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# Life Cycle Oriented Planning Of Changeability In Factory Planning Under Uncertainty

Lennart Hingst<sup>1</sup>, Yeong-Bae Park<sup>1</sup>, Peter Nyhuis<sup>1</sup><sup>1</sup>*Institute of Production Systems and Logistics (IFA), Leibniz University Hannover, Germany*

## 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

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.

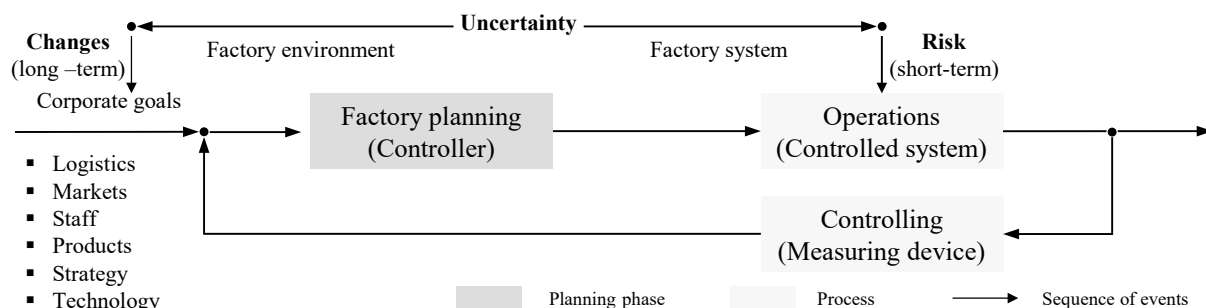


Figure 1: Uncertainty influencing the control system of factory planning, based on [42]

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 adaptations [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.

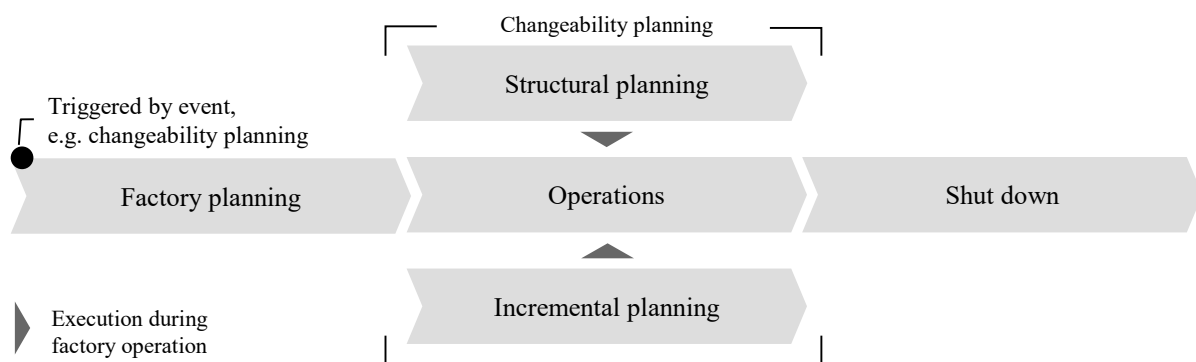


Figure 2: Classification of changeability planning in the factory life cycle, based on [2]

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 pre-planning, 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.

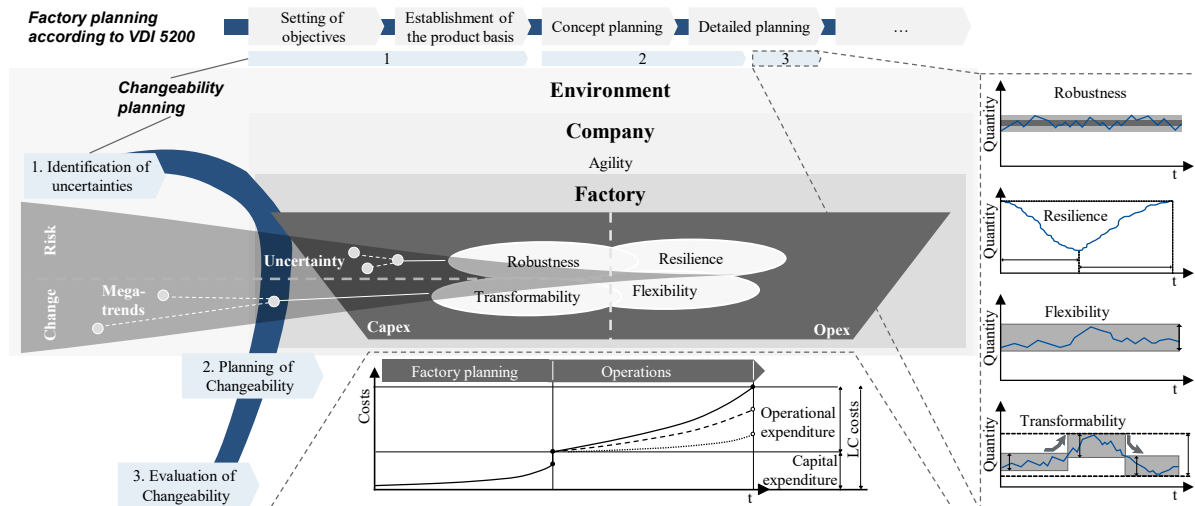


Figure 3: An overview of changeability planning in factory planning, based on [30,24,59]

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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## Biography



**Lennart Hingst, M.Sc.** (\*1989) has been a research associate in the specialist 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.



**Yeong-Bae Park, M.Sc.** (\*1994) has been a research associate in the specialist factory planning group at the Institute of Production Systems and Logistics (IFA) at the Leibniz University Hanover since 2019. He previously studied mechanical engineering at the TU Ilmenau (B.Sc.) and at the Karlsruhe Institute of Technology (M.Sc.).



**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).