# A New Approach to Consider Influencing Factors in the Design of Global Production Networks

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**Abstract.** Uncoordinated decisions that have a long-term impact on the production network lead to inefficient structures and limit the ability to change. However, the ability to change is a basic prerequisite for future decisions. At the same time, the world is becoming more volatile, uncertain, complex, and ambivalent. To counteract this, external and internal influencing factors must be considered in the early stages of planning global production networks (GPN). The design of GPN is on the one hand associated with a large number of degrees of freedom and on the other hand with a large number of influencing factors. Influencing factors can thereby be known and predictable, but also unknown and unpredictable. To make production networks capable to change in the long term, influencing factors and their effect on the network design must be considered. The combination of influencing factors with consideration of uncertainty still needs further research in the context of network design. Thus, this article aims to develop a method for network design that does not only take external and internal influences into account at an early stage but also leads to a network configuration that considers these influences and increases resilience. To achieve this, the influencing factors should first be represented in scenarios using the receptor theory. Subsequently, the scenarios can be incorporated into the optimization of the network configuration by choosing a solution from a predefined solution space. The process of solution selection and testing can be supported by a digital twin. The result is an initial concept that merges these different steps into a continuous process that can be used to design adaptable GPN in the future.

**Keywords:** Influencing factors · Network configuration · Uncertainty · Global production networks · Changeability · Resilience

## 1 Introduction

Today, manufacturing companies operate in an increasingly complex and constantly changing environment. This environment is characterized by volatility, uncertainty, complexity, and ambiguity (VUCA world) [1]. The influencing factors shaping the environment can be internal or external in origin [2] and quantitative or qualitative [3]. Many of the planning parameters used are subject to uncertainty [4]. Only a comprehensive

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consideration of the influencing factors can reduce the uncertainty associated with them [3, 5]. In addition, there are always new influencing factors that are not or only very difficult to predict (e.g. blockade in the Suez Canal, the Corona crisis, the semiconductor shortage, etc.).

The influencing factors are contrasted by network structures that have been built up over the last decades as well as resulting from short-term and uncoordinated decisions [2, 6]. Global Production Networks (GPN) are cumbersome to adapt and the complex decisions have a long-term impact [7]. Only continuous planning and proactive updating of decisions can reduce the complexity and uncertainty [8, 9]. To counteract the increasing complexity and uncertainty in the global environment, the flexibility and changeability of the considered GPN can be used [10]. This allows companies to foresee adaptation needs and changes at an early stage, which can then be quickly translated into reality. This could increase the resilience of the GPN.

Digital twins (DT) offer a way to continuously collect and provide data. A DT is the virtual and computerized counterpart of the real system [11]. With a DT, new measures can be tested easily and quickly with the help of simulations. However, the DT must be integrated into an overall concept to achieve maximum benefit. This allows shorter, proactive planning cycles to be realized and uncertainties to be minimized.

Combined with an approach from the software industry, the DevOps approach, continuous integration, updating, and deployment can also be realized for GPN. This approach is already the subject of research at the production and machine levels [24].

The presented research work pursues the goal of presenting a first overall concept, which takes up influencing factors and their uncertainty, enables a continuous and iterative procedure with the help of a DT, and can determine a suitable solution as a result of a need for change. The following research questions will be answered in this paper:

1. How can the drivers of change be quantified and their uncertainty be represented by scenarios?
2. How can the appropriate measures be selected from the solution space?
3. How the selected measures can be quickly tested and transferred into reality with the help of approaches from the software industry
4. How can the digital twin act as an enabler of the overall concept?

## 2 State of the Art

The investigation of the state of the art will be divided into two topics. On the one hand, influencing factors (Drivers of Change) and uncertainties related to their future development shall be considered. On the other hand, approaches for the design and function of GPN are to be considered with which the need for change resulting from the changing influencing factors can be met. From the deficits of the considered approaches, a research gap results, which shall be addressed with the methodology developed in Sect. 3.

