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# A Changeable Decision Support System Based on Data Models for Global Production Networks

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**Abstract**

Multiple influencing factors like changes in market demand or legal factors as well as risks, uncertainties, and dynamics have to be considered when deciding about the design and management of global production networks. To deal with the multitude of different influencing factors and possibilities of adaptations in global production networks, digital twins offer the possibility to support decisions and combine different application models. For the benefit across multiple decision support systems, the digital twins need to be standardized on the one hand, but also extendable on the other. The digital twins themselves are based on a defined concept and a clear modeling logic. With the help of the asset administration shell, data models for the description of global production networks, as well as for the influencing factors and their scenarios, are developed which enable the exchange of data via standardized interfaces. Using standardized interfaces, decision support systems in global production networks can make queries to the models via a service and receive the required information, like different demand scenarios, back. The decision support systems can then map a wide variety of these scenarios for the future. Based on this, the scenarios can be evaluated by target values and, if they are not met, an adjustment option can be sought. The foresight of all these scenarios can then help to find the most robust and resilient decision alternative. The findings and thus the optimal response to each contingency scenario can be fed back into the data model of the global production network and made available for other decision support systems. This paper proposes a theoretical framework, a possible implementation using asset administration shells, and the interaction of the different modules using an exemplary decision support system.



*Keywords:* Global Production Network; Decision Support System; Reconfigurable Manufacturing System; Asset Administration Shell; Changeability;

## 1. Introduction

Many companies that used to produce at a single location have grown into global production networks (GPN) in recent decades [1]. This development was driven, among other things, by cost efficiency, proximity to customers, or proximity to suppliers [1]. The production networks thus consist of several sites that are geographically distributed around the world and are connected by material, financial and information flows [2]. A GPN in this context includes one company with several sites and not multiple companies. Each site was created for different reasons based on the situation at the time. Capacities and capabilities are distributed among these locations.

GPNs are exposed to a variety of possible influencing factors. These must already be taken into account during planning so that operations can be maintained when they occur. The risk and uncertainty associated with the influencing factors are increasing [1] as companies today operate in the VUCA (Volatile, Uncertain, Complex, Ambiguous) world [3]. These influences increasingly include disruptions such as shutdowns, environmental catastrophes, or delivery bottlenecks. To respond to these disruptions, reconfigurable manufacturing systems (RMS) are coming into focus in the context of network design as they can increase adaptability, resilience, and robustness in the GPN [4]. Extreme scenarios can thus be better covered. The ability of a system to withstand certain disruptive events without failing completely and to return to its original state within a short time after the disruptions have ceased is called resilience [5]. In order to achieve resilience, the development of redundancies is often recommended and applied in practice. Redundancies of capacities and capabilities can be kept at various locations to be able to react quickly in the event of disruptions.

Paradigms such as RMS [6], Changeable Manufacturing Systems (CMS) [6] or Software-defined Manufacturing (SDM)

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will influence production in the future and are considered promising approaches. Among other things, hardware will be separated from software and planning cycles will be accelerated. These paradigms have the production systems in focus. The way in which they can be incorporated into the design of GPNs requires further research since often only machines and factories are in the focus [4].

To evolve the configuration of a GPN with respect to the ever faster changing constraints and to the paradigms, a holistic and changeable Decision Support System (DSS) consisting of different modules needs to be created. The modules of the DSS, based on models, and their interaction will be presented in this article. This includes (I) the representation of data models for GPNs and scenarios, (II) defined interfaces between the data models and the application model, (III) the application model itself using the example of an optimization of the existing network design (IV) and the interaction of the models with each other as modules in a DSS and between DSSs. For this purpose, the related work in this area is first presented and the research gap is elaborated in section 2. Subsequently, the modules are presented in section 3 and their interaction is shown in section 4. Finally, the overall system is evaluated and the summary as well as the next steps are presented in section 5.

