CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
CPSL 2023

4th Conference on Production Systems and Logistics

Analysis Of Uncertainty Over The Factory Life Cycle

Lennart Hingst[1], Peter Nyhuis[1]
[1] *Leibniz University Hannover, Institute of Production Systems and Logistics, An der Universität 2, 30823 Garbsen, Germany*

Abstract

The cost and performance structure of a factory is determined in factory planning and activated in the operation phase with a time delay. Even though the majority of investments result from structural planning, the first conceptual and most important step in factory planning, the majority of costs occur during factory operation, the longest phase of a factory life cycle. Life cycle-oriented factory planning seeks to anticipate operation in order to increase the performance potential and reduce total costs over the entire factory life cycle. Experience shows that this can reduce total costs by about one-third, 80% of which are unplanned operating costs. Therefore, it is imperative to be aware of possible uncertainties in the course of a factory life cycle as a factory planner. Up to now, there has been an inconsistent understanding in this regard. By definition, the emphasis has been on long-term change drivers influenced by megatrends due to the strategic orientation of factory planning. The current crisis situation illustrates the relevance of an operational view on potential short-term uncertainties. The goal of the paper is to analyze the uncertainty over the factory life cycle in its entirety and to create a common understanding for factory planning so that life cycle-oriented planning and evaluation of factories can be aligned accordingly.

Keywords

Factory Planning; Factory Life Cycle; Uncertainty; Change Drivers; Risks

1. Introduction

The meta-goal "profitability of a factory" ensures the success of a company by producing products competitively in the long term [1]. Factory planning is responsible for the design of a factory according to corporate requirements [2]. It defines the cost structure of a factory and a large proportion of its costs, although they do not emerge until the factory is in operation [3]. Factory operation is the longest and hence most important life cycle phase of a factory, which can last several decades [4,5]. On the workstation level, capital expenditures are known to account for about 25 % of life cycle costs, while operating expenditures are associated with 75 %. Therefore, a life cycle-oriented system configuration can reduce total costs by about one-third over the lifetime of a machine. In particular, unplanned operating costs are reduced by 80 %. [6] If established on factory level, this involves the consideration of increasing uncertainties during factory operation. On the one hand, long-term megatrends such as digitization, mass customization or climate change are intensifying the effect of change drivers, which repeatedly create new requirements for the factory. On the other hand, there are short-term disturbances that can lead to disruptions in operations, which have a relevant impact on the profitability of a factory and are difficult to anticipate. [7,8] Instead of permanently and reactively adapting the factory to quasi-static conditions, life cycle-oriented factory planning aims for proactive planning of the factory life cycle. Operations is considered prospectively during planning, and a factory concept is developed from a life cycle-oriented perspective. [9] However, in contrast to capital

DOI: https://doi.org/10.15488/13497
ISSN: 2701-6277

expenditures, which can be determined at the end of the conceptual factory planning phases at the latest, operating expenditures can only be forecasted and are accompanied by the operational uncertainties described above. Therefore, the goal of this paper is to establish a clear understanding of uncertainty throughout the factory life cycle in order to create the basis for life cycle-oriented factory planning and clarification of factory design decisions for coping with uncertainties.

2. Background and state of research

2.1 Life Cycle Evaluation

A life cycle describes typical cyclical patterns of an observed system over time [10]. Based on these patterns, the life cycle of technical and socio-technical systems can be divided into several life cycle phases. Life cycle models consider either the chronological sequence of life cycle phases, e.g. from the raw material to the end-of-life of a product (flow orientation) or the time-dependent state development, e.g. of customer demand from the introduction to the phase-out of a product (state orientation) [10,11]. In technical systems such as a factory, value is created by combining the production factors equipment, material, energy, information and personnel [12]. Therefore, the production system is also called a flow system that converts the inputs material, energy and information into products and services [13]. The exchange of flows with the ecosphere consequently leads to environmental impacts that can be assessed and visualized with the help of life cycle assessment (LCA) [14]. The elementary flows determined in the life cycle inventory are analyzed in the impact assessment with regard to their environmental consequences [10]. Monetarily factored elementary flows are included in the cost structure of a factory, which can be evaluated holistically using the life cycle costing (LCC) method. Life cycle costs are defined as the sum of all expenses required for the intended use of a system from acquisition to disposal [15]. A holistic view of life cycle costs supports the acquisition of capital goods and long-lived products with high investment costs [16]. The life cycle-oriented perspective on the economic and environmental sustainability of a factory is summarized in figure 1:

