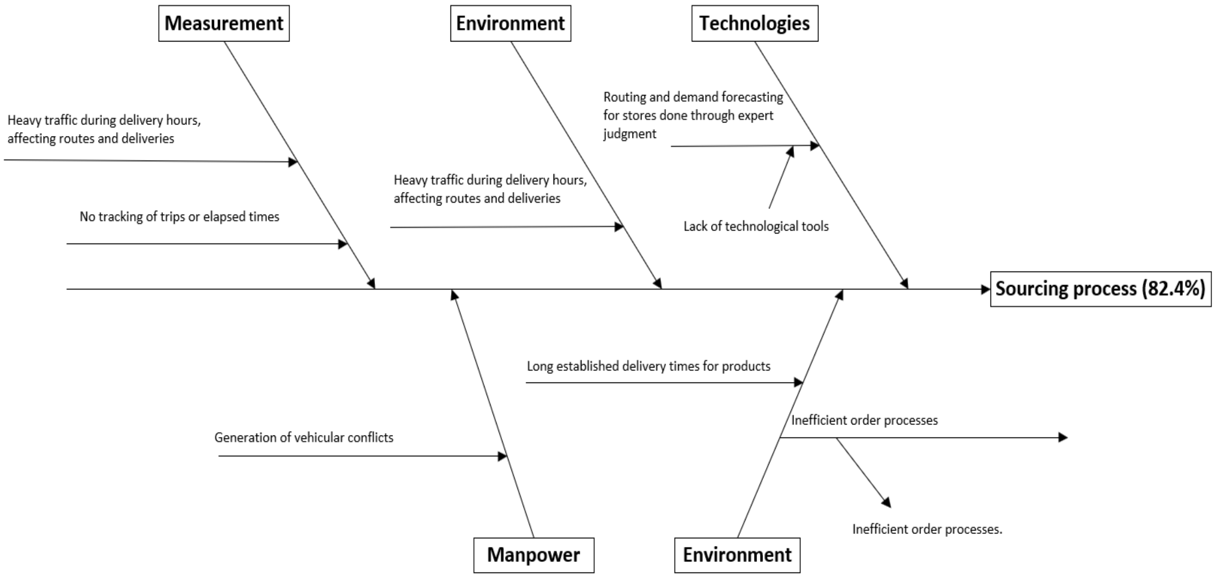


Figure 3: Ishikawa

d. Improve

To achieve better production management and have an accurate demand, we will compare two models:

• ARIMA (1)

• Holt Winter (2)

For both models mentioned, we will calculate the future values, compare the MAPE (Mean Absolute Percentage Error), and select the method with the lowest MAPE.

For both sets of data, the input will consist of 50 historical production values of the bakery's products, which will be evaluated using the equations of the two models.

$$I_t = \theta_1 * I_{t-1} + \theta *\in_{t-1} + \in_t \quad (1)$$

Where:

I_t : Integration variable differential

$\theta_1 * I_{t-1}$: Autoregressive term

$\theta *\in_{t-1}$: Autoregressive term

$\in_t$: Current error term

$$Y_{(t+h)} = L_{(t)} + h * T_{(t)} + S_{(t-l)} \quad (2)$$

Where:

$Y_{(t+h)}$: is the forecast for time t+h

$L_{(t)}$: is the level at time t

h: is the number of periods into the future.

$T_{(t)}$: is the trend at time t

$S_{(t-l)}$: is the seasonality factor from the previous period.

To optimize the delivery routes to the eight different stores, the Clarke and Wright (1964) logarithm for route optimization will be used:

$$S_{(ij)} = C_{(i0)} + C_{(j0)} - C_{(ij)} \quad (3)$$

Where:

$S_{(ij)}$: is the savings obtained by combining routes.

$C_{(i0)}$: is the cost of going from the depot to customer i.

$C_{(j0)}$: is the cost of going from the depot to customer i.

$C_{(ij)}$: is the cost of going from customer i to customer j.

e. Control

Carefully selected key performance indicators (KPIs) in Table 4 will be implemented to ensure efficient management. Two main KPIs used in this context are delivery time, distance traveled, and MAPE (Mean Absolute Percentage Error) for demand forecasting.

