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A Strategic AI Procedure Model For Implementing Artificial Intelligence

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Abstract

For most industries, Artificial Intelligence (AI) holds substantial potentials. In the last decades, the extent of data created worldwide is exponentially increasing, and this trend is likely to continue. However, despite the prospects, many companies are not yet using AI at all or not generating added value. Often, an AI project does not exceed its pilot phase and is not scaled up. The problems to create value from AI applications in companies are manifold, especially since AI itself is diverse and there is no 'one size fits all' approach. One often stated obstacle, why many AI projects fail, is a missing AI strategy. This leads to isolated solutions, which do not consider synergies, scalability and seldom result in added value for the company. To create a company-specific AI strategy with a top-down approach, a generic but holistic framework is needed. This paper proposes a strategic AI procedure model that enables companies to define a specific AI strategy for successfully implementing AI solutions. In addition, we demonstrate in this paper how we apply the introduced strategic AI procedure model on an AI-based flexible monitoring and regulation system for power distribution grid operators in the context of an ongoing research project.

Keywords

Artificial Intelligence; Strategy; Framework; Procedure Model; Digital Transformation

1. Introduction

For most companies, regardless of their industry or size, the utilization of Artificial Intelligence (AI) can generate meaningful value for companies [1–3]. Studies predict that AI will be responsible for a third of the German economic growth of the manufacturing industry [3]. Moreover, AI utilization will be necessary to keep pace with global competitors to defend its market position or extend it [4,5]. Thus, the added value that companies can achieve not only consists of a financial dimension but can also include others like competitiveness, better services for customers, or more sustainability. Within the next eight years, Germany's GDP is predicted to increase by 11.3% and its companies' productivity by 4.6% [6]. Within the next five years, a third of the growth is predicted to derive from AI applications [3]. Taking this into account, AI is an useful and necessary field of action for any company as the usage of AI is predicted to be essential to stay globally competitive and thrive economically [4,5]. Furthermore, studies indicate that AI derives meaningful value by increasing companies' revenue and reducing their costs [1]. Moreover, harnessing AI has additional objectives, such as resource deployment minimization, innovation, efficiency increase, and optimization of a company's offer [4].

In principle, companies are open to AI: 46% of German companies are concerned with the issue [4]. AI is perceived as relevant for all companies regardless of their industry and size [2].

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Despite the potentials, there are plenty of challenges and pitfalls that hinder the successful implementation of AI applications [4,2]. Although most companies expect new opportunities through AI, nearly half stated that significant investments did not yet add value [7,8]. There are many reasons why an investment in AI applications does not lead to the desired business gains and values. Companies often miss competencies and expertise within their ranks, and their recruitment. Trainings are also obstacles [9,1,4,2,10]. Furthermore, companies lack an AI or data infrastructure or invest in it without a clear understanding of applications and use cases, which leads to unfitting data governance data protection or data strategy [1,2].

Regarding the phrase ‘garbage in – garbage out’, data quality is an often-underestimated issue that leads to unsatisfying results [9,1]. Moreover, companies often develop isolated pilot solutions without linking the overall strategy if such a strategy exists and do not consider the solutions’ scalability [2]. Another obstacle is the missing collaboration across functions, partly due to the missing commitment of the top management and missing acceptance of both employees and customers [1,4,10]. In addition, high investment costs at the beginning, missing best practices, and data privacy and security hinder AI projects. The subject is highly complex – there is no ‘one size fits all’ solution [4]. For a successful AI application implementation, companies must bring together their technological, cultural, and political domain and prepare the right infrastructure with the right data and talents [2,8].

Some obstacles are not isolated but interrelated with other ones. For example, studies indicate that the lack of an AI strategy contributes to the failure of AI projects and strategic considerations to be vital for a successful implementation of AI [5,8]. Research has shown that a missing AI strategy is one reason for the failure of AI projects and that successful companies have one [9,11,1,4,5,15,16,8]. Furthermore, despite the intensification of research on AI in a business context, aggregated knowledge on this topic is limited, and managers are left with little academic support for implementing AI applications within their companies [8]. A holistic approach for AI implementation, based on an AI strategy, tackles many of the obstacles mentioned earlier and thus enhances the chance of successful value generation [9,11,12,2,13,7,14].

Due to a missing AI strategy, the technology is seldom incorporated into the organization and does not create value. This often leads to an isolated solution that cannot be scaled up comprehensively or solutions that do not fit into the company's strategic direction and contributes little towards company goals [5].

Having an AI strategy would, among others:

1. Improve a company’s situation by understanding whether the particular use case is linked to the overall objectives or their organization.
2. Estimate the use case’s added value.
3. Prevent projects to remain in the pilot phase by planning their scalability from the start.
4. Define requirements for an AI infrastructure for the entire company, which may plan to implement more than one use case.
5. Consider strategic topics, e.g., legal, privacy, security topics, from the beginning.
6. Ease the management and employees’ concerns by communicating the goals and showing them to achieve added value.

The research presented in this paper addresses the aforementioned issues by suggesting the application of a holistic, top-down AI strategic procedure model. In the following, we will present such a procedure model framework. It will enable companies to approach AI projects with a holistic concept, reducing the risk of an AI project failure and supporting its competitiveness and profit.

In the beginning, we will focus on the research gap concerning this subject. We will also define the term ‘corporate strategy’ that is used in the following. Thereupon, we present a framework for a holistic strategic AI procedure model. Afterward, we apply the suggested framework on an AI-based flexible monitoring and regulation system for power distribution grid operators. Finally, we take an outlook on developments to come.

2. Methodology

We based the development of the proposed AI strategy procedure framework on the method described afterward. First, we conducted extensive desk research to gather information on the current state of the art regarding available AI frameworks and procedure models. Following the collection, we compared the existing strategic AI frameworks and procedure models to gain important and successful factors that affect AI implementation. Using these insights, we derived a procedure considering the working aspects of existing solutions but specifically addressing identified shortcomings. To test the applicability and evaluate the framework, we applied it to a grid operator use case. Finally, to enhance the proposed procedure, we used the results and feedback to further develop the framework.

3. Research results

In the following we will present the results of our research.

3.1 Research gap for AI strategies

Studies show that companies that successfully use AI applications often have an AI strategy with a clear enterprise-level roadmap of use cases that aligns with the corporate strategy [1,16]. Although numerous publications in an industrial context state the need for a holistic AI strategy, there is little scientific research concerning this topic. This might be caused by AI technologies' diverse and non-uniform nature and the strong focus on technical research rather than business-strategic research. Thus, it is necessary to provide academic support for managers implementing AI applications in their companies to reduce the risk of project failure and unwanted results [8].

The strategy has to enable companies to make strategy-oriented AI decisions rather than opportunistic or tactical ones [15]. Moreover, it has to bring together the technological, political, and cultural domains, including data and security issues from the very beginning [17,8]. Unfortunately, research shows that such AI strategies cannot be uniform step-by-step manuals. They rather have to be a framework that allows companies to formulate individual strategies [7].

3.2 Corporate strategy & AI strategy

To be able to define an AI strategy, we first define a corporate strategy. According to Gleißner and Hungenberg, a corporate strategy consists of five components [18,19]:

1. Vision, mission, and long-term goals: A vision describes the long-term target state, which the corporation wants to achieve. Based on this, the mission substantiates three sub-aspects for the company's orientation, namely the field of activity, competence, and values of the company. Out of the mission, long-term company goals are conducted [19].
2. Core competence: The core competencies include those abilities of a company that is essential to operate successfully [18].
3. Business fields and competitive advantages: Business fields describe the field of activity in which a company operates. The market attractiveness and the competitive advantages are its properties as well as the target groups or customers. Out of the customers' needs, the company can deduct products and services [18].

4. Design of the value chain: The value chain is a business process in which value is progressively added to the product. Due to limited resources, the value chain must be designed based on core competencies and competitive advantages [18].
5. Strategic thrust: The strategic thrust consists of factors that may affect the corporation's value. There are three general directions as strategies' main variants: growth strategies, profitability-oriented strategies, and risk-oriented strategies [18].

We define the AI strategy as a subset of the corporate strategy. It comprises 'business fields and competitive advantages' and the 'design of the value chain'. This is due to the four fields of AI application. These are:

1. Internal optimization [20,21],
2. supplementing the existing business area [22],
3. new business areas [22], and
4. digital business models [20].

Except for the internal optimization, all application fields concern the corporate strategy's subfield business fields and competitive advantage. The internal optimization concerns the design of the value chain.