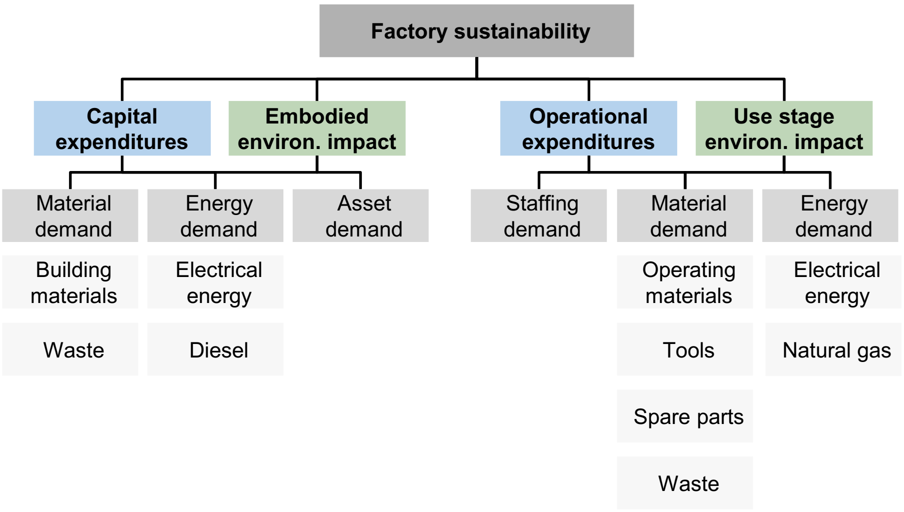

Figure 1: Performance measurement system for factory life cycle evaluation (following [17])

2.2 Factory Life Cycle

The life cycle approach was first applied to an entire factory system by SCHMENNER [18]. In recent publications, the approach has been adopted, and the term "factory as product" is used. Thus, a factory can be considered a very complex product with a long life cycle. As a result, the life cycle concept of a product can also be applied to a factory [19]. However, the factory consists of diverse factory elements that can be assigned to the design fields of technology, space or organization as well as to a hierarchical structure of the factory. The levels of the factory are plant, factory, section and workstation with decreasing level of detail [20]. The sustainability of a factory cannot be influenced directly. It is determined indirectly through the design of the factory elements within the framework of factory planning [21]. The process of factory planning has been described by various authors [22–24,20], which have been combined in VDI Guideline 5200 [25]. Throughout the planning process, developed planning variants are evaluated, and a preferred option is selected for subsequent planning steps or the eventual implementation. An overview of factory models and models for life cycle evaluation of factories was given by Nielsen et al. [26] and updated by Dér et al. [17]. Several detailed models are available for describing the life cycle of individual factory elements. These models address life cycle costs and environmental impacts quantitatively so that they can be used for decision-making. Qualitative description models are predominant for the entire factory. The qualitative approaches either represent phase models or address abstract qualitative key figures such as the utility value shown in Figure 2.

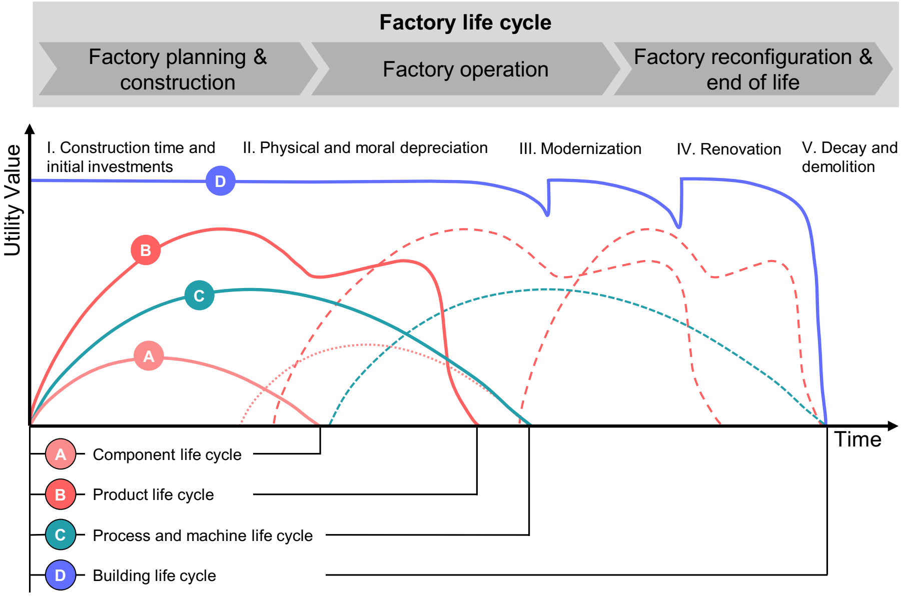

Figure 2: Qualitative model of the factory life cycle, based on [26,27]