Table 4: **KPIs**

Indicator	Meaning	Formula	Objective
Delivery Time	The measure of the average time required to complete deliveries.	The sum of delivery times to each location/Total number of locations.	Reduce delivery time by 30%.
Distance Travelled	The measure of the average time required to complete deliveries.	The sum of kilometers traveled in a day.	Reduce distance traveled by 30%.
MAPE	The measure of the average absolute percentage difference	The sum of absolute percentage errors of all data points / Total number of data points.	Maintain MAPE below 50%.

4. Results

Regarding the demand forecasting model, the MAPE for two products in the store was analyzed for the two compared methods in Table 5. For product 1, the ARIMA method yielded a MAPE of 7.08%, indicating relatively high accuracy in the predictions. On the other hand, the Holt-Winters method obtained a MAPE of 9%, indicating slightly lower accuracy in the forecasts for this product. For product 2, the ARIMA method showed a MAPE of 23.9%, indicating moderate accuracy in the predictions. In comparison, the Holt-Winters method exhibited a MAPE of 35%, indicating lower accuracy in the forecasts for this specific product. Based on these results, the ARIMA method will forecast the demand for the products in the study.

Table 5: **Results of future values using the ARIMA method**

Day	Product 1	Product 2
1	1055	325
2	1042	325
3	1042	325
4	1042	325
5	1042	325

On the other hand, demand optimization. It yielded the optimal route with the Clark-Wright model in Figure 4. It achieved an average time of 5 hours and 19 min and a distance traveled of 59 km, which will be discussed in more detail in the discussion chapter.

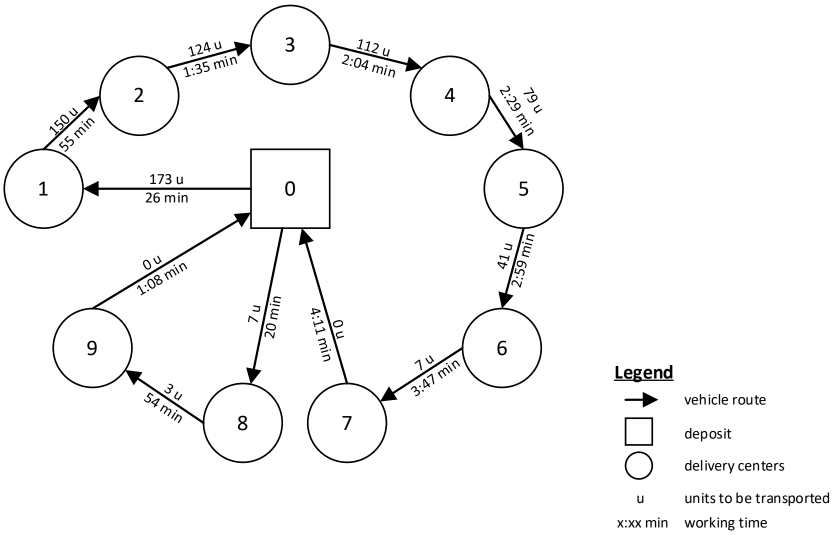


Figure 4: Finally Routing Diagram of 1 vehicle.

5. Discussion

The use of MAPE as an indicator of effectiveness is essential when forecasting and diagnosing future calculations; this statistic compares the results between 2 or more simulation models, granting the optimal result. This error indicator can also be interpreted as the amounts necessary to keep in the safety stock since it estimates the probability that the predicted value is far from the actual value; the lower its value, the more accurate the estimate is and, therefore, the required safety stock will be lower, and vice versa. Until now, the Holt-Winters and ARIMA models, among others, suggest and propose effective forecasts to project future values with different applications and consider additional criteria such as time series or seasonality. However, there is still no unanimous agreement that certifies that one is better than the other in general; it will always depend on the scenario in which it is applied.

On the other hand, the results obtained after the simulation using the Clark-Wright model are contrasted with the initial situation in Table 6.