3.3 Applying a top-down-approach for the strategic AI procedure model framework

Several reasons speak in favor of using a top-down approach for an AI strategy. First, it enables coordination throughout the company, which prevents the isolation of AI use cases and promotes synergies [11]. In addition, the coordination of experiments, implementations, selection of AI technologies and vendors across the business prevents the duplication of effort, the usage of competing methods, and multiple vendors [23]. A top-down approach facilitates companies to include strategic goals and consequences into implementing AI projects' running or planned implementation [24–26,14]. Due to these reasons, we propose a top-down approach for the framework of the strategic AI procedure model presented later in this paper.

4. Description of the framework

The framework of the strategic AI procedure model consists of three levels along the top-down-approach as shown in figure 1:

- the corporate strategy level to set the target,
- the meta-level of archetypal AI use cases to mediate between the corporate strategy and AI infrastructure level,
- and the AI infrastructure level, including design fields.

The result is a defined roadmap with prioritized design fields for the implementation.

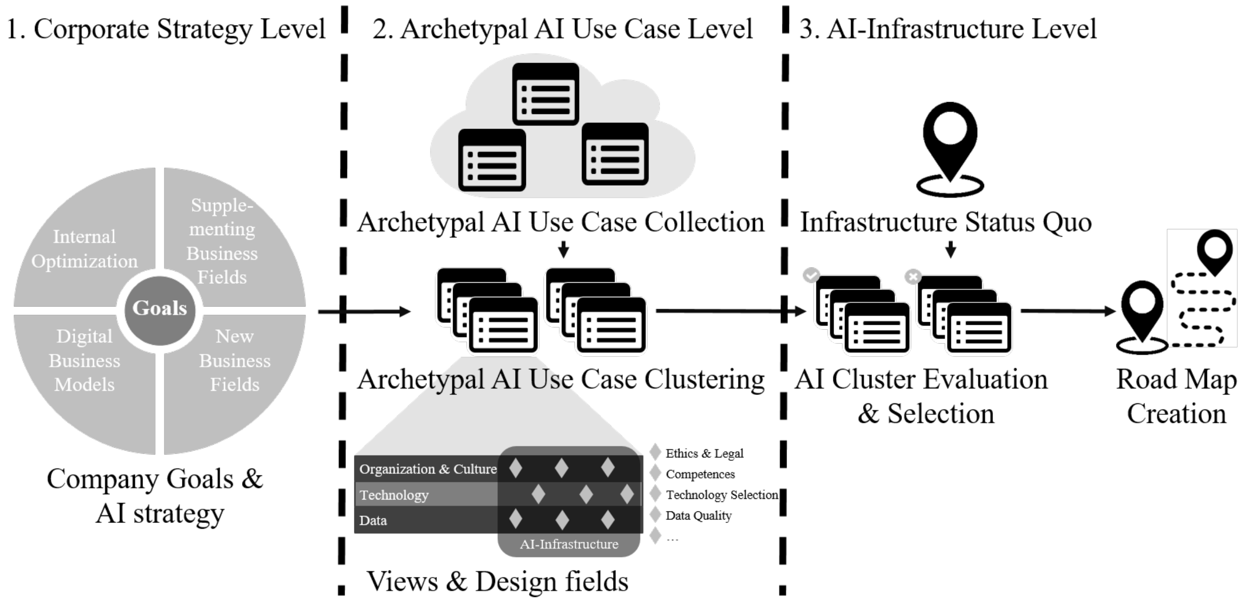

Figure 1: Framework of the strategic AI procedure model

4.1 Corporate strategy level:

Ransbotham et al. have shown that tying a strategy for AI to the company's overall strategy is essential [7]. As stated above, we define an AI strategy as a subset of a corporate strategy, as it comprises the design of the value chain and sometimes the design of the business fields. It follows and aims to realize the corporate goals.

The corporate strategy is a precondition. Based on the enterprise's mission and long-term goals, it provides a frame and extracts specific corporate goals for the AI strategy. The company should consider multiple questions: Which of its core competencies is affected, or does it have to elaborate on new ones? What is the thrust of the AI strategy (is it a growth strategy, profitability-oriented strategy, or risk-oriented strategy)? What is the AI approach, and does it affect business fields (internal optimization, supplementing existing business areas, new business areas, or digital business models)? The long-term goal of implementing AI applications must be pointed out clearly, and it has to fit into the overall corporate strategy.

4.2 Meta level: Archetypal AI Use case collection:

This level contains a collection of archetypal AI use cases. Due to technological progress and wide variety, the collection remains open for additions. This collection shall support identifying use cases under the aspects of identifying synergies with other use cases and technologies, planning scalability, preparing for selection, and supporting understanding of AI capabilities. Supporting this, each archetypal use case contains variables that are important for the selection process. In the following, we list a selection of key questions for several variables, which shall help to determine the relevant variables: *Type of AI:* What is the technology capable of? Does it assess, deduce, or react? Does it imitate human behavior or make rational decisions? *Value creation:* How does the use case create added value? How is it used? What are its limits? *Addressed problem*s: Which problems is it tackling? *Input:* What is the required information or data input? *Output:* What is the required information or data output? *Requirements:* What are its requirements on data (amount, quality), domain knowledge, resources, talents, hardware (sensors, GPU, etc.), infrastructure, etc.? *Interconnections:* Are there interconnections with other technologies or use cases, e.g., synergies, dependencies, exclusions, or redundancies? *Interpretability:* Can humans interpret the technology? Do they have to? *Time:* Are there time constraints? How long is the approximate computing time? How long is the approximate training time? *Capacity:* How much server capacity is needed? *Scalability:* Does the use case has to be scaled up? How do we ensure its scalability? *Models:* What models can be used for this use case?

Based on the company goals using the archetypal AI use case collection, use cases can be pre-selected. Important factors are the use cases AI infrastructure requirements, corporate strategy fit, scalability ability, and possible synergies with other use cases or technologies. The single pre-selected AI use cases can then be clustered according to their synergies, value, etc. For instance, an autonomous vehicle use case represents such an AI use case cluster, as it contains several computer vision and decision-making models.

4.3 AI-infrastructure level:

The infrastructure is essential for the success of implementing AI applications. To examine the future AI infrastructure thoroughly, we use three views proposed in the Aachen Digital-Architecture-Management: the **organization** expanded with **culture**, **technology**, and **data** [27]. The AI infrastructure can be divided into three views. For each view, we assign several design fields. A design field contains concrete steps, tasks, and methods to create a part of the AI infrastructure. Each design field belongs to a view, although some are comprehensive and cannot be assigned to only one view. Not necessarily all design fields must be addressed by each company; that depends on the existing infrastructure and the requirements of the to be introduced AI use cases. Examples for the design fields are *Ethics & Legal*, *Cybersecurity (comprehensive)*, *organizational structure*, *roles*, *data governance*, *sourcing & ecosystems (organizational)*, *identification of new technologies*, *platforms*, *user experience (technology)*, *data procurement*, *data storage*, *data processing*, and *data quality (data)*.

On the AI infrastructure level, we propose three steps. First, a status quo analysis needs to take place. It should include infrastructure, system, and data environment analysis. Second, the company should identify relevant design fields for the pre-selected AI use case clusters, specify and compare them to the current infrastructure to estimate the needed effort. Based on this, a value and cost analysis for all clusters is to be conducted. With this information, the company can select its AI applications. Third, the selected AI use case clusters design fields must be customized and prioritized. With the prioritization of all applicable design fields of the selected AI use case cluster, the company can now create a road map for the implementation.

5. Application of the Framework of the Strategic AI Procedure Model

Although the German power grid is one of the most stable grids in the world, measured by minutes of power outages per year, the current energy (higher share of renewable energies) and mobility (battery-powered electric vehicles) transitions and the resulting volatility in the power grid are predicted to harm the grid stability. Higher volatility leads to increased usage and thus wear of the grid components. If grid operators maintained their currently time-based maintenance procedures under these conditions, either increasing power outage times due to grid component-related faults (higher wear and tear) or higher costs due to additional personnel (adjusted maintenance cycles) would be expected. Therefore, grid operators are particularly interested in condition monitoring and predictive maintenance. Developing an AI-based approach for these particular challenges is part of the ongoing research project FLEMING. [28]

While the development of AI algorithms is a fundamental part of the FLEMING project, the project also aims at enabling grid operators to generate value by deploying AI applications. To ensure a strategic approach for implementing this project's solution and for further AI opportunities, the proposed AI strategy procedure framework comes in. We will illustrate this AI Strategy Framework application in this context for a German grid operator who currently has no AI-based solutions in place.