The abstract concept of utility value describes whether the main function of a factory element meets the set requirements. Once the required performance cannot be fulfilled, the utility value drops, and the life cycle comes to an end. Therefore, it represents the individual life cycle behaviour of a factory element. The factory elements interact with each other so that requirements are also mutually placed [9]. Ultimately, however, the requirements come from the market, namely the products to be produced [28]. In the past, change and new requirements have always accompanied human, social and industrial developments [29]. In this context, three main stages of industrial development can be differentiated, which result in a static, dynamic and turbulent zone [30]: In the static zone of craftsmanship, it was not mandatory to adapt to economic changes. The beginning of the industrial revolution marked the dynamic zone, where strategic market developments were easy to predict given their low dynamism. The current globally interlinked information age is characterized as a turbulent zone due to the unpredictability of economic, technical and political events. The behaviour of the factory environment was first compared to the physical concept of turbulence in the early 1990s by H.-J. Warnecke [31]. Here, turbulence describes instabilities of gases and fluids as well as cyclonic actions that are difficult to control [32]. In factory planning, the turbulence behaviour of the factory environment was derived from its dynamics and complexity. Environment dynamics describe erratic and unpredictable changes at an unprecedented speed. The significant increase in environmental complexity describes the numerous, strongly linked influencing factors whose interaction is constantly changing [33]. Hernández therefore summarizes that due to the given uncertainty, the traditional ability to forecast developments is practically non-existent. The risk of misjudgment and misinterpretation exceeds the tolerable level. [29] The term risk is closely related to uncertainty as a lack of knowledge or information that makes the occurrence of a future environmental condition or event not predictable with certainty [34]. If uncertainty can be described as a state of incomplete information and decision-makers can estimate subjective or objective probabilities of occurrence, different environmental states or characteristics of events are referred to as risks [35]. Recent crisis situations such as the Covid pandemic or the Ukraine war show that these uncertainties are no longer just about change but also about sudden disruptions so that the original turbulence characteristics of instability and uncontrollability apply more than ever today. At the same time, the efficiency gains sought in the past as well as the increasing complexity of production processes and the associated organization are contributing to the increasing vulnerability of factories [36,37]. 50% of all companies surveyed rank operational disruptions as the most serious business risk [38]. Earlier legalities are at least temporarily suspended, and stability of operations cannot be assumed. Due to the increased occurrence of unpredictable, disruptive events, the factory system sometimes rarely reaches a steady state. Therefore, life cycle-oriented factory planning must prepare the factory not only for medium- to long-term changes but also for short-term disruptions in the future.

2.3 Life cycle-oriented factory planning

The inherent uncertainties in both the factory and the factory environment mean that continuous reorganization of the factory is necessary [20]. Instead of permanently and reactively adapting the factory to quasi-static conditions, life cycle-oriented factory planning aims for proactive planning of the factory. Factory operation is anticipated and a factory configuration is developed and selected whose life cycle costs are minimal [9]. A final evaluation of the economic efficiency of the planned factory configuration can only be made by considering the factory life cycle. Any efforts to prepare the factory for turbulence will only pay off in the event of need. However, the occurrence of the event remains an uncertain variable. The higher the number and intensity of possible turbulences in the course of the factory life cycle, the faster the break-even point of additional expenditures is reached. Therefore, it is essential that life cycle-oriented factory planning takes into account both short-term as well as medium- to long-term uncertainties when planning and evaluating a factory configuration. Against this background, existing approaches are examined regarding their consideration of uncertainties over the factory life cycle.

Due to the historical development of the understanding of turbulence, there are many approaches in the field of factory planning that deal with uncertainties in the form of possible changes over the factory life cycle and the resulting new requirements for the factory. HERNÁNDEZ uses scenario management to determine the need for change [29]. KLEMKE aims to simplify existing approaches of transformability and examines change drivers in more detail [39]. Other approaches focus in particular on the product as a significant change driver in the form of quantity developments [40,41] or new product variants [42–44]. Short-term uncertainties with a disruptive effect on factory operations are anticipated by only a few approaches in factory planning. Usually, the focus is on demand fluctuations (as opposed to demand trends related to medium- to long-term uncertainties) and associated capacity requirements [45,46]. PEUKERT and KNÜPPEL are the only ones to consider disruptions holistically from a strategic perspective, with KNÜPPEL focusing on improving system understanding through system dynamics modelling of the cause-effect relationships of disturbance variables in complex factory systems [37] and PEUKERT considering the factory merely as a network element of a production network. Her approach is based on a catalogue of disruptions from the production and logistics point of view, whose effects are evaluated for strategic network design [47].

Currently, there is no approach in factory planning that considers the entire uncertainty spectrum over the factory life cycle. In particular, the effects of short-term disruptive events are only investigated to a limited extent. There is a lack of an adequate quantitative approach to evaluate the interactions of a factory with its turbulent effects. A dynamic consideration of randomness in terms of disturbances and change drivers is non-existent. Therefore, a literature review is conducted next in order to analyze uncertainty over the factory life cycle so that a basis for differentiation is established.