Westkämper for example states that drivers of change refer to the turbulent environment in which a company operates. The drivers of change can occur both externally and internally [12]. For example, the drivers of change are applied in site selection [13]. Once the drivers of change are known, they can be analyzed and evaluated. The approaches of Gille and Zwißler [14] and Lanza et al. [15] attempt to categorize the change drivers and thereby enable quantitative analyses. A sound analysis of the drivers of change can reduce the uncertainties associated with them [15].

In addition to the described approaches that focus on the change drivers, further approaches consider change drivers and their uncertainties. Hawer models and classifies the fuzziness of planning parameters using a guideline to achieve the most accurate mapping of fuzziness, for example, through probability distributions. Using appropriate uncertainty propagation mechanisms, uncertainties of the planning parameters that depend on other influencing factors are identified. The identified fuzziness forms the basis for planning a factory's ability to change [16]. In his work, Möller develops a scalable, cross-stage, and valuation-oriented model of production that specifically focuses on uncertainties and defines a hierarchical, life-cycle cost model [17].

The approaches of Hawer and Möller focus on the production and factory level [16, 17]. Further approaches contemplate the network level. In their approach, Reinhardt and Krebs consider several factors that influence site selection. Their method allows the consideration of multidimensional, qualitative, and quantitative uncertainties. These are modeled with probability distributions and the fuzzy method and integrated into a model for structured monetary costing [3]. The paper by Schuh et al. presents a quantitative approach for uncertainty assessment. By evaluating consistent scenarios possible developments of external factors are transformed into a measure of uncertainty [6]. The scenario model is based on the work of Gausemeier [18]. Dobler et al. also describe an approach based on scenarios. It is used for the early detection of production technology deficits under uncertainty derived from megatrends [19].

In the following, approaches that try to counteract the uncertainties in the design of GPN by proposing different configurations or which propose measures to reduce the influence of the change drivers are, presented. Neuner distinguishes between certain and uncertain, uninfluenceable factors. On a more detailed level, a representation of the uncertainty behavior can be done either with or without exact probabilities. Neuner thereby uses the uncertainties to better configure international production networks. The result always represents a network variant or alternative [20]. Lanza and Moser present a model for dynamic multi-objective optimization of GPN. It evaluates the impact of influencing factors and optimizes the design of the GPN [21]. Moser presents an approach for migration planning in GPN in a volatile environment. The approach can be used to identify robust migration paths of the network configuration considering multidimensional drivers of change from the business environment [8]. Ude presents a decision support model for the configuration and evaluation of a globally distributed value network. Dynamics and uncertainties are taken into account in the input data by integrating a Monte Carlo simulation in the simulation model [22]. Schuh et al. present a systematic approach to determine the necessary level of agility in GPN. The necessary agility levels are based on the consideration of the volatility of the influencing factors and a cost-benefit decision [23]. In his work, Sager combines existing approaches to create a new approach for configuring GPN. To reduce time and cost, he applies a cyclic approach to develop alternatives to incrementally improve GPN [9].

Based on the analysis of the state of the art, it can be concluded that influencing factors are taken into account, but no approach continuously considers the uncertainty of influencing factors and transfers them into a DT. Uncertainty is often only used as an input into an optimization model which tries to reduce the uncertainty. Different approaches focus on one part of an overall solution. A combination into an overall concept is not done so far. Rather, Sager's integration into a cyclic approach is only done for a one-time optimization and not a continuous approach over the entire life cycle.

For this reason, a new concept is needed, which takes influencing factors and their uncertainties into account. To use the model over the entire life cycle the concept needs to be continuously useable. To not only treat a part of an overall solution, but to develop an overall concept, a DT must be provided, in which the status quo is represented and the step of selecting alternatives is taken into account. Only by an overall view and a harmonization of the steps, a continuous iterative concept can be created.

## 3 Conception of a Methodology for GPN Design

This concept of the methodology is presented in Fig. 1 and explained in more detail in the following sections. This is done by the different phases of the loop. The loop is based on the DevOps approach, which originates from the software industry [24]. It is intended to improve quality, increase speed and improve collaboration.