Table 6: **Comparative table of situations**

	Initial situation	**Optimal situation**
Vehicles	Two without refrigeration 1 with refrigeration	One without refrigeration 1 with refrigeration
Times	3 vehicles x 3h = 9h	4h 11min + 1h 8min = 5h 19min
Distance	87.81 km	48.27km + 10.73km = 59km
Compliance to return before the 2nd shift (3:30 pm)	Each vehicle returns: V1 = 11:30 am V2 = 12:30 pm V3 = 12:53 pm	Each vehicle returns: V1 = 14:11 pm V2 = 11:08 am

As the ideal situation can be seen, it was possible to reduce the number of vehicles used in the initial situation; this would imply lower transportation and driver costs. It could even be used solely as a private vehicle for personalized deliveries, whose expense would be assumed by the consumer.

Regarding travel times, in the initial situation, a maximum of 3 hours was allocated to each vehicle since the route to be used was random and at the discretion of the distributors; unlike the optimal situation, the best option to distribute has been mapped products in up to 3 hours and 41 minutes. Likewise, it optimizes the conservation of the product since it remains in the vehicle for less time.

For the distances traveled factor, in the new situation, it was possible to reduce the distribution route by almost 30km; with this improvement, the level of destruction of the products increases since they would spend less time in motion, and therefore, the probability of accidents is minimized.

Finally, both situations meet the indicator of returning for the 2nd delivery turn, but this does not limit the optimal situation to not being implemented since it returns with more than one hour before starting the next turn.

References

[1] Yetkin, B., & Mullaoğlu, G. (n.d.). Optimization of Review Periods and (s, S) Levels of Floor Stock Items in a Paint Production Environment.

[2] Kumar Bhardwaj, A., Garg, A., & Gajpal, Y. (2021). Determinants of Blockchain Technology Adoption in Supply Chains by Small and Medium Enterprises (SMEs) in India. Mathematical Problems in Engineering, 2021. https://doi.org/10.1155/2021/5537395

[3] INFOBAE. (2022, junio 25). El costo del combustible se incrementaría desde el 1 de julio: ¿Qué alternativas hay? infobae. https://www.infobae.com/america/peru/2022/06/25/el-costo-del-combustible-se-incrementaria-desde-el-1-de-julio-que-alternativas-hay/

[4] Herrera. (s/f). SUNARP. Gob. Pe. Recuperado el 15 de julio de 2023, de https://www.sunarp.gob.pe/PRENSA/inicio/post/2020/01/08/sunarp-numero-de-autos-que-circulan-en-el-pais-acumula-una-decada-de-crecimiento-continuo

[5] Sepúlveda, J., Escobar, J. W., & Adarme-Jaimes, W. (2014). An algorithm for the routing problem with split deliveries and time windows (SDVRPTW) applied on retail SME distribution activities | Un algoritmo para el problema de ruteo de vehículos con entregas divididas y ventanas de tiempo (SDVRPTW) aplicado a las . DYNA (Colombia), 81(187), 223–231. https://doi.org/10.15446/dyna.v81n187.46104

[6] Rahman, M. A., Hossain, A.-A., Debnath, B., Zefat, Z. M., Morshed, M. S., & Adnan, Z. H. (2021). Intelligent Vehicle Scheduling and Routing for a Chain of Retail Stores: A Case Study of Dhaka, Bangladesh. Logistics, 5(3). https://doi.org/10.3390/logistics5030063

[7] Tsang, Y. P., Wu, C. H., Lam, H. Y., Choy, K. L., & Ho, G. T. S. (2021). Integrating the Internet of Things and multi-temperature delivery planning for perishable food E-commerce logistics: a model and application. International Journal of Production Research, 59(5), 1534–1556. https://doi.org/10.1080/00207543.2020.1841315

[8] Brockwell, P. J., & Springer, R. A. D. (2002). Introduction to Time Series and Forecasting, Second Edition.