3. Literature Review

3.1 Overview

Accidents, probability and possibility are historically the first terms associated with uncertainty, dating back to Aristotle [8]. Uncertainty is omnipresent in a socio-technical system and variability is inevitable during the production of products, which is why MORSE ET AL. conducted an extensive literature review on uncertainty throughout the product life cycle [48]: According to THUNNISSEN, aleatory and epidemistic uncertainties form a basic distinction [49]. Aleatory uncertainty is the inherent variation or variability in a physical system and its environment that cannot be reduced. Epidemistic uncertainty means total unawareness about some constituent elements of the system or environment. ENGELHART ET AL. also refer to aleatory uncertainty as stochastic in terms of the probability and spread of an event and epidemistic uncertainty as unknown in terms of lack of knowledge about an event, effect, or behavior of a system. Estimated uncertainty involves both classifications because the effect is known, but the probability of the event is only partially quantifiable [50].

Economic decision theory [51] differentiates between a decision under certainty and a decision under uncertainty in terms of the completeness of the information. If probabilities for uncertainty are known, it is a decision under risk, otherwise it is a decision under incertitude. In many cases, risk is considered to be value-neutral, so both negative deviations in terms of loss possibilities (danger) and positive deviations of an expected outcome in terms of profit possibilities (opportunity) are included [52]. The subdivision of decisions under uncertainty can be traced back to KNIGHT, who attributes incertitude to one-time decisions that do not occur again [35]. In the field of order management for planning and controlling factory operations, uncertainties are also called turbulence drivers, which result in possible triggers for turbulence [53]. For planning, plan adjustments, fluctuations and variances are relevant because mean key figure values then become insignificant for values of individual orders. Unexpected deviations are relevant for controlling because they jeopardize the fulfilment of promised dates and thus the adherence to the planned schedule. Uncertainties can trigger certain events or environmental conditions [8]. In the literature on economics, they include the possibility of a deviation in target achievement and are called risk if it can be identified, analyzed, managed and controlled [8,54]. In this regard, WINCH AND MAYTORENA have elaborated four pairs of terms in a cognitive approach for project management [55]:

- **Known knowns:** Cognitive state of risk for which the source can be identified, and a probability distribution applied.
- **Unknown knowns:** Cognitive state of risk for which the source can be identified and a probability distribution applied, but the information is not accessible.
- **Known unknowns:** Cognitive state of incertitude for which the source can be identified, but a probability distribution cannot be applied to determine the probability of a risk event.
- **Unknown unknowns:** Cognitive state of incertitude for which the source of risk cannot be identified and, therefore, the probabilities cannot be applied.

IVANOV extends that the occurrence of an event can also be described non-stochastically. Instead of aleatory variables with known distributions, fuzzy descriptions can be used [8]. The events and environmental conditions will be considered in more detail below as disturbances and change drivers.

3.2 Disturbances

Disturbances refer to specific individual events in factory operations that cause an unplanned impairment or deviation from the desired system state or process flow [56]. They can be distinguished by system boundaries, the place of occurrence, their duration or their frequency of occurrence [47]. The occurrence of an event (disturbance cause) is also referred to as a disturbance variable, which has a random and uncertain effect on a factory and can result in an undesirable effect (disturbance effect) [57]. In order management, events with a disturbing effect are called turbulence seeds, which are caused by the impact of the explained turbulence drivers on the three essential process steps procurement, production and delivery and resulting in possible triggers for turbulence. The morphology of the turbulence seeds shows that time, date and quantity changes apply predominantly to procurement and delivery, while in production, rather changes in the order mix and the availability of the production resources cause turbulences.[58] Disturbances represent causal cause-effect chains, which in practice are often multi-level situations [59]. By affecting factory elements and processes, disturbances can lead to business disruptions, depending on how vulnerable or sensitive the factory is to disturbances [8]. They have a negative impact on the performance of a factory, which means that the overall targets time, cost and quality can be missed [56,37]. In order management, such an operational disruption is regarded as full turbulence, in which the current actual values of relevant characteristic key figures deviate significantly from their mean value. A tolerance derived from different requirements defines the permissible deviation from the target value, which according to H.-H. WIENDAHL is subjectively defined and objectively strained:[58]

- **Objective** turbulence represents an unexpectedly occurred deviation beyond the planned tolerance so that the assumptions made in the planning for the future have failed in their predictability. In contrast to predictable and weak deviations, sudden and strong deviations cause turbulence and, thus, uncertainty within the planning horizon [60]
- **Subjective** turbulence describes an expected deviation due to a turbulence seed, whose relevance is to be evaluated during planning in order to provide sufficient tolerance for the actual occurrence and thus prevent deviations from the plan.