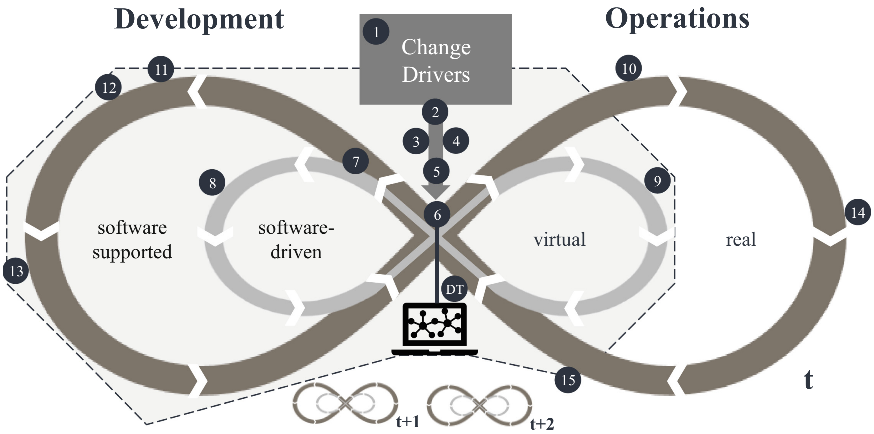

**Fig. 1.** The concept for continuous integration of change drivers into an iterative planning cycle for the design of GPN (adapted from [24])

The starting point of the network design methodology are change drivers that emerge from the external environment of a GPN or internally from the network itself. These change drivers are mapped to the GPN via the receptor theory [25] and the uncertainty of the change drivers is modeled via scenarios (Sect. 3.1). To derive the need for change from the scenarios a DT is needed in which the change drivers are considered and continuously updated. This DT is updated in case of future changes. On the one hand, this DT must be created and, on the other hand, it must be structured in such a way that changes can be implemented without increased effort (Sect. 3.2). With the help of a DT, a simulation model can be created. If the change drivers and the verification of these in the simulation model result in a need for change, this is examined in more detail in the next step and a solution is sought from a solution space (Sect. 3.3). With a further model, the best possible solution for the specific need for change is figured out (Sect. 3.4). This process is divided into a development phase and an operation phase both in reality and by the DT.

### 3.1 Change Drivers and Uncertainties

The starting point of the methodology for designing GPN are change drivers that have an external or internal origin (Fig. 2). External change drivers are, for example, new laws or market changes, while internal change drivers reflect the number of employees or the sequence of processes (1). All of these change drivers have an impact on the GPN targets. An established approach to create the link between change drivers and production is the receptor theory according to Cisek et al. [25]. With the receptor theory, the influencing factors can be transferred to GPN. The goal is to be able to derive quantitative statements about the receptors, which can then be used for further steps. By defining receptor key figures the change drivers can be consolidated and quantified (2) [26]. The fuzzy logic [27] supports the transfer of qualitative drivers into quantitative values. This logic has been applied several times in the context of production and has proven to be reasonable. For this reason, fuzzy logic shall also be used in this work to quantify influence factors. Fuzzy logic is relevant for the influencing factors that cannot be modeled using empirical data or probability distributions. In fuzzy logic, the first step is to transform linguistic variables into membership functions by fuzzification. Subsequently, with IF-THEN rules (so-called inference rules) the input variables can be transferred to an output variable. In the last step, the defuzzification enables the derivation of a quantitative value for the target variable which can be used in the scenarios of the receptor key figures.