## 2. Related Work

In the following section, the related work of the different modules of this approach is presented. First, an overview of GPNs and their representation as data models is given (section 2.1). Subsequently, the consideration of change drivers (CDs) and scenarios in GPNs is outlined (section 2.2). Next, fundamentals of DSSs are given, and more specifically the problem of network configuration with RMSs in GPNs is shown in section 2.3. In section 2.4 concepts of system interaction in DSSs are given.

### 2.1. Global Production Networks

Today, a large number of companies of all sizes operate in GPNs. A GPN consists of geographically dispersed production entities, which are interlinked by material, information and financial flows [1]. Looking at the levels of the factory [7], the network and site levels are particularly relevant for decisions in the GPN. Nevertheless, in some cases, information from the lower levels is also needed for decisions in the GPN. In order to create a virtual representation of the GPN to support decisions, the different levels below have to be included and connected with each other to maintain information consistency. Furthermore, a structure that is as generally valid as possible must be specified so that the relation of the data to each other is defined. As a further relevant point, an implementation of the data models must take place in order to make them usable. Benfer et al. [8] propose a digital twin of the GPN, which pulls data from information systems and not from the hierarchical underlying digital twins. This is done automatically and version controlled. There is no mapping of the layers of the factory and no standardized structure or implementation of this. Milde et al. [9] create a data model of the GPN for a simulation model. However, this is not a universally applicable model. Yang et al. [10] use standardized terms that appear in many data models for production, such as process, product and resource. They take a meta-model approach. There is no specific consideration of the GPN or levels of the factory. Park et al. [11] propose a data model based on a P4R (Product, Plant, Process, Plan, Resource) structure implemented using Asset Administration Shells (AAS). There is no consideration of the GPN.

Thus, there is a need for a standardized, hierarchical data model that can be used for the different levels of the factory so that DSSs can build on the same information and information consistency is given. The data model should allow being further detailed, depending on the use case for which it is used. However, the focus of this article is on the network and site level [7]. This leads to research question 1 (RQ1): How can GPNs be represented as a standardized and extensible data model in order to be able to generate digital twins?

### 2.2. Change Drivers and Scenarios

Influencing factors include, for example, market conditions or legal factors that are subject to risk and uncertainty [1]. Several approaches categorize the influencing factors of global production [12]. The influencing factors can be transferred to the production system via the receptors' product, quantity, time, costs, quality, and technology [13]. In order to take into account the dynamics and uncertainty in which GPNs operate, scenarios are used often. For example, one or several influencing factors also called change drivers (CD), are transferred to one or several receptor key figures (RKF) via receptors [14]. The RKFs can then be considered in scenarios given a probability with the help of Monte Carlo Simulation (MCS). The focus is for example on a consideration of demand scenarios [15]. Such scenarios are then used to determine the right time for a change in the configuration of the GPN [16]. This serves as input to the decision-making process. As many scenarios as possible should be considered in the solution to foresee the behavior of the GPN under uncertainty. The scenarios refer purely to the use case and a transfer to other DSSs is missing. Further research is needed to consider the scenarios not only for one use case but to create a module that can serve as input for different DSSs by standardization. This leads to research question 2 (RQ2): How can the uncertainty resulting from the influencing factors be represented as a data model and how can scenarios for different DSSs be created on this basis?

### 2.3. Decision Support Systems and GPN Configuration

DSSs help decision-makers to structure the context, provide information on the problem and thus select the right decision alternative for a specific problem [17]. Many context-specific DSSs were developed in the last decades. In the context of DSSs, these can be categorized as qualitative and quantitative DSSs [18]. While the first can again be grouped in generalistic and specific frameworks the latter can, in the context of model-based DSSs, be categorized as descriptive, analytical, predictive or prescriptive DSSs. [17, 18] In this article, a prescriptive DSS is developed, since the focus is on what will happen and the foresight of events as well as a recommendation for action.

