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Evaluation of the influence of change drivers on the factory life cycle

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Abstract

Factories consist of numerous factory elements with individual life cycles. Besides technical aspects such as wear, their actual lifetime is influenced by change drivers from an increasingly dynamic market environment. As a result, factory elements may experience a premature end due to changed requirements before the end of their technical lifetime. The difficulty in factory planning is to understand the behavior of the life cycles in order to make management decisions. Therefore, the goal is to identify change drivers and evaluate their influence on the factory life cycle, while taking into account the technical functionality.

Keywords: Factoy life cycle; Transformability; Change drivers; Factory planning; Life cycle evaluation

1. Introduction

Production companies and their factories operate in an increasingly dynamic and hardly predictable market environment. The constant change resulting from megatrends and the associated uncertainty lead to ever new requirements for the factory such as a greater variety of product variants, smaller production volumes or shorter delivery times [1]. As a result, there is a permanent need for transformation at different levels of a factory. Factories have developed into highly complex systems consisting of numerous factory elements such as production machinery, technical building equipment or the building shell [2]. These factory elements have to be designed transformable according to the changing requirements. However, transformability comes at a price. Investments rise exponentially with the degree of transformability. Otherwise, in case of insufficient investments, typically higher cost occur during operations [3]. In order to make management decisions in a targeted manner, life cycle information on the factory elements is needed, so that the economic efficiency of the factory is ensured over its entire lifetime.

Factory elements are characterized by individual life cycles that differ in their behavior. Technical aspects such as wear or the failure rate change over the life cycle and determine the technical functionality [4]. Additionally, factory elements may experience a premature end of the life cycle due to change drivers, e.g. when a new product no longer requires a specific machine. Decision making in factory planning needs to understand the individual life cycles as well as their interdependencies. Therefore, it is essential to extract those factory elements in a given factory configuration that are critical with respect to future changes and to derive the required degree of transformability from a life cycle perspective.

Against this background, the goal of this paper is to present an approach for identifying change drivers based on megatrends and for evaluating their influence on the factory. A methodology is proposed for determining the life cycle relevant factory elements by combining the influence of change drivers with their technical functionality. By outlining the factory elements with a planning need, the proposed approach forms an important basis for the envisioned factory life cycle forecast model, which shall evaluate the derived planning measures in the future. The practicality of the approach is demonstrated within a case study.

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2. Background and state of research

2.1. Factory planning and operation

Due to an ever increasing turbulent environment, the frequency of factory planning projects has been increasing. They have become a permanent task for companies [5]. Factory planning is interdisciplinary and must provide solutions based on personnel, technical-organizational, economic and environmental points of view. The defined capacities and resulting capabilities can be exploited during factory operation for different target alignments. [6] In order to secure the competitiveness during operations, production companies must change their capabilities with the help of factory planning. From a factory planning point of view, the ability to change can be distinguished into flexibility and transformability. [3, 7] Flexibility describes the ability to react to anticipated changes within a defined range. Typically, it does not require new investments. Transformability exceeds this ability by realizing change beyond this range with the help of a farsighted solution space, which must be activated and is not immediately available for use [5]. The implementation requires new investments and the return can only be evaluated over the long term [3]. Therefore, factory planning must take a holistic perspective on the factory life cycle, so that a factory configuration meets socio-economic targets over lifetime [8].

2.2. The factory life cycle

Factory planning, operations and factory dismantling form the life cycle of a factory. A life cycle describes characteristic, cyclical patterns of an observed system over time. Managing activities in relation to the entire life cycle is originally known as (Product) Life Cycle Management [9] and has also been applied to an entire factory system [10]. Taking the life cycle (of products) from different perspectives into account, a technical, functional and economic lifetime can be discerned [11]. Within the context of a factory, Figure 1 shows qualitative utility curves of selected factory elements over the life cycle.