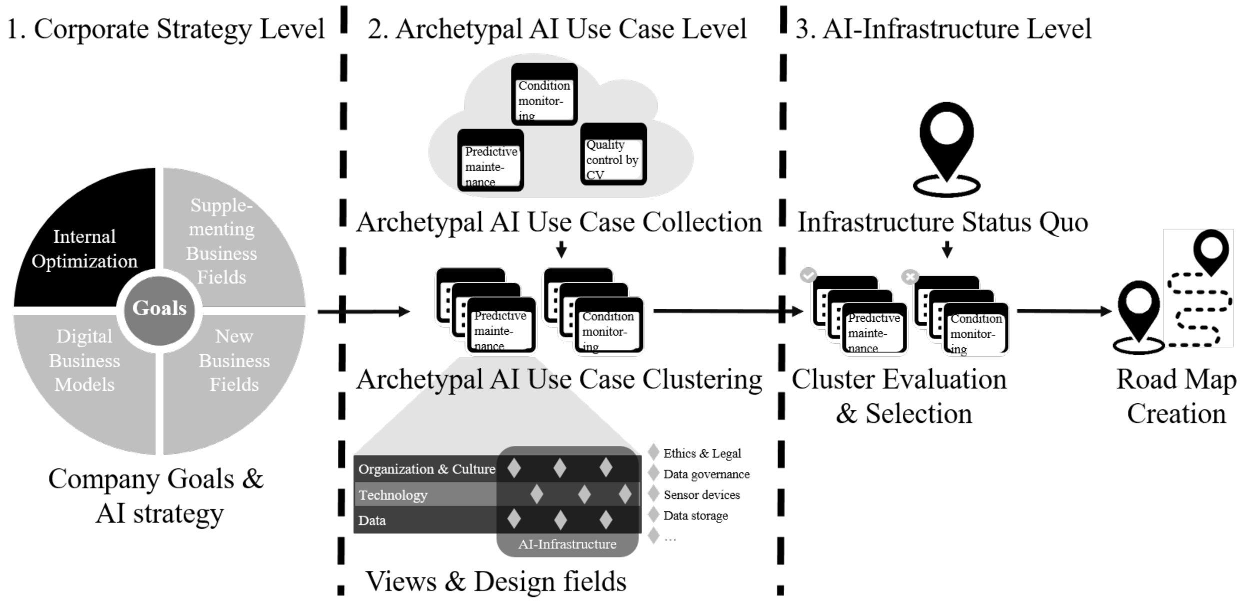

Figure 2: The Framework of the Strategic AI Procedure Model applied for a Grid Operator

As mentioned above, distribution grid operators have the strategic issue of maintaining their service quality, resulting in fewer power outages while being resource efficient. By using AI applications, they hope to strengthen their core competencies in the sense of efficient and reliable services. They focus on a profitability-oriented strategy, which does not negatively affect the corporate strategy. Thus, the AI approach is one of internal optimization. We then matched these company goals to the archetypal use case collection. For internal optimization, the collection proposes archetypal use cases as ‘predictive maintenance’, ‘condition monitoring’ or ‘quality control by computer vision’. These use cases can be considered by themselves or be clustered to a multiple-use case solution, considering their synergies, corporate strategy fit, and scalability ability. Since ‘quality control by computer vision’ does not support its goals, it is rejected.

In contrast, the first two use cases are pre-selected and, if applicable, specified (‘predictive maintenance for switchgears’). Each pre-selected archetypal use case cluster or single-use case contains comprehensive design fields and those connected to a view (organization & culture, technology, data), representing necessary elements of a holistic AI infrastructure. For the use case “predictive maintenance,” some relevant design fields could be, for example, *ethics & legal, cyber-security (comprehensive view), data governance, change management (organization & culture view), sensor-devices, platform infrastructure (technology view), data collection, storage*, and *quality (data view)*. They can be compared to the current infrastructure after conducting corresponding analyses. Moreover, the design fields can be specified and identified, which are necessary for the transformation or building of the novel AI infrastructure. For example, if the grid operator already has all the necessary sensors needed for “predictive maintenance” operating, there is no need to further stress this design field. In the following, the clusters can be evaluated regarding their value and costs, which leads to their selection.

At last, the selected cluster’s design fields are prioritized, and a roadmap for implementing it is developed. Since this approach is being developed in an ongoing research project, no validation exists at this time. However, the results from the research project will be examined and validated in more detail in subsequent publications.

6. Summary & Outlook

This paper briefly presents the opportunities and pitfalls of AI applications for the industry. We identified a missing AI strategy as a major obstacle to a successful AI implementation. To tackle this obstacle, we introduced a framework of a strategic AI procedure model and applied it to a grid operator in the context of an ongoing research project. The framework is the subject of further development. We will create a collection of archetypal use cases and elaborate on relevant factors of the AI use cases. Moreover, we will complete a list of the design fields as far as possible and specify each field. Finally, we desire further research for the selection process of AI use cases and their cost and value analysis.

7. Acknowledgements

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References

[1] Cam, A., Chui, M., Hall, B., 2019. Global AI Survey: AI proves its worth, but few scale impact, 11 pp.

[2] Hartmann, P., Liebl, A., Waldmann, A., Brakemeier, H., 2019. Applying AI: The elements of a comprehensive AI strategy, 14 pp.

[3] Seifert, I., Bürger, M., Wangler, L., Christmann-Budian, S., Rhode, M., Gabriel, P., Zinke, G., 2018. Potenziale künstlichen Intelligenz im produzierenden Gewerbe in Deutschland, 68 pp.

[4] Gentemann, L., Lange, B., 2020. Germany is Learning AI.: How Companies are Making Use of Digital Technologies, 39 pp.

[5] Heinz, S., 2020. The 6 key elements of an AI strategy.

[6] Kirschniak, C., 2018. Auswirkung und Nutzung von künstlicher Intelligenz in Deutschland, 18 pp.

[7] Ransbotham, S., Khodabandeh, S., Fehling, R., LaFountain, B., Kiron, D., 2019. Winning With AI: Pioneers Combine Strategy, Organizational Behavior, and Technology, 27 pp.

[8] Reim, W., Åström, J., Eriksson, O., 2020. Implementation of Artificial Intelligence (AI): A Roadmap for Business Model Innovation. AI 1 (2), 180–191.

[9] agiles Group, 2020. 3 reasons why many AI projects fail. https://agiles.com/en/blog-3-reasons-why-ai-projects-fail/. Accessed 7 June 2021.

[10] Sallaba, M., 2020. State of AI in the Enterprise: Ergebnisse der Befragung von 200 AI-Experten zu Künstlicher Intelligenz in deutschen Unternehmen, 24 pp.

[11] Boll-Westermann, S., Faisst, W., 2019. Neue Geschäftsmodelle mit Künstlicher Intelligenz: Zielbilder, Fallbeispiele und Gestaltungsoptionen, 76 pp.

[12] Caner, S., Bhatti, F., 2021. A Conceptual Framework on Defining Businesses Strategy for Artificial Intelligence.

[13] Kitsios, F., Kamariotou, M., 2021. Artificial Intelligence and Business Strategy towards Digital Transformation: A Research Agenda. Sustainability (4).

[14] Schoonhoven, J.J., Roelands, M., Brenna, F., 2019. Nach dem Hype: Was Führungskräfte über die erfolgreiche Implementierung künstlicher Intelligenz wissen müssen, 20 pp.

[15] Joshi, A., Wade, M., 2020. The Building Blocks of an AI Strategy: Organizations need to transition from opportunistic and tactical AI decision-making to a more strategic orientation. https://sloanreview.mit.edu/article/the-building-blocks-of-an-ai-strategy/.

[16] Kruhse-Lehtonen, U., Hofmann, D., 2020. How to Define and Execute Your Data and AI Strategy. Harvard Data Science Review.

[17] Leprince-Ringuet, D., 2020. AI for Business: What's going wrong, and how to get it right. Managing AI and ML in the enterprise 2020, 3–9.

[18] Gleißner, W., 2004. Future Value: 12 Module für eine strategische wertorientierte Unternehmensführung.

[19] Hungenberg, H., 2014. Strategisches Management in Unternehmen. Springer Fachmedien Wiesbaden, Wiesbaden, 605 pp.

[20] Gentsch, P., 2019. Künstliche Intelligenz für Sales, Marketing und Service: Mit AI und Bots zu einem Algorithmic Business – Konzepte und Best Practices, 2nd ed. Gabler Verlag.