To concretize the DSS to a specific use case, this article deals with a DSS for the reconfiguration of GPNs. For this, the literature on GPN configuration was analyzed. A focus is set on RMSs and the configuration of GPNs in general. Lanza and Moser [19] present a dynamic multi-objective optimization model for GPNs, which takes the uncertainty of influencing factors into account. They divide the DSS into an optimization, uncertainty and control module. Nevertheless, the uncertainty module is only applicable to this DSS and cannot be used for other DSSs. Also there is no database with all the input information. Moser et al. [16] use a stochastic-dynamic optimization model to identify a cost-optimal migration strategy. They use a procedural model which consists of a configuration and optimization model, but a connection to a database with the network configuration in it is missing. Preising et al. [20] present a framework for a systematic reconfiguration process of manufacturing networks with the help of simulation and optimization. They use a database and input data to consider the network configuration and uncertainty. Also Kjelgard et al. [21] do not use modules for the GPN and the uncertainty by evaluating the expenses of reconfigurable designs of production systems within a GPN. Thus, research question 3 (RQ3) is: How can the concept of RMSs and the paradigms of section 1 be used to support the reconfiguration of GPNs?

### *2.4. Module Interaction*

A DSS consists of five different modules: (i) the database, (ii) the models and analytical tools, (iii) architecture and network, (iv) the user interface and (v) the user itself [17]. While the first three modules are addressed in this article (see Figure 1), the latter two are focused on the user and not part of this article. Nevertheless, for real-life application of the DSS, they are necessary but can be designed in a second step. Different existing DSSs for the configuration of GPN need input data in a structured way or use scenarios to predict the future [2, 20]. Nevertheless, they are focused on one decision type and result in one time uses [8]. Benfer et al. [8] propose a conceptual framework for digital twins of production networks but remain unclear how this is technically implemented to use it in practice. While they already suggest an ontology for the reference model, the connection to the DSS needs further research. AASs [22] offer a good solution here because they provide standardized interfaces. Stamer et al. [23] use the AAS in the context of GPN to support interaction between production systems but not in the context of module interaction. This leads to research question 4 (RQ4): How can the modules of a DDS interact based on AASs?

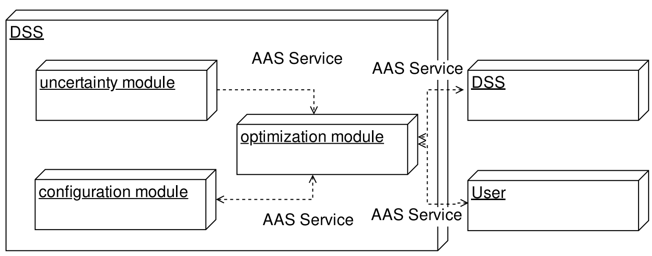


Fig. 1. Deployment diagram of the DSS

## 3. A Changeable Decision Support System Based on Data Models

In the following section, an exemplary DSS based on different modules is presented for the reconfiguration of GPNs (see Figure 1).

For a changeable DSS to emerge, the first step is to create a data model for a GPN and one for the uncertainty associated with it due to CDs (section 3.1). The first represents the configuration module. From this, the necessary information for the DSS is to be extracted. Subsequently, a data model for the uncertainty, the uncertainty module, is to be provided in the same way. This is necessary to be able to map RKF by CD [14] and to transfer them into the optimization module. The model, in this case, the optimization module, is in a central position of the DSS, which is to be represented in the example of the reconfiguration of GPNs (section 3.2). The optimization module itself is changeable because on the one hand, it should be exchangeable with other models and on the other hand, it should be adapted by a change in the data models without adapting parameters or constraints in the model itself. To answer RQs 1-4, the different modules of the DSS are presented in the following.

### *3.1. Data Model for a GPN and Scenarios*

The data model for GPNs serves as a digital representation of reality. For this purpose, a digital master [24] of the GPN is first created using the Unified Modeling Language (UML), which is implemented using AASs and which provides the answer for RQ1. A hierarchical structure of the data model is recommended. On layer 0, a simple object is represented, which can be connected to further objects. Layer 1 consists of a general representation of production by products, orders, processes, resources, and capabilities, which should apply to all factory levels [7] accordingly. The factory levels represent a second dimension, which is represented on layer 2 of the data model. Layer 2 is an instantiation of layer 1, thus a fractal model is created. Here, more concrete information about the network, a site or a machine can be found. The focus of this article is on the network level and the site level. Information from the levels below can be aggregated to the top, by using the AAS and protocols like REST APIs, OPC UA and MQTT with clear rules and policies around data sharing for example through data anonymization or contractual agreements. So the site levels get the information from the level below plus additional, site-specific information from other data sources. The same applies to the network and site level respectively. An overview of the two dimensions and the structure of the data model can be found in

Figure 2. On a potential layer 3, further company-specific information can be added. This means that the data model remains expandable and can be used universally.

