Increasing Resilience in Production Networks: A Practical Approach Based on Scenario Planning and Simulation-Based Capacity Analysis

David Kunz[1][a], Tim Maisel[2], Andreas Kunze[2] and Jörg Franke[1][b]
[1]*Institute of Factory Automation and Production Systems (FAPS), Friedrich-Alexander-Universität Erlangen-Nürnberg, Egerlandstraße 7-9, 90158 Erlangen, Germany*
[2]*Siemens Healthineers AG, Siemensstr. 3, 91301 Forchheim, Germany*

Keywords: Resilience, Simulation, Scenario Planning, Simulation-Based, Capacity Analysis, Global Production Networks, International Supply Chains, Case Study.

Abstract: In the current global economic landscape, companies with an international presence face the challenge of ensuring that their production networks are not only efficient but also resilient to unpredictable events. Recent technological advancements and the close integration of global production networks have been increasingly disrupted. During times of global crises, it becomes evident that traditional approaches are no longer sufficient. Therefore, the focus is shifting from reactive measures to proactive prevention. This paper presents a novel approach for increasing resilience in a production network based on a combination of systematic foresight of unpredictable events using scenario planning and a simulation-based capacity analysis for the identified scenarios. To demonstrate and validate the application of the proposed approach, a case study for the production network of a large German healthcare company is conducted and presented.

1 INTRODUCTION

The integration of globally spread-out production sites and rapid technological advancements have led to increased optimization of resource utilization. However, this has also increased vulnerability to interruptions in production. To combat these issues, the focus has shifted from reactive measures to proactive prevention. (Schollemann et al., 2022)

The term **resilience** is frequently used in both natural and social sciences (Hoffmann, 2017), and has more recently been applied to organizations and production networks. Resilience is commonly defined as the measure of the persistence of systems and their ability to absorb change and disturbance, as defined in (Holling, 1973).

Overall, resilience is not only about getting back to the initial state after a failure occurs but also means to adopt to the changing circumstances (Rydzak et al., 2006). This especially relevant as some failures may be inevitable in a complex and dynamic world.

Organizational resilience depends on the organization and its circumstances. For example, a financial company may encounter significant challenges due to a loss of trust, whereas a production-focused company may face more substantial difficulties in the event of a key supplier's failure (Seville, 2008). (McManus, 2007) proposes an expanded definition of organizational resilience that encompasses coping with both day-to-day business problems and longer-term change-related issues. According to their model, resilience in manufacturing organizations is contingent upon three factors: situational awareness, effective management of key vulnerabilities, and adaptability in a complex, dynamic, and interconnected environment.

(Zhang & van Luttervelt, 2011) describe resilience in the context of manufacturing and production systems which are depicted as a network that contains not only directed but also undirected connections. The authors describe five different types of failures in a production system: oversatisfaction of demand, inability to satisfy demand, unavailability of resources to meet demand, damaged infrastructure, and operations damaging internal systems. For the authors, organisational resilience differs from the resilience of a production system in the sense that a

[a] https://orcid.org/0009-0002-8801-8231
[b] https://orcid.org/0000-0003-0700-2028

Kunz, D., Maisel, T., Kunze, A. and Franke, J.
Increasing Resilience in Production Networks: A Practical Approach Based on Scenario Planning and Simulation-Based Capacity Analysis.
DOI: 10.5220/0012830100003758

In *Proceedings of the 14th International Conference on Simulation and Modeling Methodologies, Technologies and Applications (SIMULTECH 2024)*, pages 158-169
ISBN: 978-989-758-708-5; ISSN: 2184-2841

stable state is not a necessary condition for the success of a production system.

Global Production Networks (GPN) are open-ended systems with complex links and multiple independent actors whose goals may be in direct conflict. They depend on a variety of internal and external influencing factors that change dynamically and require adaptions of the design of GPNs (Váncza, 2016). Therefore, managing GPNs involves not only organizing production sites within the company, which are often heterogeneous and require differentiated consideration (Erlach et al., 2023), but also managing strategic partners, suppliers, and external influences from global political and economic sources (Henderson et al., 2002).

For these reasons, companies require practical approaches for the assessment of their vulnerabilities and identification of potential avenues for increasing their resilience based on their specific circumstances. This paper argues for the close integration of GPN simulations into the analysis of potential strategies for increasing resilience through scenario planning. This integration provides a more comprehensive understanding of the relationships within the model, reveals the underlying assumptions and produces quantitative estimates for developed scenarios (Paich & Hinton, 1998). In order to reduce the time and resources required for simulation and evaluation, it is essential to identify the most relevant and crucial scenarios at the outset.