[21] Gläß, R., 2018. Künstliche Intelligenz im Handel 1 – Überblick: Digitale Komplexität managen und Entscheidungen unterstützen, 1st ed. Springer Vieweg.

[22] Grell, A., 2019. Digitale Transformation bei einem technischen Dienstleister, in: Dahm, M., Thode, S. (Eds.), Strategie und Transformation im digitalen Zeitalter. Inspirationen für Management und Leadership, 1 ed. Springer Fachmedien, Wiesbaden, pp. 309–325.

[23] Ammanath, B., Hupfer, S., Jarvis, D., 2020. Thriving in the era of pervasive AI, 28 pp.

[24] Braadbaart, J., 2019. An illustrated guide to AI for the handsome corporate executive. Towards Data Science, May 17.

[25] Hofmann, P., Jöhnk, J., Protschky, D., Stähle, P., Urbach, N., Buck, C., 2020. KI-Anwendungsfälle zielgerichtet identifizieren. Wirtschaftsinformatik & Management 12, 184–193.

[26] Mazzei, C., Duffy, N., 2017. Putting artificial intelligence (AI) to work: Innovation mates: insights on the latest disruptive technologies.

[27] Hicking, J., Wenger, L., Abbas, M., Benning, J., Bremer, M., Clemens, F., Engländer, J., Heimes, P., Henke, L., Kaminski, L., Kremer, S., Niederau, M., Seelmann, V., Stroh, M.-F., Walter, T., 2020. Aachener Digital-Architecture-Management: Wegweiser zum digital vernetzten Unternehmen. FIR e.V. an der RWTH Aachen, Aachen, 32 pp.

[28] Hoffmann, M.W., Wildermuth, S., Gitzel, R., Boyaci, A., Gebhardt, J., Kaul, H., Amihai, I., Forg, B., Suriyah, M., Leibfried, T., Stich, V., Hicking, J., Bremer, M., Kaminski, L., Beverungen, D., zur Heiden, P., Tornede, T., 2020. Integration of Novel Sensors and Machine Learning for Predictive Maintenance in Medium Voltage Switchgear to Enable the Energy and Mobility Revolutions. Sensors (Basel, Switzerland) 20 (7).

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 supports companies in various industries in the design and implementation of the information logistics of business processes.

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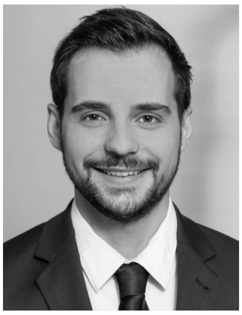

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Prof. Dr.-Ing. Volker Stich (*1954) has been head of the Institute for Industrial Management (FIR) at the RWTH Aachen University since 1997. Prof. Dr.-Ing. Volker Stich worked for 10 years for the St. Gobain-Automotive Group and led the management of European plant logistics. His research focuses on operations management, logistics and business applications systems.

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Life Cycle Oriented Planning Of Changeability In Factory Planning Under Uncertainty

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Abstract

Factory planning and factory operation collectively form a major part of the factory life cycle. The growing awareness of uncertainties throughout the factory life cycle is not only a consequence of recent events, but also the realization that factories are operating in an increasing turbulent environment. In factory planning, various sources of risk (e.g. location, process) can cause uncertainties due to deviations in the planning parameters (e.g. filling quantity load carrier) that affect the capacities to be dimensioned. During factory operation, sources of uncertainty (e.g. lead time, quality) expose the factory to numerous events that may disrupt their business process (e.g. machine failure). Despite these short-term and random risk events, factories are confronted with long-term change drivers (e.g. new product variants) in the course of their life cycle due to continuously rising requirements. Instead of responding reactively in case of uncertainty, it is much more appreciated to proactively prepare the factory for the uncertainties. It is the task of factory planning to gear up the factory for whatever uncertainties may occur over the factory life cycle. But the ability to change goes hand in hand with higher cost levels, either in the form of capital or operational expenditure depending on the type of changeability. Since there is a wide range of factory planning measures that allow the factory to be configured in different ways, factory operation must be considered in order to select a suitable factory type from life cycle perspective. Therefore, the goal of this paper is to integrate an approach in the sense of risk management within factory planning. Consistent factory types for coping with uncertainties are defined in order to present a way on how to position the factory in the area of tension between profitability and changeability.

Keywords

Factory Planning; Uncertainties; Changeability; Factory Life Cycle

1. Introduction

In the course of a turbulent environment, factories are confronted with various uncertainties [1]. Specifically, the manufacturing sector encounters internal and external change drivers arising from so-called megatrends [2], but also short-term and operational risks or disruptions [3]. The effects of the uncertainties are further intensified by the ever-increasing dynamics and synchronization of processes in the factory. Even minor incidents can have significant consequences for factory operations. [4] As part of factory planning, suitable measures must be taken in advance so that possible consequences can be reduced to a minimum in the course of the factory life cycle [5]. The goal is to eliminate or reduce the probability of occurrence. If the effects of uncertainty manifest themselves nevertheless, the factory must at least be able to reduce them quickly. Therefore, an approach must be integrated within factory planning in order to be able to assess the exposure to uncertainties and determine the required degree of changeability of the factory planning variants. The

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literature describes various forms of changeability that can mitigate both short-term and long-term uncertainties. In addition to the proven concepts of flexibility and transformability, resilient or robust factories, among others, are promoted in the wake of current events. A precise comparison of the terms has not taken place yet. Furthermore, factory planners are faced with the question of what level of uncertainty is to be expected over the factory life cycle and what level of changeability seems appropriate from an economic point of view. The goal of this paper is to provide a solid basis for managing uncertainties in the context of factory planning. Potential effects of uncertainties throughout the factory life cycle will be characterized and different concepts of changeability will be described as factory types. By linking different kinds of uncertainties to possible factory types, a first approach is given on how to position the factory in the field of tension between economic efficiency and changeability.

2. Basics and Need for Research

The factory as a socio-technical system is composed of both technical and social elements that have mutual interactions [6]. The factory and all its associated elements operate in a turbulent environment. In addition to the constantly emerging changes in this environment, internal changes also influence the factory and its elements [7]. This requires a wide variety of responses and adjustments at different times, which are usually planned, prepared and implemented as part of factory planning. In the literature, there are numerous definitions of the term factory planning, which have been combined in the VDI 5200 as a "systematic, objective-oriented process for planning a factory, structured into a sequence of phases, each of which is dependent on the preceding phase that extends from the setting of objectives to the start of production“ [8]. In addition to factory planning, the life cycle of a factory consists of realization, ramp-up, factory operation and shut down. The manufacturing of products takes place during factory operation using raw, auxiliary and operating materials [9]. The processes involved form the basis for order fulfillment. In addition, there are the processes of steering and controlling the operations in a factory [1].

A number of approaches dealing with the life cycle and life cycle management of a factory can be found in the existing literature. The overall factory life cycle is composed of different life cycles of the individual elements of a factory, which must be aligned and therefore requires a holistic, end-to-end planning activity [10]. Due to the turbulent environment, factory planning projects are becoming increasingly necessary and are consequently triggered at ever shorter intervals. In the meantime, they have become an interdisciplinary ongoing task for companies. [11] In the course of factory planning, the factory is usually designed for a certain time horizon of up to 10 years, depending on the planning case, and thus only covers a part of the factory life cycle [9]. Uncertainties must be taken into account within this time horizon in order to ensure that the factory is future-proof. To evaluate the effectiveness and efficiency of possible changeability concepts in the context of factory planning, a life-cycle oriented evaluation of the factory over the time horizon under consideration is required. Both initial capital expenditure for realizing the factory planning variants and operational expenditure in the course of factory operation must be included. Methods for evaluating costs over the life cycle are summarized under the term life cycle costs (LCC). [10] Literature reviews in the field of life cycle costs have shown that a quantitative evaluation of a factory has not been conducted yet [12]. The turbulent factory environment was not included in previous reviews though. Therefore, possible approaches for evaluating changeability in a factory have not been examined from a life-cycle perspective yet.