[9] Cui, X., Ai, P., He, J., & Wang, S. (2021). The Research of Monte-Carlo Method for Aviation Materials Demand Forecast Based on the Life of the Reliability. Journal of Physics: Conference Series, 1838(1). https://doi.org/10.1088/1742-6596/1838/1/012009

[10] Huber, J., Gossmann, A., & Stuckenschmidt, H. (2017). Cluster-based hierarchical demand forecasting for perishable goods. Expert Systems with Applications, 76, 140–151. https://doi.org/10.1016/j.eswa.2017.01.022

[11] Huber, J., & Stuckenschmidt, H. (2021). Intraday shelf replenishment decision support for perishable goods. International Journal of Production Economics, 231. https://doi.org/10.1016/j.ijpe.2020.107828

[12] Asgharizadeh, E., Jooybar, S., Mahdiraji, H. A., & Garza-Reyes, J. A. (2022). A Novel Travel Time Estimation Model for Modeling a Green Time-Dependent Vehicle Routing Problem in Food Supply Chain. Sustainability (Switzerland), 14(14). https://doi.org/10.3390/su14148633

[13] Lugo Oré Jarol Jerens. (2012). Pontificia Universidad Católica Del Perú Facultad De Ciencias E Ingeniería. http://www.iadb.org/res/consultasanjose/files/summary_sp_esp/infrastructure_summary_esp.pdf

[14] Zuo, X., Cui, Z., Lin, H., & Wang, D. (2022). Route Optimization of Agricultural Product Distribution Based on Agricultural Iot and Neural Network from the Perspective of Fabric Blockchain. Wireless Communications and Mobile Computing, 2022. https://doi.org/10.1155/2022/5106215

[15] Yu, Q., Wang, Y., Jiang, X., Zhao, B., Zhang, X., Wang, X., & Liu, Q. (2021). Optimization of Vehicle Transportation Route Based on IoT. Mathematical Problems in Engineering, 2021. https://doi.org/10.1155/2021/1312058

Bibliography

Emory Pablo Bazan Flores is a candidate to receive the title of industrial engineer from the Faculty of Engineering and Architecture of the University of Lima, Lima, Peru.

Candice Maria Fe Gamarra Villanueva is a candidate to receive the title of industrial engineer from the Faculty of Engineering and Architecture of the University of Lima, Lima, Peru.

Yvan Jesus Garcia-Lopez is a Ph.D. (c) in Engineering and Environmental Science, UNALM, "Master of Business Administration" from Maastricht School of Management, Holland, and a "Master in Strategic Business Administration" from Pontificia Universidad Católica del Perú. "Master of Science" in Computer Science, Aerospace Technical Center - Technological Institute of Aeronautic, Brazil. Stage in Optimization of Processes and Technologies, University of Missouri-Rolla, USA, and Chemical Engineer from the National University of Callao. Specialization Study in Digital Transformation, by Massachusetts Institute of Technology, Business Analytics, Wharton School of Management; Data Science by the University of California, Berkeley; Big Data and Data Science by MITPro, USA Postgraduate Professor: Specialized Master in IT, MBA Centrum Católica, MBA from Calgary, Canada, and Centrum Católica. Ex-Vice Dean of Information Engineering of the Universidad del Pacífico, He has over 25 years of extensive experience managing investment projects, execution, and commissioning in Peru, Colombia, USA, Brazil, and China.

José Antonio Taquía is a Doctoral Researcher from Universidad Nacional Mayor de San Marcos and holds a Master of Science in Industrial Engineering from the University of Lima. He is a member of the School of Engineering and Architecture, teaching courses on quantitative methods, predictive analytics, and research methodology. He has vast experience in applied technology related to machine learning and industry 4.0 disrupting applications. In the private sector, he was part of several implementations of technical projects, including roles as an expert user and on the leading deployment side. He worked as a senior corporate demand planner emphasizing the statistical field for a multinational Peruvian company in the beauty and personal care industry with operations in Europe and Latin America. Mr. Taquía has a strong background in supply chain analytics and operations modelling applied to different industry sectors. He is also a member of the Scientific Research Institute at the Universidad de Lima, part of the exponential technology and circular economy groups. His main research interests are statistical learning, predictive analytics, and Industry 4.0.