Disturbances or turbulence seeds are, therefore, either known and predictable or unknown and unpredictable. The known events can be modelled with deterministic or stochastic methods, and their disturbance effect can be estimated [57]. Here, the objective view describes the market requirements and determines the theoretically necessary factory configuration. The subjective aspect evaluates the capabilities compared to the requirements and determines the practically realized factory configuration. For example, the greater the volume fluctuations compared to the available volume flexibility, the higher the turbulence. Significant deviations from the idealized flow pattern of the factory result and the lead time of individual orders varies enormously. In the case of full turbulence, the requirements can no longer be met due to the variability of the turbulence drivers. The planning in the classical sense loses its task, and operations cannot be maintained permanently or only with high effort, leading to an operational disruption. [61]

3.3 Change Drivers

Change drivers influence the basic conditions of a factory, place new requirements and thus lead to a strategic need for change [62]. They influence and determine the required values of the change dimensions cost, time and quality as essential production indicators as well as the required quantity and product variants, that must be met for competitive factory operations [39]. Change dimensions are also referred to as receptors, as they represent receiving devices of a system that is sensitive to specific stimuli, which is then passed on: A change in the dimensions by change drivers leads to a need for change in a factory. Some drivers have a direct influence on the factory and its elements. [63] Following KLEMKE, a distinction can thus be made between target drivers as well as process and element drivers [39]:

- **Target drivers** influence the change dimensions and thus place new requirements on the factory. If the changed target values of a dimension cannot be met, a factory adjustment is necessary.
- **Process and element drivers** have an influence on the basic conditions of a factory. When the drivers occur, specific elements of the factory must be adapted to the changed conditions, which in turn can have a negative impact on the target values of all dimensions.

Due to the unpredictable environment, it is difficult to predict which adjustments will be necessary in the future [1]. However, in contrast to disturbances, a predictive ability is assumed in general. That is why

KLEMKE excludes uncertainties which cannot be predicted with approximate accuracy even by technical experts (e.g. natural disasters) [39]. The forecasting ability results from the influence of megatrends, which represent long-term developments with great relevance from an economic, political and social perspective. Due to the influences of megatrends, the environment of manufacturing companies is constantly changing [64]. Change drivers are also referred to as the impact of megatrends on the factory environment [39]. This in turn results in complex cause-effect relationships between megatrends, change drivers and the factory [62]. The interactions between megatrends, depending on their geographic manifestation, determine the probability and extent of change drivers [65]. They can affect factories internally, i.e. from within a company, or externally, i.e. from the environment of a company. The factory elements affected by the change are themselves in a complex multi-level network with dynamic feedback [62]. Change drivers are therefore medium- to long-term uncertainties that are generally known and predictable.

4. Differentiation Of Uncertainty Over The Factory Life Cycle

Using insights gained from the literature review, the short-term disturbances are to be consistently differentiated from the medium- to long-term change drivers in the following. Hereby, a theoretical basis for the alignment of life cycle-oriented factory planning is provided. Due to the increased inclusion of operations during the conceptual design of a factory in life cycle-oriented factory planning, it is particularly important to focus more strongly on possible disturbances and potentially associated operational disruptions, which have a high relevance in the current time. Stress tests of design variants are carried out in order to select the variant that can cope best with uncertainty during factory operations. For this purpose, the term uncertainty is divided into risk and incertitude in the context of a factory life cycle (see Figure 3).

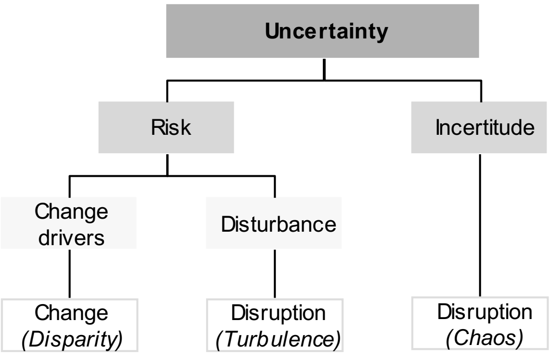

Figure 3: Differentiation of uncertainty over the factory life cycle

Incertitude results from epidemic uncertainty with no knowledge of the origin, probability of occurrence, or possible effect (known/unknown **unknowns**). It is an unforeseen deviation from an outcome. Accordingly, a subjective evaluation can only be made without the expertise or experience that is actually required. In contrast, a risk results from aleatory uncertainty, for which knowledge is available about the probability and distribution of variation in a system and its environment (known/unknown **knowns**). In most practical planning situations, objective probabilities do not exist [51]. Subjective probabilities incorporate the experience and intuition of a factory planner. Therefore, incertitudes are also handled as a risk in real planning situations, using assumptions nevertheless. Otherwise, incertitude would remain completely unconsidered in factory planning.

Risks describe the possible occurrence of different environmental conditions or events as a state of incomplete information, which can lead to a deviation between the target and actual values in controlling. If risks actually occur, a distinction is made between change drivers and disturbances. *Change drivers* can lead to both a positive (opportunity) and negative (danger) deviation. As an environmental condition, they cannot be influenced by factory planning, but they determine the outcome of a decision. In contrast, *disturbances* refer to events affecting individual factory elements that may lead to missed targets. Given their origin in aleatory uncertainty, they are usually known and predictable. As long as a factory is not in a steady state, they are deterministic or predetermined. In the case of reasonably stable processes, they are stochastic or random.