The required level of changeability is determined based on the assessment of uncertainties. The origin in the assessment of uncertainties comes from the concept of risk management, which originates from the insurance industry [13]. Initially, various process models in the literature have dealt with risk management as a systematic and continuous approach [14,15,13,16,17]. Subsequently, the focus shifted towards the assessment of individual, short-term uncertainties, such as fluctuations in demand [18–20], disruptions in the production process [21–24] or supplier or quality issues [25,26], in order to derive suitable measures for dealing with short-term uncertainties. Only a few approaches address the effects of different categories of short-term uncertainties on the entire factory [27–29], also lacking a life-cycle evaluation of cost effects. Same applies to an approach, which not only takes into account short-term uncertainties but also long-term uncertainties such as changes in technologies, laws, products, etc. [30]. Mostly, similar approaches in the literature focus exclusively on long-term uncertainties and attempt to evaluate respective responses either monetarily [31–33], to investigate the interactions between uncertainties and the factory [2,34,35] or to develop process models for managing long-term uncertainties based on the scenario analysis [36,37] or control systems [38–40]. In the light of current developments, new terminologies for the concept of changeability continue to emerge. There is a lack of an approach that combines the different strategies of changeability with the claim to consider both short-term and long-term uncertainties within factory planning. The key requirement is the targeted adaptation of the influenced factory elements to the expected uncertainties during factory planning or operation in a life cycle cost-efficient manner based on the assessed level of impact and probability.

3. Changeability through factory planning from life cycle perspective

The first step in overcoming the aforementioned shortcomings will be to establish a universal understanding of the concept of changeability in the context of factory planning throughout the paper as a basis for further work. For this purpose, a distinction between short-term and long-term uncertainties is made first. This is followed by an explanation of how these uncertainties are taken into account in the factory planning process. Finally, various strategic factory types are described in the context of changeability and both differences and similarities between the factory types are identified.

3.1. Differentiation of short- and long-term uncertainties

In transaction cost theory, uncertainty is associated with the variability of outcomes, lack of knowledge about the distribution of potential outcomes and uncontrollability of outcome attainment [41]. Figure 1 shows that this uncertainty leads to changes that are the result of long-term developments in the factory environment. Alternatively, it emerges directly from the factory as a complex socio-technical system. Complexity drivers in factory planning or operations increase the level of uncertainty leading to an occurrence of events that cause disruptions in factory operations.

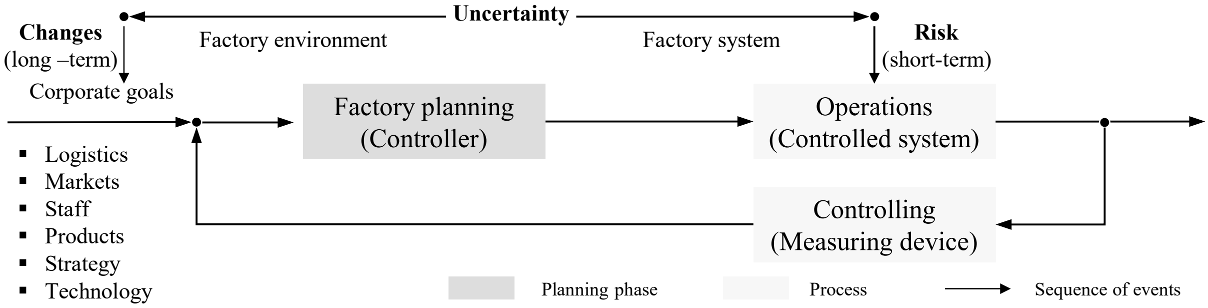

Figure 1: Uncertainty influencing the control system of factory planning, based on [42]

The control system of factory planning provides for an adjustment of the factory by factory planning as soon as controlling detects a deviation of the target/actual values of strategic and operative key figures. The target values can be derived from the corporate goals, while the actual values are recorded via the controlled system. [42] In the following, it will be explained how short- or long-term uncertainties lead to a negative influence of the actual values or an adjustment of the target values.

Uncertainty is present in any complex system. Sources of uncertainty may include lead time, market demand, product quality, and information flow among others [41]. The resulting events are usually random and have a probability of occurrence. They are disruptive, have a relevant impact on performance, and are sometimes difficult to anticipate. Therefore, an uncertain event occurring on a short-term basis is also defined as a risk, whose occurrence will have an impact on the achievement of one or more goals. [43] Regarding the interpretation of the term, a distinction can be made between a cause-related and an effect-related definition of risk. The risk can be considered as a causal factor that triggers an event (e.g. change of supplier in factory planning, faulty operation of equipment in factory operation). According to the effect-related definition, risk is understood as the possible occurrence of an event that negatively affects the achievement of a goal. [44] Consequently, risk is defined as the potential damage of a future event (e.g. change in container filling quantity in factory planning, machine failure in factory operation).

In addition to risks as short-term uncertainties in factory planning and operation, change drivers appear as medium- and long-term uncertainties that lead to ever new requirements for the factory. They result from megatrends that have a global impact in all areas of society and are described as long-term developments with major economic, political and social relevance. [42] Due to the strong pressure of megatrends for change, companies are forced to adapt their strategy and corporate goals. Some prominent examples of current megatrends include climate change and demographic change [45]. They influence the business models of companies and their entrepreneurial actions [46]. However, megatrends only have an indirect influence on the factory. A direct influence results from the caused change drivers such as customer demands, the sales markets or the product and technology life cycle, which describe the effects of megatrends on the environment of manufacturing companies [1]. Constantly new requirements for the factory require increasingly frequent adaptions [2]. Various authors have developed catalogs for change drivers. An exemplary catalog was consolidated as part of the study of relationships between megatrends and change drivers [5]. The catalogs support companies in identifying relevant change drivers in order to respond to a changing environment at an early stage.

3.2. From changeability planning to life cycle oriented consideration of uncertainties in the factory planning process

During factory operation, defined threshold values can be continuously breached or exceeded. In this case, the factory no longer meets the desired requirements, so that a new factory planning process has to begin. Changeability planning facilitates the comparison of actual and target values and thus supports the planning decision to initiate a planning process. As factory planning is a recurring process, monitoring the threshold values to trigger a further planning loop is considered an essential part of changeability planning. [2] The temporal classification in figure 2 is done with the help of the factory life cycle.

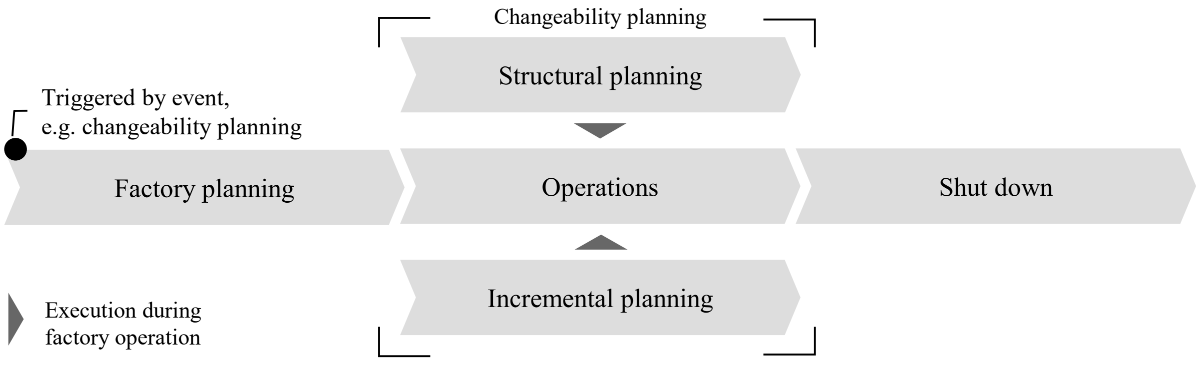

Figure 2: Classification of changeability planning in the factory life cycle, based on [2]

The new planning of a factory is followed by factory operation. Further factory planning loops are triggered by certain events during factory operation. These are captured by changeability planning. Two types of changeability planning can be distinguished. Structural planning involves the ability to recognize trends early on in order to initiate the necessary measures. In contrast, incremental planning involves a high level of responsiveness in order to be able to react to short-term changes in the production environment. [42] As the incremental planning seeks to establish a certain capability for turbulence in the factory, it equates risk management in the following.

At the beginning of the incremental planning, the company defines its risk awareness [47]. To this end, certain risk strategies must be defined for determining which risks are to be taken and how they are to be handled in case of the occurrence of risk events. The individual phases consist of risk identification, risk assessment, risk control and risk monitoring [48]. In risk identification, all relevant risks are recorded holistically. This requires the exposure of all sources of danger, causes of damage or potential for disruption. Risk assessment focuses on the estimation and evaluation of risks. The purpose is to quantify the impact of risks in order to be able to estimate danger potentials. [16] This step is necessary in order to correctly assess and prioritize the need for further action [25]. The cause of risk as the actual reason for the occurrence of risk determines which risks can be influenced by the company. Risks of external origin cannot be influenced, or can only be influenced with great difficulty. Risk control involves the treatment of the previously identified and assessed risks. A distinction is made between risk avoidance, risk reduction, risk diversification, risk transfer and risk acceptance. [48,25,47] The main factors influencing the determination of measures are the risk class, the level of impact, and the probability of occurrence of the risks [47]. Risk monitoring is at the end of incremental planning. It runs alongside the processes and monitors the dynamic development of the risks [25]. Incremental planning of changeability does not necessarily result in the initiation of the factory planning process, as it is limited to an adjustment of the factory in terms of detailed planning [42]. As a result, very limited degrees of freedom are available. The focus of incremental planning especially lies on the mitigation of short-term disruptions.