2 STATE OF THE ART

A variety of approaches for **simulating GPNs** are discussed in existing literature. (Peukert et al., 2023) present an approach for optimizing responses to disturbances in GPNs using simulation models and control circuits. The authors emphasize considering production- and logistics related countermeasures first. Proactive strategies are evaluated based on a simulation model of the production network, with experiments comparing the performances under different conditions: (1) without disruptions and countermeasures, (2) with disruptions, and (3) with disruptions and countermeasures.

(Alexopoulos et al., 2023) introduce the framework 'FLEX4RES', which supports the reconfiguration of production networks to achieve resilient production value chains. The introduced platform enables the integration of live data from production based on Gaia-X and Asset Administration Shell.

(Tan, 2020) compares various complex systems approaches for modelling and simulating supply chains to enhance their resilience. The evaluation is based on modelling real supply chains and developing mitigation and contingency strategies based on hypothetical scenarios.

The authors in (Ivanov, 2018) investigate disruption propagation in supply chains to increase resilience with consideration of sustainability factors and employ simulation to assess the impact of various factors.

(Carvalho et al., 2012) presents a case study on the redesign of a supply chain of a Portuguese automaker to increase resilience using simulation. The study examines two common strategies, the creation of redundancies and of flexibilities, and evaluates six scenarios. The simulation is restricted to the supply chain and does not consider the impact of material shortages on production processes.

Scenario Planning is a popular approach to managing uncertainty in strategic planning. The focus is on creating awareness and preparing for uncertainty and disruptions (Cordova-Pozo & Rouwette, 2023) which is why it has been applied to identify ways to improve resilience in disaster mitigation (Debnath et al., 2024).

To summarize, the existing literature mainly focuses on simulating production networks or examining the impact of selected scenarios and countermeasures on production networks. As resources for increasing resilience are limited, it is essential to identify and prioritize the most critical elements of a system (Balakrishnan & Zhang, 2020). The applicability of the presented approaches for production companies seeking to enhance their resilience is limited due to the lack of consideration given to whether the examined failures in the production network are relevant to the specific companies. On the other hand, current approaches for using scenario planning focus on areas outside of production networks.

This publication aims to address these issues by providing practitioners with guidelines for how to identify areas of potential for increasing resistance in production networks and to evaluate the scenarios and possible countermeasures using simulation.

3 METHODS AND APPROACHES

The above examples of different strategies for increasing resilience in a production network clearly show that no strategy has so far been useful as a basis for the stated objectives. Among other things, there is a lack of reference to the capacity performance of a production network, the rapid adaptation and mapping of a complex GPN and the quantitative analysis of various resilience strategies. For these reasons, a separate approach for increasing resilience in a production network is introduced in this publication using simulation-based capacity analyses.

As a full-factored resilience optimisation of a GPN is a highly resource-intensive process, the objective of the introduced approach is to initially identify the most relevant levers. The scenario development approach was selected to determine these levers because of its systematic approach and widespread application. The proposed approach consists of three phases, as shown in Figure 1.

After specifying the project, scenarios are systematically developed based on scenario planning technique by (Gausemeier et al., 1996) in the second phase. The identified scenarios are then modelled, and possible countermeasures are developed and evaluated in the third phase. Following (Cordova-Pozo & Rouwette, 2023) this approach can be characterized as following the probabilistic modified trend school using a cross-impact analysis technique.

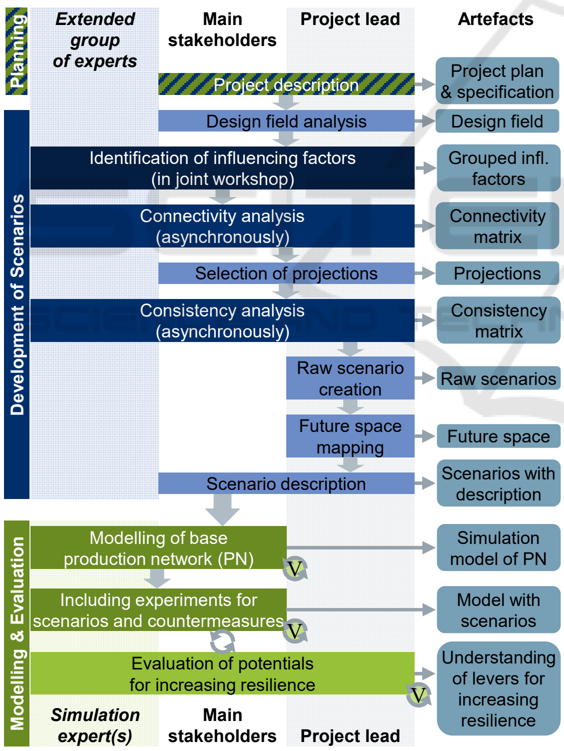

Figure 1: Proposed three-phase approach for increasing resilience in production networks with forecasting scenarios (blue) based on (Gausemeier et al., 1996) and modelling and evaluating the scenarios (green) extended by artefacts.