For the GPN reconfiguration, the capabilities of the individual sites are of particular interest. These are needed for the network configuration, as they determine which site has which capability and capacity. Figure 3 shows the implementation of layer 1 in the UML diagram. Building on the contribution of

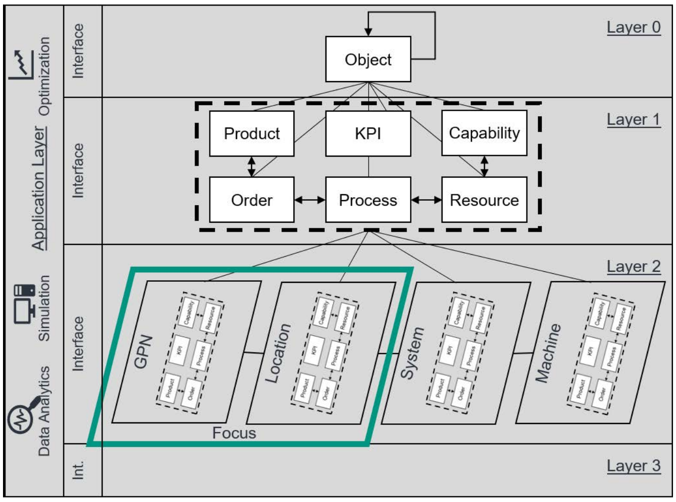


Fig. 2. Data model in layers and the levels of a factory

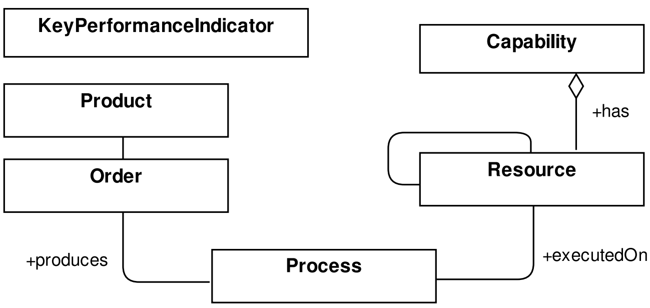


Fig. 3. Data model of the configuration module (layer 1)

Stähr [14], a data model for uncertainty and scenario mapping was created which provides the answer for RQ2. This was first modeled as a UML class diagram (see Figure 4) and implemented using AASs. The central part are the CDs, which occur based on certain distribution functions and are related to the RKFs via the receptors. Both classes are connected to the simulation base, which is connected to the model in the optimization module. Here, meta-information such as the time horizon of the desired scenarios is specified and a MCS can be started in the next step. For this reason, the simulation base is linked to the RKF scenarios, for example, demand scenarios via the CD scenarios, which represented the expression of the CDs. The uncertainty module is detached from the optimization model and can therefore be used universally to generate scenarios for a wide variety of DSSs (see Figure 1).

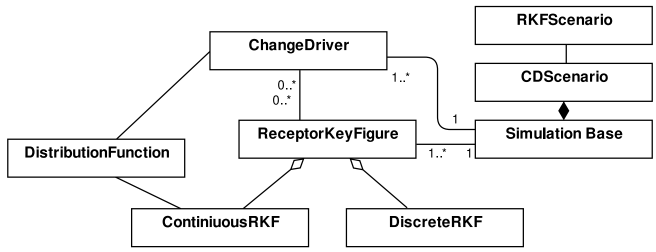


Fig. 4. Data model of the uncertainty module

### 3.2. Network Reconfiguration as DSS

The heart of any DSS is a model (see Figure 1). In this article it is an optimization model designed to identify the right capabilities at the right time in different locations supported by the paradigms. With the help of this model, RQ3 can be answered. In doing so, this approach extends existing approaches such as that of Moser et al. [16] by adding the properties of RMSs. A modular design of production systems and stations allows reconfigurations within the GPN to be performed faster and at a lower cost. Individual modules can be kept redundant in order to protect against uncertainties. Uncertainties are to be taken into account via scenarios.