If the factory cannot be adequately prepared for the uncertainties through incremental planning, the factory is adapted using structural planning of changeability. In the process of questioning organizational and structural relationships in the factory, it is mandatory to go through the factory planning process again [37]. The success of the structural change process is not so much dependent on the ability to react, but rather on the timely recognition and implementation of necessary measures [42]. Emerging trends must be identified at an early stage through forecasting and must be shaped proactively by creating a new solution space. Structural planning consists of the monitoring of changes, the assessment of the quality of changeability and the determination of corrective measures in case an increase of changeability is necessary. It is divided into the two phases monitoring and assessment of changeability. [31,2] The assessment is only triggered if unknown changes in the environment are registered that have an impact on the factory. For this purpose, potential change drivers are derived from megatrends as a first step in monitoring. Relevant developments of the drivers as well as the resulting need for change are concluded. The need for change results from the change dimensions of quantity, variants, costs, time or quality. [2] At the end of the monitoring phase, the processes and elements of the factory that are affected by the need for change must be determined. This is followed by an assessment of the factory to determine whether the changeability of the affected processes and elements is sufficient to cope with possible future developments. If a need for action is identified, corrective measures to increase the changeability must be specified and implemented. [31,2]

Changeability planning can be applied in cycles during factory operation. Another possibility as an addition to the continuous monitoring of uncertainties during factory operation is the use of the planning method in the factory planning process. [2] By identifying future requirements, these can be addressed in conceptual and detailed planning [37]. Provided that the factory's ability to change is identified as an essential target field, possible risks and change drivers that may occur during the factory life cycle should be identified when setting the objectives in factory planning. Depending on the necessary degree of changeability identified in this way, the factory can be designed accordingly. There are various strategies of changeability available to the factory planner in this regard, which can result in different factory planning variants. The final selection of a preferred variant can only be made on the basis of a factory lifecycle-oriented evaluation by anticipating the later factory lifecycle and testing how the various planning variants deal with the uncertainties. This allows the capital and costs expenditures for changeability to be compared with the generated benefits along the factory lifecycle. In the following, the different strategies of changeability will be briefly introduced and distinguished from each other in the form of factory types.

3.3. Selection of factory types in the context of changeability for coping with uncertainties

Change is also defined as the "agreed establishment of a new state instead of the previous state" [49]. The ability to cope with change triggered by uncertainty can involve different levels and parts of the factory. Only isolated sections of the overall system are subject to a change process with first-order change. In contrast, all organizational dimensions are affected in the case of second-order change [50]. From a factory planning perspective, second-order changes are particularly relevant. In order to give an overview of different strategies of changeability in the literature, a preliminary review was performed and the resulting factory types are described below (Table 1).

Table 1: Comparison of the different strategies of changeability as possible factory types

	Robustness	Resilience	Flexibility	Transformability	Agility
Robustness	Robustness represents the insensibility to internal and external disruptive events in relation to the performance of the production system.	Resilience has a dynamic behavior compared to static system property of robustness.[3] Adaptations are allowed (require opex instead of capex), in the same way as temporary performance drops.[21]	Flexibility is also intended for dealing with mid-term uncertainties. In contrast to robustness with fixed capacities, reactive system adaptations are carried out that are reversible.[51]	Transformability is also intended for dealing with mid- and long-term uncertainties. [6] In contrast to robustness, potential is held for specific events and changes are made responsively when needed. [51]	Agility is established for a complete company and network. [52] It does not require preplanning, thus future developments do not have to be known. [53]
Resilience	Both types are conceived in the short term and operationally. The goal is a certain resistance to disturbances. Resilience can be a kind of balance between robustness and transformability. [45]	Resilience refers to the ability of a system to endure certain disruptive events without failing completely and to return to its original state within a short time after the disruptions have ceased.	Flexibility is also intended for dealing with mid-term uncertainties. Classification according to flexibility types. Besides the swiftness of adaptation, a strong focus is put on simplicity of adaptation. [51]	Transformability is also intended for dealing with mid- and long-term uncertainties. Increased focus on change drivers with the help of specific enablers that require capital expenditures for implementation. [9]	Agility is established for a complete company and network. Very long-term impact horizon. [52,54]
Flexibility	Implementation of predefined fields of action in the form of flexibility corridors [20] and robustness limits to deal with potential developments within this field of action. [53]	Both types are rather operational. Fast reactions are a crucial factor for success. [20] Flexibility is an implicit resilience characteristic. [21]	Flexibility refers to the ability to adapt to change requirements simply in a short time and without major investment within defined flexibility corridors, with no significant changes to the structure.	Flexibility represents reversible changes, affected operating costs, and maintained corridors, [30] whereas transformability represents irreversible changes that go beyond corridors and require an activation effort. [3,9]	Agility refers to a complete company and network. Much more comprehensive, e.g. by switching between entire product families. [55,56]
Transformability	Proactive strategies by means of capital expenditures and thus considered rather irreversible once implemented.[3,53]	Resilience can be achieved through a balance between robustness and transformability. Human creativity is important. [21,45]	Represent the two categories of conventional changeability. [42] Transformability has historically emerged from flexibility.	Transformability is the potential to carry out organizational, technical, spatial and logistical changes outside the flexibility corridors provided at all system levels by means of transformation enablers.	Agility refers to a complete company and network and is thus more comprehensive. [52,9] It does not require preplanning, thus future developments do not have to be known. [53]
Agility	-	Both types have quickness as a characteristic, as well as proactive and reactive elements in common. [21,52]	Both are prone to change/ adaptations. Flexibility is an integral part of agility. [52]	Both require extensive adaptation and are designed to cope with increasing market complexity in a strategic way. [57] Transformability is an integral part of agility. [52]	Agility gives the entire company the ability to respond to uncertainties and impulses for change strategically within the shortest possible time.

Legend: ☐ Definition ▨ Similarities ■ Differences

Five different strategies of changeability have been identified in the literature as possible strategic factory types. First, a closer look is taken at robustness, for which divergent definitions exist. However, previous analyses agree that robustness describes the ability of a system to be insensitive to changing environmental influences [3]. To some extent, it is added that system adaptations do not need to be made in order to cope with these influences [51]. In case of changing environmental conditions or deviations caused by disruptions, the function of the system can still be maintained [58]. Thus, a robust production system can withstand a certain level of stress without suffering deterioration or loss of functionality [59].

The word resilience comes from the Latin verb "resilire" meaning "to spring back, bounce back". Interdisciplinary, resilience is described as the ability to handle critical situations, to prevent damage when disruptions occur, and to return to the previous state as quickly as possible through rapid recovery. [60] Transferred to a production system, a resilient system is allowed to leave the steady state for a short period of time. After a brief drop in the performance level following the occurrence of the disruptive event, the system must be able to return to its original performance as quickly as possible through self-regulation [53]. In this regard, humans as intelligent elements of a socio-technical system are at the center of resilient production systems due to their anticipation, interpretation, and decision making [21]. Other central notions include interconnectivity, resistance, adaptivity, decentralization, and learning capability [61].

At the turn of the millennium, the term flexibility was one of the most frequently discussed approaches with regard to the ability of companies to change [9]. Over 50 different definitions and interpretations for the term flexibility have already been identified in 1990 [62]. Meanwhile, the concept of changeability continued to evolve. Former elements of flexibility are assigned to other strategies of changeability today. Essentially, flexibility refers to the ability of a factory to adapt quickly and with very little cost within flexibility corridors that are defined at the point of factory planning [54]. There is an increased focus on the simplicity and reversibility of adaptations [51]. Due to the flexibility corridors, the response options are limited [42]. The previous explanations correspond to the definitions of short- or medium-term as well as static flexibility. The literature also provides definitions of long-term and dynamic flexibility [31,37], part of which is associated with transformability.