Disturbances can have an immediate effect on the actual values and thus on the current target achievement of factory operation or cause short-term changes in target values. Without further measures, they can lead to *operational disruption*, depending on the vulnerability of a factory. Based on the turbulence classes of order management, *turbulence* gradually arises [66]. In the case of weak turbulence, individual disturbances affect the primary movement of the material flow within a section. The lead time of individual orders deviates significantly and a high level of control effort is required to maintain the flow. Full turbulence affects the entire factory. There is no continuous material flow, which is overlapped by disturbances and can break off leading to a disruption. If incertitude suddenly occurs as an unknown or objectively unpredictable event, it can directly trigger an operational disruption. The event is unexpected, the effect can usually not be absorbed economically so that an unprepared factory is threatened with *chaos*. The material flow breaks off immediately. In contrast, change drivers do not have a disruptive effect and thus have no direct influence on the current processes in factory operation. At the most, they can facilitate the occurrence of disturbances through a change in system state (e.g. ageing behaviour). Instead, they result in new restrictions, potentials for the actual values or requirements for target achievement as new medium- to long-term target values. This prevailing *disparity* is balanced by implemented *changes* that ultimately transform operations and adapt processes to new conditions. Change drivers explicitly refer to future environmental conditions after factory planning is completed. During a factory planning project, uncertainties in environmental conditions are referred to as planning risks. These are assumptions about parameters that are detailed and confirmed during the planning process [67]. Such assumptions pose a risk to the target achievement of a factory configuration.

Life cycle-oriented factory planning therefore combines the preliminary considerations on turbulence from classic factory planning and order management in order to prepare the factory in the best possible way for any kind of uncertainty over the factory life cycle. Factory configurations must be designed differently, depending on whether medium- to long-term changes in environmental conditions (change drivers) or short-term operational disturbances (disruptions) are expected. Ideally, a life cycle-oriented factory configuration manages to maintain target achievement despite the upcoming uncertainties. If target achievement is permanently impaired by disturbances or if the capability of a factory configuration to achieve a target value is insufficient due to a change driver, the current factory life cycle comes to an end and a new factory planning project must be initiated.

5. Discussion and outlook

In summary, future challenges in factory operation can be anticipated based on the developed differentiation of uncertainty. It forms a useful basis for considering the unavoidable uncertainties in life cycle-oriented factory planning. Nowadays, factory planners have to become more aware of possible disruptions and thus of the entire factory operation in addition to possible change drivers. Consideration must be given to whether the capacities and capabilities provided in a factory configuration are sufficient and effective enough for the uncertainties to be expected during factory operation. Future research is needed to make the uncertainties identified in this paper assessable as part of a factory life cycle model in order to be able to select factory planning measures and determine their scope of action depending on the evaluated effect of the uncertainties. This involves a prognosis model in a suitable level of detail, which simulates the temporal behaviour of a factory after the occurrence of uncertainty. Furthermore, explicit design principles based on the strategies of risk management are to be developed in the future for the sophisticated handling of uncertainties.

Acknowledgements

Partially funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – 412409961. The authors wish to thank Antal Dér and Christoph Herrmann for the valuable discussions.

References

[1] Heger, C.L., 2006. Bewertung der Wandlungsfähigkeit von Fabrikobjekten. Dissertation. PZH, Produktionstechnisches Zentrum, Garbsen.

[2] Wiendahl, H.-P., Harms, T., Heger, C.L., 2003. Die Fabrik als strategisches Wettbewerbsinstrument, in: Reinhart G., Z.M. (Ed.), Marketchance Individualisierung. Springer, Berlin, Heidelberg.

[3] Gairola, A., 1981. Montagegerechtes Konstruieren: Ein Beitrag zur Konstruktionsmethodik. Dissertation, Darmstadt.

[4] Gebler, M., Cerdas, J.F., Thiede, S., Herrmann, C., 2020. Life cycle assessment of an automotive factory: Identifying challenges for the decarbonization of automotive production – A case study. Journal of Cleaner Production 270.

[5] Herrmann, C., Kara, S., Thiede, S., 2011. Dynamic life cycle costing based on lifetime prediction. International Journal of Sustainable Engineering.

[6] Perlewitz, U., 1999. Konzept zur lebenszyklusorientierten Verbesserung der Effektivität von Produktionseinrichtungen. Dissertation. PTZ, Berlin.

[7] Hingst, L., Park, Y.-B., Nyhuis, P., 2021. Life Cycle Oriented Planning Of Changeability In Factory Planning Under Uncertainty. Proceedings of the Conference on Production Systems and Logistics : CPSL 2021.

[8] Ivanov, D., 2018. Structural Dynamics and Resilience in Supply Chain Risk Management, 1st ed. 2018 ed. Springer International Publishing; Imprint: Springer, Cham.