For this reason, from the decision theory, a finite discrete stochastic optimization is used, which finds the approximately optimal configuration of the GPN under given uncertainties. The focus is on RMS. This problem can be solved with a Markov Decision Process (MDP) according to Puterman [25]. A sequential decision process is a model for a dynamic system under the control of a decision-maker. At each point in time when a decision can be made, the decision-maker observes the state of the system. Based on the information gained from this observation, he selects an action from a set of available alternatives. [25]

The set $T$ consists of all the times at which the system is observed and decisions can be made. For finite time horizons, $T = \{1, 2, ..., N\}$ is applicable. For the planning of the reconfiguration of GPNs, we assume a period of 3 years, which is divided into monthly segments, so that $N = 36$. The set of possible states of the system at time $t$ is denoted by $S_t$ which is the configuration of the GPN at time $t$. For finite horizon problems, $S_t$ is defined for $t = 1, 2, ..., N + 1$, although the decisions are made only at times $t = 1, 2, ..., N$.

If at time $t \in T$ the decision-maker observes the system in state $s \in S_t$, he chooses an action $a$, from the set of actions $A_{s,t}$ that are admissible at time $t$. In the case of GPNs an action can be to create a new capability at one location by adding a new module to the RMS or by increasing capacities.

If the system is in state $s$ at time $t$, the choice of an action $a$ has two consequences: The decision-maker receives an immediate reward and the probability distribution for the state of the system in the next phase is determined. The reward is denoted by the real function $r_t(s, a)$. In some applications, it is convenient to consider $r_t(s, a)$ as the expected reward at time t. This is the case when the reward for the current period depends on the state of the system in the next decision epoch. In such situations, $r_t(s, a, j)$ is the reward received in period $t$ if the state of the system at time $t$ is $s$, action $a \in A_s$ is chosen, and the system is in state $j$ at time $t + 1$. Then the expected reward in period $t$ is

$$r_t(s, a) = \sum_{j \in S_{t+1}} r_t(s, a, j) p_t(j|s, a) \tag{1}$$

where $p_t(j|s, a)$ denotes the probability that the system is in state $j \in S_{t+1}$ if the action $a \in A_s$ is chosen at time $t$ in state $s$. $p_t(j|s, a)$ is called the transition probability function. To estimate and validate the transition probabilities, simulation techniques can be used by simulating scenarios. Accordingly, the optimization parameters can be adapted. It is required that

$$\sum_{j \in S_{t+1}} p_t(j|s, a) = 1 \tag{2}$$

The tuple $(T, S_t, A_{s,t}, p_t(j|s, a), r_t(s, a))$ defines the MDP. It is characterized by the fact that the transition probability function and the reward function depend only on the current state of the system and the currently chosen action.

Bellman's principle of optimality [26] can be used to solve MDPs. The minimum expected total cost consists of single-step costs and the expected value of the total cost of an optimal policy starting in the following period. Thus, an optimal decision leads to an optimal trade-off of one-time short-run costs and long-run subsequent costs. The value function can be calculated recursively.

To turn the MDP-based optimization model into a user-friendly DDS, the model must be connected to a database. This is done by connecting to the data models from section 3.1 in section 4.

## 4. Module Interaction Based on AAS

This section deals with the architecture and the network of the modules already described and will answer RQ4. Only through appropriate interaction and linking of the modules with each other, a DSS can be created. The configuration module, the uncertainty module and the optimization model as the optimization module must be linked together (see Figure 1). Therefore it is explained, how the deployment of the individual modules is arranged, before the interaction of the entire system is represented.