Transformability puts the factory into a commitment to change using a transformation potential, whose activation expands the original function or shifts the flexibility corridors [40]. Irreversible changes can be made responsively when needed, which are beyond the flexibility corridors held in reserve [54]. As a result, the time and cost required to prepare the necessary adaptations is significantly higher compared to the concept of flexibility. As soon as the preparations have been completed, organizational, technical and logistical changes can be implemented outside of maintained flexibility corridors in a short time when required, with low investments and taking into account the interactions of the system elements. [37] For example, the infrastructures for change are already configured and in place before specific needs for change are known or arise [9].

The final element is agility, which is defined in broader terms than the conventional ability to change. The strategic focus also includes units outside production, such as sales, purchasing and controlling [9]. An agile approach empowers the company to change its entire production networks or its entire product and service portfolio [54]. This includes measures such as relocating the production site or switching from multiple to single sourcing [31]. By reducing planning activities to a minimum, it is also possible to respond to change drivers immediately during the planning phase. Thus, agile systems are able to cope with unforeseen and unpredictable events [53]. Generally, the identification of market opportunities is addressed through an agile business model, so that a prompt fulfillment of every customer request can be achieved [32].

The factory types derived from the strategies of changeability are overlapping. To some extent, the terms are used mutually in the literature when defining strategies of changeability. One possible definition of transformability, for example, is a combination of the four aspects robustness, flexibility, agility and adaptability [51]. A clear distinction of the strategies of changeability does not exist, partly because the concept has been extended gradually over the last decades. Based on flexibility, transformability and agility were complemented first. Due to the current circumstances, the terms resilience and robustness are currently used repeatedly in the literature. The conclusions of this paper have been summarized in Figure 3.

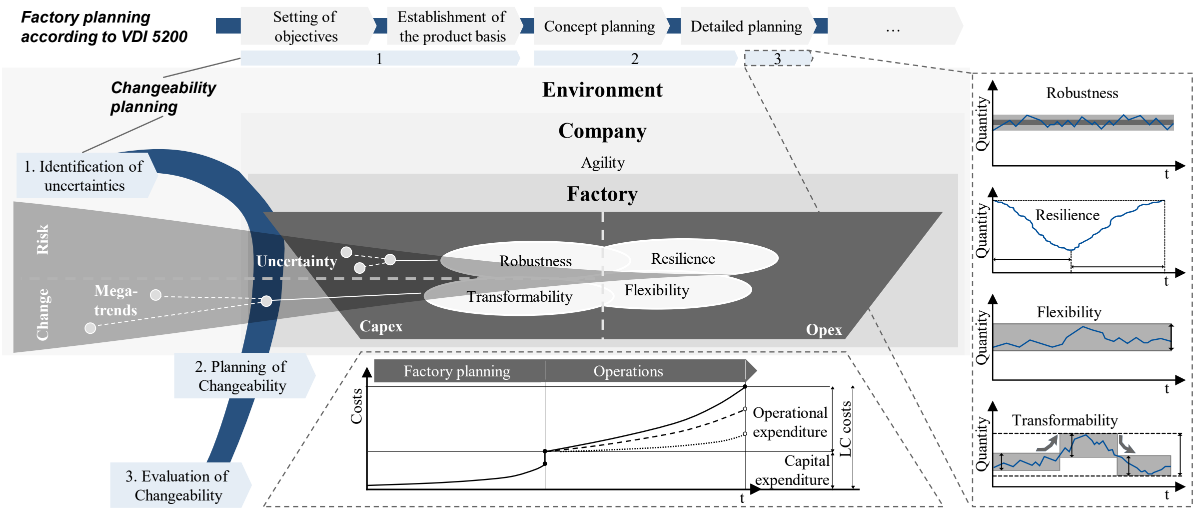

Figure 3: An overview of changeability planning in factory planning, based on [30,24,59]

The factory is part of a manufacturing company, which is located in an enterprise environment. In recent years, the degree of uncertainty has increased steadily both in the company's environment and in the factory system. On the one hand, this is expressed by long-term and continuous change in the form of superordinate megatrends, with effects on the company environment that are very difficult to predict. On the other hand, short-term disruptive events within the production system due to performance deviations inside or outside the factory are becoming more frequent. It is the task of factory planning to prepare the factory in the best possible way for the further course of the factory life cycle. For this purpose, different factory types or strategies of changeability are available to factory planning. Depending on the actual uncertainty present, the strategies of changeability capable of coping with the uncertainties most effectively over the further course of the factory life cycle must be designed. In order to be able to make such decisions in the context of factory planning, changeability planning must be integrated into factory planning. It is important that the uncertainties present in the use case are identified at the start of factory planning and considered from the very beginning. Subsequently, the changeability must be planned as part of the concept and detailed planning. An evaluation of the resulting factory planning variants is repeatedly carried out during this process, whereby changeability is usually only one of several factory objectives. In terms of changeability, it is important to evaluate whether the degree of changeability is sufficient for the predicted uncertainties in the course of the factory life cycle, so that the required performance level can be achieved, and which of the factory planning variants generates the lowest life cycle costs on top of that.

It can be concluded that resilience and robustness are rather mentioned in the literature in the context of short-term risks. Resilience ensures that when a disruption occurs, the performance curve only drops to a minimum that is tolerable for the system and then returns to the previous level in the shortest possible time. Robustness sets robustness limits to design a system to be able to operate under as many environmental conditions within the boundaries as possible. However, this is only optimal in a few cases, which is characterized by the narrow optimal range. Flexibility and transformability use static and dynamic flexibility corridors as classic characteristics of the capability for managing long-term change drivers. At the same time, implementing the dynamics of transformability and installing redundancies as part of robustness requires increased capital expenditures. The benefits of flexibility and resilience become more apparent during operations and consequently come along with increased operating expenditures.

4. Summary and Outlook

The increasingly complex factory systems are located in an extremely turbulent environment, resulting in numerous requirements and challenges. Therefore, the goal of this paper was to elaborate the planning process as well as different strategies of changeability. This knowledge will serve as a basis for identifying starting points for coping with diverse influences in the form of risks and change drivers. An analogy to the "two-factor theory according to Herzberg" accurately summarizes the findings: robustness and resilience are assigned to the area of dissatisfaction, meaning the negative effects on the factory. In contrast, transformability and agility refer to the area of satisfaction and enable the exploitation of opportunities and developments. Flexibility is ultimately found in both areas to some extent. Factory planning offers the opportunity to make decisions at an early stage, sometimes under considerable uncertainty, in order to prepare the factory for operation in the best possible way. However, mere knowledge of the factory types is not sufficient for this. They must be broken down to the inherent elements and processes in order to prepare them for risks and change drivers depending on their needs. The needs can be met in different ways. There will not only be one factory planning measure, resulting in different planning variants depending on the use case. Future research of the Institute of Production Systems and Logistics will work towards the quantitative evaluation of changeability over the factory life cycle. The impact of change drivers and risks over the factory lifecycle will be evaluated quantitatively in order to determine the right level of changeability in the context of economic efficiency. By knowing the behavior of the factory planning variants over the factory life cycle, they can be compared with each other. This should enable factory planners to select the factory planning variant that shows the lowest life cycle costs.

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References

[1] Schenk, M., Wirth, S., Müller, E., 2010. Factory planning manual. Springer, Berlin, Heidelberg.

[2] Klemke, T., 2014. Planung der systemischen Wandlungsfähigkeit von Fabriken. Dissertation, Hannover.

[3] Stricker, N., 2016. Robustheit verketteter Produktionssysteme. Dissertation, Karlsruhe.

[4] Meyer, M., 2007. Logistisches Störungsmanagement in kundenverbrauchsorientierten Wertschöpfungsketten. Dissertation, Aachen.

[5] Hingst, L., Dér, A., Herrmann, C., Nyhuis, P., 2021. Evaluation of the influence of change drivers on the factory life cycle: (under revision). Procedia CIRP.

[6] Westkämper, E., Zahn, E. (Eds.), 2009. Wandlungsfähige Produktionsunternehmen. Springer-Verlag, Berlin, Heidelberg.

[7] Westkämper, E. (Ed.), 2013. Digitale Produktion. Springer Vieweg, Berlin, Heidelberg.

[8] Verein Deutscher Ingenieure, 2011. Factory planning - Planning procedures: VDI 5200.

[9] Wiendahl, H.-P., Reichardt, J., Nyhuis, P., 2015. Handbook Factory Planning and Design. Springer, Berlin, Heidelberg.

[10] Herrmann, C., 2010. Ganzheitliches Life Cycle Management. Springer, Berlin, Heidelberg.

[11] Pawellek, G., 2014. Ganzheitliche Fabrikplanung, 2. Aufl. ed. Springer Vieweg, Berlin.

[12] 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.