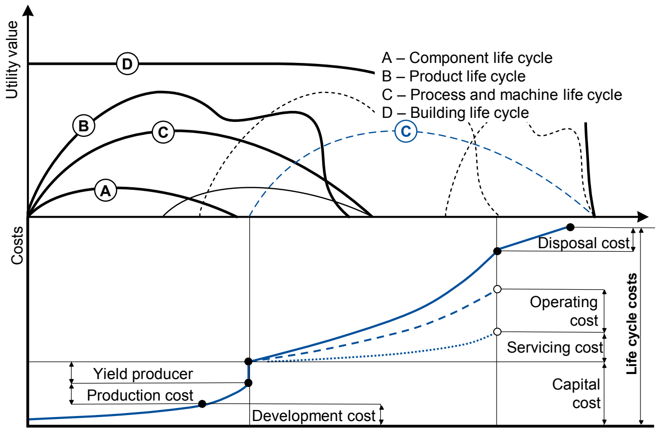

Fig. 1.: Factory life cycle and qualitative representation of life cycle costs of an exemplary factory element in the factory life cycle, based on [12, 13]

The utility value is the value of an element in terms of its suitability for a specific purpose. Following the utility curves, costs can be calculated over the life cycle of a factory. For example, capital costs arise before the beginning of the life cycle, followed by service and operating costs resulting from maintenance, energy demand etc. during the life cycle (curve “C”) [13]. Methods for the evaluation of costs over the life cycle are summarized under the term Life Cycle Costing (LCC) [9]. The challenge in factory planning is to understand and forecast the heterogeneous individual life cycles, so that management decisions can be made that lead to an improved factory configuration from a life cycle perspective.

Regarding the evaluation of factory life cycles, Nielsen et al. [8] reviewed existing qualitative and quantitative models and approaches. Based on the identified lack of comprehensive dynamic evaluation approaches, they proposed a conceptual framework for an integrated assessment of economic and environmental key figures on factory level [8]. Recent contributions show that this is still only done for individual factory elements [14] [15]. However, the unsettled factory environment is not included in their review. Thus dynamic changes or rather uncertainties during the factory life cycle are not considered. Against this background, the role of change drivers in life cycle evaluations is examined in the following.

2.3. Dynamic changes during factory life cycle

Factories are positioned in a tension field between technology push and market pull factors. The immanent factory elements are thus subject to dynamic changes or uncertainties and require a high transformability [5]. In the context of transformability, change drivers have been analyzed to allow a more accurate forecast of the future behavior of a factory [1, 16]. Change drivers can be very diverse. Besides short term effects like risks [17], technology driven change drivers are predominant within the previous approaches [18–22]. They often have a cyclic pattern, which can be anticipated in order to coordinate the innovation process in a factory [18]. Based on the investigation of the interrelations between different cycles, like manufacturing technologies or product engineering, a dynamic behavior was observed within the cycles [20]. Additionally, interdependencies with the factory were modeled on a qualitative basis with the help of fuzzy sets [21]. The dynamic modeling of the technology driven cycles made their interdependencies and time-dependent behavior tangible and gave insights into their influence on manufacturing resources and structure [19]. However, the various resources in a factory have not been distinguished yet. Consequently, interdependencies within a factory remain intransparent. It is only concluded that technology driven change drivers are generally causing changes in a factory [22].

Existing life cycle evaluation approaches addressing the dynamic changes during factory life cycles solely focus on the individual behaviour of technology change drivers. Other change drivers, that are already an integral part of transformability studies [1], have not been taken into account yet. Furthermore, their influence on the factory is only partially investigated as not all relevant factory elements are currently included. Finally, there is no factory life cycle evaluation approach at this point that examines the life cycle costs of a factory under uncertainty. Taking this into account in the form of change drivers is intended to give the envisioned forecast

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model the necessary quality to enable a reliable evaluation of factory planning measures over the entire life cycle. The need for measures depends on the need for change, which in turn is determined by the factory environment. This can be met with the help of transformability. The factory elements in the need of transformation and also the required extent of transformability in consideration of life cycle costs must be identified. A comprehensive and applicable approach is missing that adequately considers change drivers and their influence on the life cycle of factory elements.

3. Development of a systematic approach

3.1. Overview

In order to overcome the aforementioned shortcomings based on the identified research gap, an approach is proposed for identifying starting points for factory planning measures. Those measures become necessary, when either the technical functionality is no longer sufficient or the level of uncertainty is too high for the current transformation level of the factory. Since no precise factory planning measures can be derived based on the functionality of the factory as a single, stationary and stand-alone object of investigation as well as the general uncertainty resulting from the factory environment, systems engineering was applied to develop a systematic 3-step approach. Fig 2 illustrates the effect chain initiated by megatrends, which forms the basis for the approach.