If all influencing factors are available in a quantitative value, the influencing factors can be transferred to the receptor key figures. In this step, the uncertainties associated with the change drivers must be taken into account. This is to be made possible by scenarios. In addition to the quantitative and qualitative uncertainties, which can be taken into account e.g. via different distributions (3) or as described above via fuzzy logic (4) [3] a distinction should also be made between epistemic and aleatory uncertainty. While aleatoric uncertainty is already taken into account by stochastic distributions and cannot be reduced further, epistemic uncertainty can be reduced by information acquisition [5]. Through the Continuous Improvement and the Continuous Integration approach from Fig. 1, the epistemic uncertainty is reduced step by step. This can simplify the selection of solutions because fewer developments of the future have to be considered.

Once the uncertainties have been taken into account, scenarios are available for the various receptors (5). In the next step, these scenarios must be transferred to the DT (6). For this purpose, existing standards are to be used to enable transferability to other use cases. The transformation scenarios are to be integrated into a data model of the DT. One possibility for a standardized transfer of data to the DT is, for example, the Core Manufacturing Simulation Data model (CMSD) [28] or the idea of the Asset

Administration Shell (AAS) [29]. Such a standardized data format can support the fast creation and update with regard to the transformation scenarios.

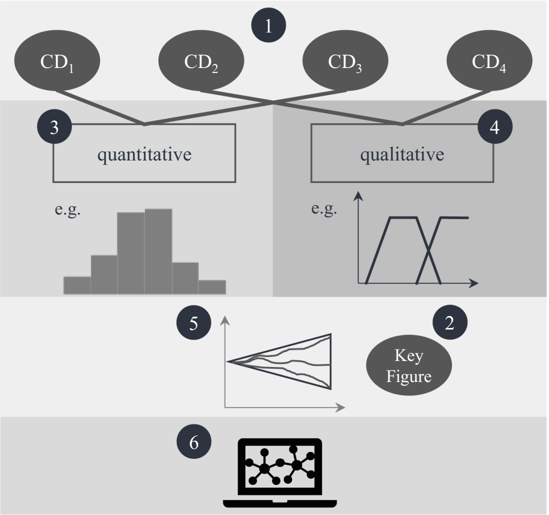

**Fig. 2.** Consideration of the uncertainties of the change drivers in scenarios of the receptor key figures and consideration in the DT

### 3.2 Mapping of the Current Status—Simulation Model

To be able to map the scenarios of the receptor key figures in the DT, they must first be available in their current form. This can be done by building on the data model from Sect. 3.1, which does not only contain the scenarios, but also other modules, the logic, and the parameters of a DT. The structure of the DT is thus already determined by the design of the data model. The concrete information and thus the parameterization of the DT takes place via the continuous improvement and updating of the data model. The later form of the DT can then be derived from this data model and instantiation with real values. The result is a DT that takes into account the previous external and internal change drivers. Future developments of the change drivers can then be compared with this model by scenarios.

The separation of the DT as a software solution from the hardware (the physical production network) enables a realistic check of changes within the DT without increased adaptation effort on the DT itself as well as in reality. This enables rapid trials of an alternative solution for coping with the scenarios. If the investigation reveals a more efficient solution in terms of the receptor key figures than the actual state, it can be tested digitally and then, if successful, transferred to reality (Continuous Deployment). However, as described above, this does not only apply to external change drivers, but also to internal ones. This means that the internal adaptations of the network, such as other types of transport between locations, are always mapped in their most current form. Finally, it should be mentioned that the availability of an up-to-date DT means that the need for change resulting from the drivers of change can be identified more quickly and solutions for this can be found. If a need for change arises that cannot be made possible by simple adjustments in the GPN, the task is to select the appropriate solution from a set of solutions, evaluate them and, if successful, transfer it back into reality. The need for change can be defined as the difference between the capabilities of the current state (CS) and the requirements of the target state ($TS_n$) resulting from the different scenarios.

$$NfC = CS - \sum_{1}^{n} TS_n \tag{1}$$

## 3.3 Measures for Network Adaption

If a need for change arises from the consideration of the scenarios within the DT (7), this must be addressed to maintain the functionality of the real system. For this purpose, a distinction should be made between the terms flexibility and changeability [30]. If only minimal adjustments or adaptations result from the consideration of the scenarios, which were already considered and taken into account in previous cycles, then these can be taken over directly both in the DT (software-driven) (8) and after a check (9) in the real system as well (10). An example of such an adjustment is a change in the process sequence that was already recognized in the previous cycle and is now only finally checked and transferred again due to its occurrence in the scenario. In such a case, the adaptation is within the flexibility corridor of the system. Another example of flexibility is the increase of the produced quantity of a location by adding further working shifts of the employees in the production.