[9] Hingst, L., Dér, A., Herrmann, C., Nyhuis, P., 2023. Towards a holistic life cycle costing and assessment of factories – Qualitative modeling of interdependencies in factory systems. Sustainability.

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

[11] Herrmann, C., Bergmann, L., Thiede, S., Halubek, P., 2007. Total life cycle management-an integrated approach towards sustainability, in: 3rd International Conference on Life Cycle Management, Zurich.

[12] Helbing, K.W., 2018. Handbuch Fabrikprojektierung, 2., aktualisierte und ergänzte Auflage ed. Springer Vieweg, Berlin, Heidelberg.

[13] Müller, E., Engelmann, J., Löffler, T., Strauch, J., 2009. Energieeffiziente Fabriken planen und betreiben. Springer Berlin Heidelberg, Berlin, Heidelberg.

[14] International Organization for Standardization, 2021. Environmental management – Life cycle assessment – Principles and framework.

[15] Verein Deutscher Ingenieure, 2005. Purchase, operating and maintenance of production equipment using Life Cycle Costing (LCC): VDI 2884.

[16] Hauschild, M.Z., Rosenbaum, R.K., Olsen, S.I., 2018. Life Cycle Assessment: Theory and Practice. Springer International Publishing, Cham.

[17] Dér, A., Hingst, L., Nyhuis, P., Herrmann, C., 2022. A review of frameworks, methods and models for the evaluation and engineering of factory life cycles. Advances in Industrial and Manufacturing Engineering.

[18] Schmenner, R.W., 1983. Every Factory has a Life Cycle. Harvard Business Review 61 (2), 121–129.

[19] Westkämper, E., Constantinescu, C., Hummel, V., 2006. New paradigms in manufacturing engineering: factory life cycle. Annals of the Academic Society for Production Engineering. Research and Development 13 (1), 143–147.

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

[21] Nyhuis, P., Kolakowski, M., Heger, C.L., 2005. Evaluation of Factory Transformability, in: 3rd International CIRP Conference on Reconfigurable Manufacturing, Ann Arbor, USA. May.

[22] Grundig, C.-G., 2018. Fabrikplanung: Planungssystematik - Methoden - Anwendungen, 6., neu bearbeitete Auflage ed. Hanser, München.

[23] Pawellek, G., 2014. Ganzheitliche Fabrikplanung, 2. Auflage ed. Springer Vieweg, Berlin, Heidelberg.

[24] Schenk, M., Wirth, S., Müller, E., 2014. Factory Planning Manual: Situation-Driven Production Facility Planning, Aufl. 2010 ed. Springer Berlin, Berlin.

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

[26] Nielsen, L., Schmidt, C., Blume, S., Schmidt, M., Thiede, S., Nyhuis, P., Herrmann, C., 2016. Towards Quantitative Factory Life Cycle Evaluation. Procedia CIRP 55, 266–271.

[27] Wirth, S., Günter, U., David, T., 2000. Durchgängiges Planungskonzept mit ganzheitlicher simulationsbasierter Layoutplanung, in: Vortragsband "Vernetzt planen und produzieren", Chemnitz, pp. 56–61.

[28] Hingst, L., Nyhuis, P., 2022. Controlling Product Variance in a Factory Through the Evaluation of the Factory Life Cycle. Advances in Production Management Systems. Smart Manufacturing and Logistics Systems: Turning Ideas into Action. APMS 2022. IFIP Advances in Information and Communication Technology, vol 663. Springer, Cham.

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

[30] Spur, G., Stöferle, T., 1994. Fabrikbetrieb. Hanser, München.

[31] Warnecke, H., 1992. Die Fraktale Fabrik: Revolution der Unternehmenskultur. Springer Berlin Heidelberg, Berlin, Heidelberg.

[32] Grote, K., Feldhusen, J. (Eds.), 1995. Dubbel: Taschenbuch für den Maschinenbau. Springer Berlin Heidelberg, Berlin, Heidelberg.

[33] Zahn, E., Tilebein, M., 1999. Führung wandlungsfähiger Unternehmen – eine Herausforderung in neuen Dimensionen. Industrie Management 14 (6), 49–52.

[34] Schneeweiß, C., 1991. Planung: Systemanalytische und entscheidungstheoretische Grundlagen. Springer, Berlin, Heidelberg.

[35] Knight, F., 1921. Risk, Uncertainty and Profit.

[36] Ivanov, D., Sokolov, B., Dolgui, A., 2014. The Ripple effect in supply chains: trade-off ‘efficiency-flexibility-resilience’ in disruption management. International Journal of Production Research 52 (7), 2154–2172.

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

[38] Allianz, 2021. Allianz Risiko Barometer 2021. https://www.agcs.allianz.com/news-and-insights/news/allianz-risk-barometer-2021-de.html.