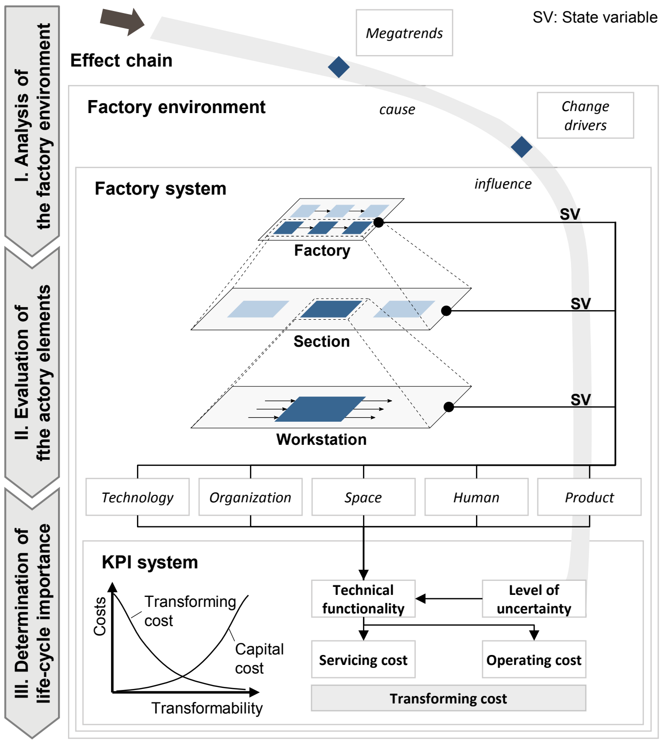

Fig. 2. Systematic approach for identifying change drivers and evaluating their influence on factory elements

The effect chain comes along with a structured approach. First, the factory environment is to be analyzed, whose effects are differentiated into indirect megatrends and the resulting direct change drivers (Step I). The initial step involves a collection of possible megatrends and drivers. The developed catalogs assist in identifying company-specific drivers as a starting point for determining the impact on the factory. Afterwards, the factory is divided into factory elements and the influences of change drivers is investigated in combination with the technical functionality (Step II). A methodology is proposed that evaluates the degree, to which each factory element is influenced by change drivers (level of uncertainty). Hence, along with the technical functionality, the life cycle relevance of factory elements and the resulting need for factory planning measures can be determined (Step III). Based on this, different types of lifetimes can be distinguished. The transparency regarding the level of uncertainty allows a target-oriented design of transformability in the factory. The higher the desired degree of transformation, the higher are initial capital costs due to factory planning measures [3]. At the same time, changing costs over the life cycle decrease, because the change process can be carried out much faster and more cost-efficiently [3].

3.2. Analysis of the factory environment

Uncertainties during factory operation are resulting from an unsettled factory environment due to constant changes caused by megatrends which characterize the present and future of the industry [5]. Megatrends have a formative influence on the underlying structure, behavior and value system in a society. They form and unfold slowly, but when they appear, they last over a period of 10-20 years with a high economic, political and/or social relevance [23]. Megatrends are thus at the starting point of the effect chain that triggers the need for change in factory elements. In order to give an overview of current megatrends, a preliminary review was performed and the resulting list of megatrends was clustered subsequently (Table 1).

Table 1. Consolidated megatrends and their assigned subtrends [24–28]

Categories	Short description
Globalization	Ongoing global interactions with efforts of local action **e.g.** mobility and transport, disparities between states
Prosperity orientation	The growing urge for an individual quality of life **e.g.** mass customization, urbanization, healthy lifestyle
Sustainability	Sustainability trends due to burden on the environment **e.g.** depletion of natural resources, pollution
Demographic change	Alteration of the population structure, e.g. birth rate **e.g.** ageing of society, change in gender roles
Technological progress	Increasing integration of different scientific disciplines **e.g.** digitalization, connectivity
Knowledge society	Knowledge through excellent access to information **e.g.** changing world of work, increasing role of services

The megatrends listed above often cannot be observed independently and the sphere of influence can vary greatly from country to country. In order to assess the extent, to which a megatrend could have an effect on the closer factory environment, it is advantageous to keep track of the interrelationships between the megatrends. These interactions determine the probability of the occurrence of a change driver in the end. Change drivers are not the result of one megatrend, but are the result of the interaction of several megatrends.