[13] Schimmelpfeng, K., 2001. Risikomanagement in Industrieunternehmen, in: Götze, U., Henselmann, K., Mikus, B. (Eds.), Risikomanagement. Beiträge zur Unternehmensplanung. Springer-Verlag, Berlin, Heidelberg, pp. 277–297.

[14] Krebs, P., Müller, N., Reinhardt, S., Schellmann, H., Bredow, M. von, Reinhart, G., 2009. Ganzheitliche Risikobewertung für produzierende Unternehmen. ZWF 104, 174–181.

[15] Rogler, S., 2002. Risikomanagement im Industriebetrieb. Dissertation, Wiesbaden.

[16] Strohmeier, G., 2007. Ganzheitliches Risikomanagement in Industriebetrieben. Dissertation, Leoben.

[17] Wildemann, H., 2005. Management leistungswirtschaftlicher Risiken in der Produktion. ZWF 100, 187–191.

[18] Gottschalk, L., König, R., 2004. Bedarfsunsicherheiten durch flexible Kapazitäten beherrschen. ZWF 99, 715–719.

[19] Rühl, J.E., 2010. Monetäre Flexibilitäts- und Risikobewertung. Dissertation, Aachen.

[20] Wagner, C., 2012. Kontinuierliche Gestaltung skalierbarer Produktionsstufen. Dissertation, Hannover.

[21] Heinicke, M., 2017. Resilienzorientierte Beurteilung von Produktionsstrukturen. Dissertation, Magdeburg.

[22] Knüppel, K.M., 2016. Modellbasiertes Störungsmanagement in Produktionssystemen. Dissertation, Hannover.

[23] Ostgathe, M., Zäh, M.F., Grimmert, P., Schöler, T., 2011. Wissensbasiertes Störungsmanagement in Produktionsabläufen. ZWF 106, 838–843.

[24] Stricker, N., Lanza, G., 2014. The Concept of Robustness in Production Systems and its Correlation to Disturbances. Procedia CIRP 19, 87–92.

[25] Merz, M. Entwicklung einer indikatorenbasierten Methodik zur Vulnerabilitätsanalyse für die Bewertung von Risiken in der industriellen Produktion.

[26] Schmitt, R., Kostyszyn, K., 2015. Fehlerrisiken in der Produktion. wt Werkstatttechnik online 105 (11/12), 775–780.

[27] Pohl, J., 2013. Adaption von Produktionsstrukturen unter Berücksichtigung von Lebenszyklen. Dissertation, München.

[28] Unzeitig, W., 2014. Methodik zur frühen Fabrikplanung bei Unsicherheiten. Dissertation, Graz.

[29] Weig, S., 2008. Konzept eines integrierten Risikomanagements für die Ablauf- und Strukturgestaltung in Fabrikplanungsprojekten. Dissertation, München.

[30] Hawer, S., 2020. Planung veränderungsfähiger Fabrikstrukturen auf Basis unscharfer Daten. Dissertation, München.

[31] Heger, C.L., 2006. Bewertung der Wandlungsfähigkeit von Fabrikobjekten. Dissertation, Hannover.

[32] Löffler, C., 2011. Systematik der strategischen Strukturplanung für eine wandlungsfähige und vernetzte Produktion der variantenreichen Serienfertigung. Dissertation, Stuttgart.

[33] Möller, N., 2007. Bestimmung der Wirtschaftlichkeit wandlungsfähiger Produktionssysteme. Dissertation, München.

[34] Koch, J., Plehn, C., Reinhart, G., Zäh, M.F., 2014. Cycle Management for Continuous Manufacturing Planning, in: Zäh, M. (Ed.), Enabling manufacturing competitiveness and economic sustainability. Springer, Cham, pp. 9–12.

[35] Lübkemann, J., 2016. Ermittlung des Restrukturierungsbedarfs von Fabriken. Dissertation, Hannover.

[36] Benkamoun, N., 2017. Systemic design methodology for Changeable Manufacturing Systems. Dissertation, Aubière.

[37] Hernández, R., 2002. Systematik der Wandlungsfähigkeit in der Fabrikplanung. Dissertation, Hannover.

[38] Delbrügger, T., Döbbeler, F., Graefenstein, J., Lager, H., Lenz, L.T., Meißner, M., Müller, D., Regelmann, R., Scholz, D., Schumacher, C., Winkels, J., Wirtz, A., Zeidler, F., 2017. Anpassungsintelligenz von Fabriken im dynamischen und komplexen Umfeld 112, 364–368.

[39] Schenk, M., Seidel, H., Garrel, J. von, Grandt, C., 2012. Change Management in der Produktion – Flexibilisierungspotenziale nutzen., in: Rosenstiel, L., Hornstein, E. (Eds.), Change Management Praxisfälle. Springer, Berlin.

[40] Zäh, M.F., Müller, N. Prasch, M., Sudhoff, W., 2004. Methodik zur Erhöhung der Wandlungsfähigkeit von Produktionssystemen. ZWF 99, 173–177.

[41] Cucchiella, F., Gastaldi, M., 2006. Risk management in supply chain: a real option approach. Jnl of Manu Tech Mnagmnt 17 (6), 700–720.

[42] Wulf, S., 2011. Bewertung des Einflusses von Produkt- und Technologieveränderungen auf die Fabrik. Dissertation, Hannover.

[43] Sheffi, Y., Rice, J.B., 2005. A Supply Chain View of the Resilient Enterprise. MIT Sloan Management Review.

[44] Brünger, C., 2011. Nutzenkonsistente Risikopriorisierung: Die Risk-Map im Kontext rationaler Entscheidungen. Dissertation, 1. Aufl. ed. Gabler Verlag / Springer Fachmedien Wiesbaden GmbH Wiesbaden, Paderborn.

[45] Westkämper, E., Löffler, C., 2016. Strategien der Produktion. Springer Vieweg, Berlin.

[46] Krause, D., Gebhardt, N., 2018. Methodische Entwicklung modularer Produktfamilien, 1. Auflage ed. Springer Vieweg, Berlin, Germany.

[47] Rosenkranz, F., Mißler-Behr, M., 2005. Unternehmensrisiken erkennen und managen. Springer, Berlin.

[48] Löhr, B., 2010. Integriertes Risikocontrolling für Industrieunternehmen. Dissertation, Frankfurt a.M.

[49] Deutsches Institut für Normung e.V., 2001. DIN6789-3: Dokumentensystematik: Änderungen von Dokumenten und Gegenständen allgemeine Anforderungen. Beuth Verlag,, Berlin.

[50] Becker, H., Langosch, I., 2016. Produktivität und Menschlichkeit, 5. Auflage ed. De Gruyter; De Gruyter Oldenbourg, Berlin.

[51] Fricke, E., Schulz, A.P., 2005. Design for changeability (DfC): Principles to enable changes in systems throughout their entire lifecycle. Syst. Engin. 8 (4).

[52] Schurig, M., Rabitsch, C., Ramsauer, C., 2014. Agile Produktion. ZWF 109, 956–959.

[53] Wieland, A., Wallenburg, C.M., 2012. Dealing with supply chain risks. International Journal of Physical Distribution & Logistics Management 42 (10), 887–905.

[54] 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.

[55] Tsourveloudis, N.C., Valavanis, K.P., 2002. On the Measurement of Enterprise Agility. Journal ofIntelligent and Robotic Systems 33, 329–342.

[56] Yusuf, Y.Y., Sarhadi, M., Gunasekaran, A., 1999. Agile manufacturing. International Journal of Production Economics 62 (1-2), 33–43.

[57] Rauch, E., Spena, P.R., Matt, D.T., 2019. Axiomatic design guidelines for the design of flexible and agile manufacturing and assembly systems for SMEs. International Journal on Interactive Design and Manufacturing 13 (1), 1–22.

[58] Vlajic, J.V., van der Vorst, J.G.A.J., Haijema, R., 2012. A framework for designing robust food supply chains. International Journal of Production Economics 137 (1), 176–189.

[59] Tierney, K., Bruneau, M., 2007. Conceptualizing and Measuring Resilience. TR news, 14–17.

[60] Trauth, D., 2019. Manufacturing Resilience : Towards Resilience Management in Production Engineering.

[61] Umsetzungsempfehlungen für das Zukunftsprojekt Industrie 4.0: Abschlussbericht des Arbeitskreises Industrie 4.0. Accessed 28 March 2021.

[62] Sethi, A.K., Sethi, S.P., 1990. Flexibility in manufacturing: A survey. The International Journal of Flexible Manufacturing Systems, 289–328.

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