The situation is different with a change that results in a change of the system. Here, the flexibility corridor is no longer sufficient and the system must be fundamentally adapted. Such an adjustment can be, for example, the opening of a new site, the extension of a site by further process steps, or the change of a transport relationship between the sites. If these adaptation options are feasible and can be implemented at the current time, these options define the system's changeability corridor. This can also be described as a solution space (11), in which different solutions can be found, with which the need for change can be compensated.

If there are no solutions in the solution space that can solve the need for change, the next step is to try to expand the solution space (12). This step is the most complex. And cannot be supported by the DT, because new possible solutions which are not considered yet need to be found. For a local company which not thought about a subsidy abroad, a new site in a new country would be an expansion of the solution space.

## 3.4 Selection of the Most Suitable Solution—Optimization Model

After the solution space is available and if necessary extended, the step of the solution selection follows (software-supported) (13). For this, again the receptor characteristics are to be consulted, which can serve as objective functions. For example, the goal can be to achieve a certain number of pieces under given boundary conditions, such as the costs. In addition, the costs themselves can also represent an objective function, which should be kept as low as possible. For the selection of a solution, the state of the art already shows approaches that focus on optimization models. What is new in the presented concept is the consideration of possibilities of extending the solution space without setting up a new DT, simulation model and optimization model (a), to consider the scenarios more strongly and thus to also map progressions of receptor key figures in the future (b), to include uncertainty more strongly (c) and to reduce it by an iterative procedure similar to Sager [9] (d). The optimization should therefore not only take place for one point in time but for different points in time, to represent a progression and find a solution s which fits today and in the future. Such an approach can be based on the migration planning of Moser, who specifies the conversion capability at different points in time to achieve the optimum [8]. In this way, the DT is not only created at a current point in time, but step by step the DT of the future are also already anticipated and updated. The DT can then be accessed at every point in time. Analogous to software development, a backlog is created and continuously adapted. Regarding the existing literature, a new optimization model needs to be created because the existing approaches lack the ability to continuously update the solution. This new model focuses on the scenarios and uncertainties of the change drivers in more detail. Furthermore, it should be in close interaction with the DT. Thus, optimal updates can be implemented at short notice.

In the last step of the method, the found solutions are brought into reality by implementing the changes at the existing GPN (10). The new configuration of the GPN is then working until the next NfC (14). Out of this configuration new data can continuously be collected and transferred back to the DT (15). In addition to running the loop in the current time plane (t), the loop can also be run in future time axes ($t$+1, $t$+2, etc.) to fully account for the scenarios. Thus, similar to Moser [8], future adjustments can already be taken into account and a pipeline for further changes can be built.

## 4 Conclusion

The environment in which globally operating companies find themselves is increasingly determined by growing uncertainty and complexity. Furthermore, companies must be able to react quickly to changes such as delivery problems, new laws, or market changes. Companies need to align their GPN to remain competitive. However, these have grown historically and decisions were made intuitively.

The presented concept should enable a continuous and early consideration of the influencing factors and their uncertainties. It uses approaches from software development that have become established there. In addition, the focus is on a DT, which enables a fast, proactive planning process that is initially carried out independently of the existing GPN. Changes in the environment or to the existing system are continuously integrated and the DT is updated. Possible solutions to meet a NfC can be tested and, if successful, transferred to reality. Further research is recommended to realize the individual sub-aspects of the overall concept. Especially the continuous consideration of the change drivers and their uncertainties requires further research. Also, the automated spanning of the solution space and the selection of a solution needs to be further investigated in the context of GPN.

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