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Additionally, a megatrend does not necessarily always lead to the same change driver within the factory environment, but can have different effects depending on the effect chain exemplary described above. Change drivers create new requirements for the factory. The result of the derivation of these different change drivers is presented in Table 2.

Table 2. Derived and categorized change drivers [24–28]

Categories	**Short description**
Product and technology cycles	Higher innovation pressure in shorter intervals **e.g.** new products/technologies, focus on core areas
Legal environment	Adaptation of laws in response to changes **e.g.** change in health care, labor law, safety rules
Global organization	Increased interdisciplinary cooperation **e.g.** change in competition, supplier/sales options
New markets and consumer patterns	Development of new regions/customer groups **e.g.** changed demand, changed product requirements
Environment and social impact	Environmental awareness and social change **e.g.** higher resource costs, higher efficiency
Working environment	New requirements on working conditions **e.g.** availability of workers, degree of automation

Table 2 further breaks down the change driver categories. Their range of action is sufficiently narrowed down to specific change drivers that can have a direct effect on factory elements. An effective direction of the specific change drivers is not assigned yet, because it is case-specific. For example in the category *working environment*, the *degree of automation* is assumed to increase in an industrialized country like Germany due to the technological progress. Additionally, the *aging workforce* requires a reduction of physical work. This may be the opposite in a developing country.

3.3. Evaluation of the factory elements

The evaluation of the influence of a change driver on the entire factory is not practicable, because the factory is defined as a complex socio-technical system. Therefore, the factory system is divided into a hierarchical structure with factory levels and factory elements [5]. Factory elements have been consolidated and complemented for the purpose of life cycle evaluation in a previous work [29]: Every factory element must serve its specific purpose, so that the factory as a whole can meet the requirements. While doing so, a certain life cycle behavior can be observed that results from different states throughout factory operation. By operationalizing the qualitative concept of the utility value, each factory element is described using state variables (SV) from the three perspectives *input-output* (e.g. power demand, process rate), *functionality* (e.g. failure rate, process rate), and *lifetime* (e.g. wear, deterioration). The interaction of the state variables determines the technical functionality of the factory elements. It describes, how and to what degree the set requirements of the factory elements can be met (e.g. throughput, stock level). As the life cycle progresses from life cycle state (LCS) I to III (see [29]), the technical functionality decreases more and more due to longer downtimes or increasing number of quality issues.

The uncertainties resulting from the unsettled factory environment are not taken into account by the LCS yet. For this purpose, a level of uncertainty (LU) is proposed for each factory element. It is calculated by quantifying the influence of change drivers as a result of megatrends. First, change drivers are weighted (w) by performing a pair-by-pair comparison to determine their priority for the considered factory. Second, the influence (I) of every change driver on every factory element is estimated individually on a scale from 1 to 10. Third, the LU is calculated as the sum of the weighted influence of the change drivers on the respective factory element.

$$LU_{Factory\ element} = \sum_{x=1}^{n} \frac{w_x I_x}{I_{max}} \qquad (1)$$

A LU > 0 indicates that a factory element is influenced by a change driver. Every additional change driver adds up to the LU. The higher the LU, the higher is the influence of change drivers. Consequently, the LU can be divided into classes I to III, describing a low, middle or high level of uncertainty. Hereby, another perspective is added to the LCS. Factory planners can additionally focus on factory elements with a high level of uncertainty when establishing transformability in order to prevent a premature end of the life cycle.

3.4. Determination of the life cycle importance of factory elements

For a holistic orientation of factory planning activities, the LCS and LU are considered together as life cycle importance (LCI) of factory elements. The LCI is calculated as maximum of LCS and LU, resulting in the respective three classes.

$$LCI_{Factory\ element} = \max(LCS, LU) \qquad (2)$$

The combination of LCS and LU allows factory planners to focus on the most critical factory elements in terms of planning need. Essentially, the factory elements, whose life cycle have come to an end must be identified. This results in different perspectives on the lifetime which are summarized in Figure 3.