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

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

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

[42] Blumenau, J.C., Kotz, T., 2005. Wandlungsfähigkeit auf Abruf: Bedarfsgerechte Gestaltung und Bewertung stückzahlflexibler Produktionssysteme für die Massenfertigung von Hochleistungserzeugnissen. Zeitschrift für wirtschaftlichen Fabrikbetrieb 100, 42–46.

[43] Khedri Liraviasl, K., ElMaraghy, H., Hanafy, M., Samy, S.N., 2015. A Framework for Modelling Reconfigurable Manufacturing Systems Using Hybridized Discrete-Event and Agent-based Simulation. IFAC-PapersOnLine 48 (3), 1490–1495.

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

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

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

[47] Peukert, S.K., 2021. Robustheitssteigerung in Produktionsnetzwerken mithilfe eines integrierten Störungsmanagements. Dissertation, Karlsruhe.

[48] Morse, E., Dantan, J.-Y., Anwer, N., Söderberg, R., Moroni, G., Qureshi, A., Jiang, X., Mathieu, L., 2018. Tolerancing: Managing uncertainty from conceptual design to final product. CIRP Annals 67 (2), 695–717.

[49] Thunnissen, D. Uncertainty Classification for the Design and Development of Complex Systems.

[50] Engelhardt, Alexander, R., Eifler, Tobias, Mathias, Johannes, Kloberdanz, Hermann, Birkhofer, Herbert, Bohn, Andrea, 2011. Linkage of methods within the umea methodology: An approach to analyse uncertainties in the product develmopment procees. INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN.

[51] Laux, H., Gillenkirch, R.M., Schenk-Mathes, H.Y., 2018. Entscheidungstheorie, 10., aktualisierte und erweiterte Auflage ed. Springer Gabler, Berlin, Heidelberg.

[52] Wildemann, H., Baumgärtner, G., 2006. Suche nach dem eigenen Weg: Individuelle Einführungskonzepte für schlanke Produktionssysteme. Zeitschrift für wirtschaftlichen Fabrikbetrieb 101 (10), 546–552.

[53] Wiendahl, H.-H., 2006. Auftragsmanagement im turbulenten Umfeld: Teil 2 – Lösungsansätze. wt Werkstattstechnik online 96 (5), 325–330.

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

[55] Winch, G.W., Maytorena, E. Managing Risk and Uncertainty on Projekts, A Cognitive Approch, in: , The Oxford handbook of project management, pp. 345–364.

[56] Heil, M., 1995. Entstörung betrieblicher Abläufe. Gabler Verlag.

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

[58] Wiendahl, H.-H., 2011. Auftragsmanagement der industriellen Produktion. Springer Berlin Heidelberg, Berlin, Heidelberg.

[59] Bormann, D., 1978. Störungen von Fertigungsprozessen und die Abwehr von Störungen bei Ausfällen von Arbeitskräften durch Vorhaltung von Reservepersonal. Günter Marchal und Hans-Jochen Matzenbacher WIssenschaftsverlag, Berlin.

[60] Mintzberg, H., 1994. That's Not "Turbulence," Chicken Little, It's Really Opportunity, in: , Planning Review, pp. 7–9.

[61] Wiendahl, H.-H., 2002. Situative Konfiguration des Auftragsmanagements im turbulenten Umfeld. Dissertation, Stuttgart.

[62] Nofen, D., 2006. Regelkreisbasierte Wandlungsprozesse der modularen Fabrik. Dissertation, Hannover.

[63] Heinen, T., 2011. Planung der soziotechnischen Wandlungsfähigkeit in Fabriken. Dissertation, Garbsen.

[64] Adolph, S., Tisch, M., Metternich, J., 2014. Challenges and approaches to competency development for future production. Journal of International Scientific Publications 12, 1001–1010.

[65] Hingst, L., Dér, A., Herrmann, C., Nyhuis, P., 2021. Evaluation of the influence of change drivers on the factory life cycle. Procedia CIRP.

[66] Westkämper, E., Wiendahl, H.-H., Pritschow, G., Rempp, B., Schanz, M., 2000. Turbulenz in der PPS – eine Analogie. wt Werkstattstechnik online 90 (5), 203–207.

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

Biography

Lennart Hingst, M.Sc. (*1989) has been a research associate in the factory planning group at the Institute of Production Systems and Logistics (IFA) at the Leibniz University Hanover since 2019. He previously studied technical logistics at the University of Duisburg-Essen (M.Sc.) and holds years of industry expertise.

Prof. Dr.-Ing. habil. Peter Nyhuis (*1957) has been head of the Institute of Production Systems and Logistics (IFA) at Leibniz University Hanover since 2003. Prof. Dr.-Ing. habil. Peter Nyhuis was a member of the German Science Council (2014 – 2018) and has been Chairman of the Science Council of the AiF (GAG3) since 2015. He is also a member of the German Academy of Technical Sciences acatech and the Scientific Society for Production Technology (WGP).