The deployment of the uncertainty module can be seen in Figure 5. New CDs or RKFs can be added or existing ones adapted via a user interface by the decision maker. The AASs are then created on a central server from the user inputs, which are then pushed to the AAS server. There, all CDs and RKFs as well as their linkage with each other are stored in the most current version. The central server also contains the code for scenario calculation using a MCS. This code calculates the selected RKF for certain CDs. The central server retrieves the corresponding AAS from the AAS server via a standardized API [22]. The uncertainty module is also connected to the optimization module via an AAS interface. This is also implemented via an AAS and described below. The deployment of the configuration module works in the same way. Via a web server, data on the configuration server can be transferred to AAS, which is stored on the AAS server. The interfaces are implemented via REST APIs. An application can use an AAS service to retrieve data from the AAS server and to change and add data there. It is important that not only one application but also several can access it simultaneously. Decision-makers with different functions who use them may be distributed across various locations. Therefore the data model needs to be designed to be adaptable to the ever-evolving information of the GPN and can be adapted to fit specific requirements. This ensures that the same data is always used and that different decisions are made on the same data basis. The uncertainty module as well as the configuration module are connected to the model, in this case the optimization module, via AAS services. The optimization module can retrieve information from the other two modules as required during each optimization run. The optimization module is connected to the user or other DSSs via another AAS service. Conflicting decisions are assessed and resolved for example by prioritization or intervention. Different scenarios can be simulated by the uncertainty module.

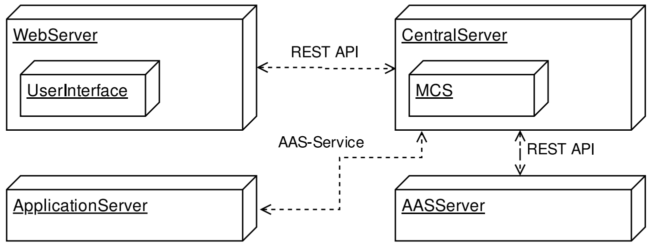


Fig. 5. Deployment diagram of the uncertainty module

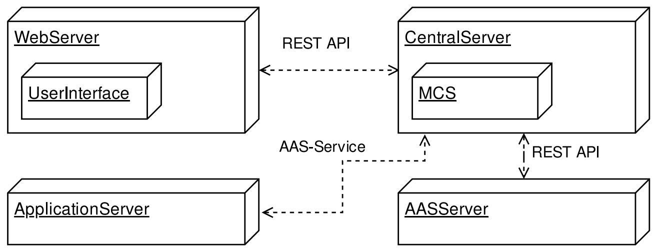


Fig. 6. Deployment diagram of the configuration module

The AAS service is implemented as an AAS that includes a submodel with an operation. An operation is an executable realization of a function [22]. It has input and output variables. In the example of the DSS, CDs and RKFs as well as a time horizon can be given to the uncertainty module, which then calculates scenarios and returns them as output to the model.

## 5. Summary and Further Research

The objective of this paper is to facilitate the reconfiguration of GPNs through a DSS in order to respond quickly to changing constraints. For this purpose, an approach was presented that enables a changeable DSS. The DSS is divided into three modules that interact with each other, based on an ASS service. The configuration module, the uncertainty module, and the optimization module with the optimization model were presented. The first two were first implemented in UML and then as an ASS and answered RQ1 and RQ2. The optimization model presents an approach to support the reconfiguration of GPNs (RQ3). In the design, care was taken to ensure that the interfaces between the modules could be easily adapted and that other models could be used in the DSS instead of the optimization model. Furthermore, this allows interaction between different DSSs based on the same data models (RQ4). Thus, the four research questions RQ1-4 have been answered.

Further research is needed, on the one hand, to detail the data models. Particular attention must be paid to standardization, but also allowing for the possibility of extension. On the other hand, the optimization model based on MDP must be modeled and implemented. Special focus is given to the reconfiguration of GPNs, since this has not been widely explored at the present stage. If all modules are implemented, the interaction based on ASSs, can be tested. Finally, the presented DSS should be tested and validated on a real use case.

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