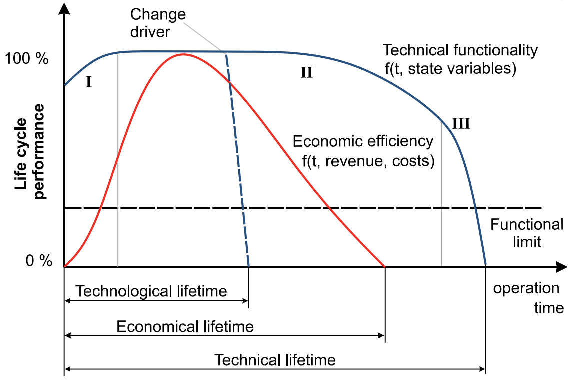

Fig. 3. Differentiation of the perspectives on the lifetime of a factory element

The technological lifetime comes to an end once the factory element cannot serve the required purpose anymore due to a change driver. The economic lifetime covers the period, in which the factory element is operated cost-efficiently. The technical lifetime describes the time span, in which the factory element is functional. As soon as the economic life cycle has come to an end, continued operation is no longer financially viable due to the cost overrun. But once the technological or technical life cycle of a factory element is over, the operation

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must be stopped. This consequently leads to the end of the factory life cycle in its current form until the factory element is replaced or adjusted.

The factory elements can be placed in a LCI portfolio of the factory (Fig. 5) in order to derive factory planning measures. Table 3 compares exemplary characteristics of the three LCI classes that subdivide the portfolio.

Table 3. Evaluation of the life cycle importance of the factory elements

LCI	Description
1	Planning is on hold until further notice due to stable functionality and fulfilled requirements.
2	Monitoring is recommended as functionality will slowly decrease or future requirements will not be met.
3	Immediate action is required, because factory operations are jeopardized by low functionality or unmet requirements.

The lower the technical functionality of a factory element due to an advanced LCS, the higher the probability of a decreased performance of the factory depending on the relevance of the factory element. When also considering the factory environment, change drivers can further strain the technical functionality through changed future requirements. They occur over the life cycle of the factory and influence the factory elements and their state variables. Either the factory element can no longer fulfill the desired purpose at all (e.g. new product), or it can no longer fulfill it to the full extent (e.g. higher demand). The exact nature of the effects depends on the intensity of the change driver and the configuration of the factory element. Factory planners can make use of this knowledge by deriving a certain degree of transformation in line with the expected change drivers. Figure 4 shows the life cycle behavior of a factory element with the according cost trend resulting from the interaction of the state variables including the appearance or non-appearance of a change driver.

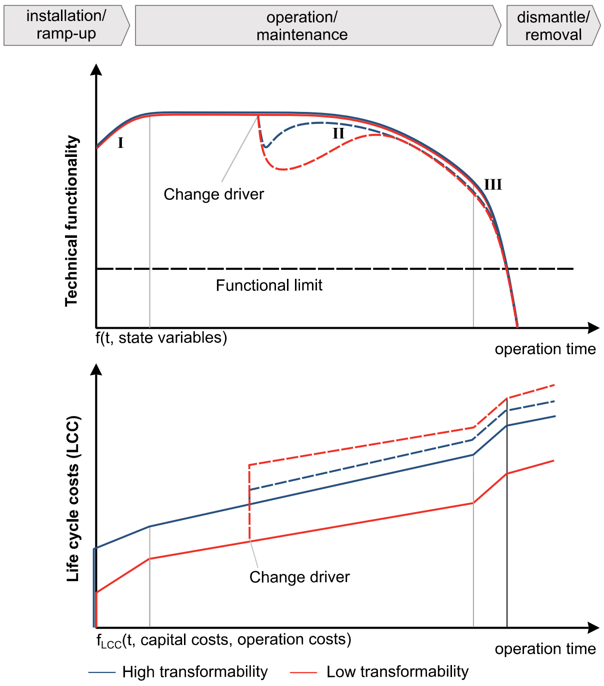

Fig. 4. Influence of a change driver on the functionality and life cycle costs of a factory element, qualitative representation inspired from [29]

When evaluating the economic performance of the factory over lifetime, the comparison of the planned transformability with different levels of change can help the factory planner to develop a factory configuration with an appropriate degree of transformation. If increased requirements are expected due to a change driver in the future, the negative impact on the technical functionality can be reduced with the help of transformability. As a result, higher initial capital costs will pay off over lifetime, because adjustments can be carried out faster and more cost-efficiently. On the contrary, these kind of changing costs are not incurred, if the change driver does not appear. Thereby, the additional capital costs cannot be amortized over the life cycle, because the baseline of the technical functionality is not interrupted by change requests.

4. Case study

The developed approach was tested in a workshop with factory planners of a small and medium sized enterprise (SME) in Germany at the Institute of production systems and logistics (IFA) to illustrate its applicability. The list of megatrends developed was presented to the SME as an introduction and possible additions were discussed. After a scoring of the most relevant megatrends, the developed change driver catalogue was filtered and exemplary change drivers from the catalogue matching the selected megatrends were presented. These formed the basis for the development of the company-specific change drivers. With the conclusion of the creative part of the workshop, the LU could now be calculated based on the change drivers in addition to the LCS from a previous workshop and merged into the LCI. Table 4 shows an extract from the calculation of the LCI for an exemplary factory element.

Table 4. Extract of the evaluation of the LCI of the storage system

…	LCS	Change driver	w_x	I_x	I_{wx}	LU	LCI
…		…	…	…	…		
…	3	Product innovations	0.3	6	0.18	2	3
…		Driving ergonomics	0.1	10	0.10		
…		Data availability	0.4	0	0		

Digitalization, *ageing society* and *mass customization* were identified as the most important megatrends, which formed the basis in order to derive change drivers like *product innovations*, *driving ergonomics* and *data availability*. In figure 5, a summary of the results of the applied methodology is presented.

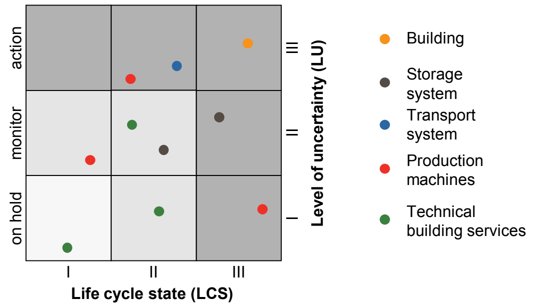

Fig. 5. Life cycle importance portfolio of a factory

Need for action was identified for five factory elements, three of which are in life cycle state III: The production

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machine is responsible for the production of standard parts and therefore not susceptible, but worn out. The storage system is an old pallet rack with a picking area located at floor level. In the medium term, the picking area no longer meets ergonomic requirements and a significant increase in components in the warehouse is expected due to new product launches. Their influence on the production space provided by the old building is much more pronounced. Besides the building, a transport system and another production machine have a high level of uncertainty. In future, the latter must be able to record and exchange various data (e.g. batch information). At the end of the analyses, it was decided to upgrade or replace the production machines, to increase the load capacity of the forklift, to plan for expansion areas in the building and to install ergonomically friendly pallet pull-outs in the racking. The remaining factory elements were either classified as uncritical (on hold) or will be reviewed regularly in the future (monitor).

5. Discussion and summary

With an increasing uncertainty in the factory environment, factory planners are struggling to make factories future-proof while maintaining economic efficiency. Transformability is one concept to prepare the factory for constant changes. In order to be able to determine an appropriate degree of transformability, factory life cycle information is required. Currently, quantitative decision support models are lacking to forecast factory life cycles under uncertainty. With the vision to fill this gap, this paper presents a first approach to evaluate the influence of change drivers on the life cycle of factory elements. Based on an analysis of the level of uncertainty, life cycle relevant factory elements can be identified in order to guide factory planning activities. Possible effects of the resulting degrees of transformability on costs over the factory life cycle were discussed. This will create an initial awareness for the relationship between transformability and life cycles, and will provide factory planners with a starting point, on where transformability is really needed. The applicability of developed methodology was shown in a brief case study.

Although the method offers a first approach to create transparency regarding the effects of change drivers on the factory and its factory elements, much more information is needed for targeted factory planning activities. An isolated consideration of individual factory elements is not sufficient because a change in one element will cause interactions within the factory. Additionally, quantitative information on the extent of the change drivers and the life cycle costs for factory planning measures is needed in order to be able to plan the exact scope of the activities. Besides transformability, other factory characteristics should be evaluated over the factory life cycle in order to be able to deal with the increasing number of short-term uncertainties in terms of disruptive risk events.

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