3.1 Concept for Forecast Generation

The developed approach for the forecasting of scenarios is based on the general scenario planning process outlined in (Gausemeier, Fink, & Schlake, 1996). This process has been adapted to meet the requirements of highly dynamic and specific production environments, refer to Figure 1.

One of the main differences is that the developed scenarios are transferred to simulations where impact analysis, contingency planning and robustness planning are integrated, see chapter 3.2 for details.

The second major difference is that specialized software catalogues and databases are not used. This ensures that the developed forecasts are tailored precisely to the specific circumstances of the respective production network and are not influenced by predetermined catalogues and databases. Additionally, the generation and selection of base scenarios and the visualization of the future space should not be restricted by specialized software.

The division of tasks represents the third significant difference. In (Gausemeier et al., 1996) most steps are performed by an external scenario team. The proposed process in contrast is characterized by the cooperation of three essential groups of actors: the project lead, main stakeholders and the extended group of experts. The project lead is in charge of organization, structuring and visualization of results, whereas the main stakeholders consist of (internal) costumers and end users of the developed scenarios and simulations which are very involved in the creation of the scenarios and application of the results. The extended group of experts is made up of experts from various specialized areas of the production network. Ideally, members of this group are selected by the project lead and main stakeholders without restraints. All groups can be employed internally in the production network or externally, e.g. by suppliers, customers or consulting companies, as not every production network has the capacity for an internal scenario team or is allowed to disclose the sensitive information externally. The following chapters describe the procedure for preparing the forecasts in detail.

3.1.1 Project Description

At the beginning of the project, the project description should give a precise definition of the target values and the intended utilization of the scenarios within the project's context. This involves specification of the goals for the scenario planning as well as the simulation project in close cooperation with the main stakeholders. For the former, it is recommended to follow the specification guidelines for scenario planning in (Fink & Siebe, 2016) which include the target audience, forecasting goals, scenario field parallelization, scenario depths and forecasting timescale. The necessary specifications for the simulation project should be defined, e.g. based on

VDI 3633. This step also involves selecting the members of the extended group of experts and creating the project plan.

3.1.2 Design Field Analysis

The aim of the design field analysis is to identify the components that constitute the scope of action. In the following steps, these components are analysed in specific scenarios. Therefore, it is crucial to identify them and their boundaries precisely. The focus of the design field analysis can vary depending on the project scope, e.g. a company, product, technology or global design field. (Gausemeier et al., 1996)

In the context of a production network, the design field analysis focuses on identifying the sub-processes to be included in the scenario project and those lying outside the project framework.

For instance, sub-processes such as production sites and suppliers within the production network may be included in the scenario project, as their future development is crucial for the network's performance. Sub-processes outside the project scope may include, for example, external customers or the development of new products, as these areas have little influence on the capacity of a production network.

In addition to the central sub-processes, the design field analysis also identifies focus areas. A focus area represents the specific points within a design field to which scenario development should be aligned. While focus areas can overlap within the network, it is crucial to differentiate them clearly in their objectives within the production network. One example of such an area might be the 'availability of qualified personnel', while another could be the 'attractiveness of the location'. Despite the clear demarcation of these areas, it is possible that they influence each other.

The design field analysis is conducted by the core project team which includes the project lead(s) and the main stakeholder group.

3.1.3 Identification of Influencing Factors

The third step in the process involves identifying influencing factors through a workshop including the extended group of experts. Participant are assigned to a specific focus area based on their experience and position in the company. Each participant independently collects influencing factors for their assigned focus area through brainstorming.

The participants then share and discuss their results, categorizing their collected influencing factors into grouped influencing factors within each design field. Grouped influencing factors are made up of very similar or identical influencing factors and reflects the focal points within a focus area. In the third step, the grouped influencing factors are collected amongst all groups and refined and developed further. The workshop aims to develop comprehensive factors for each focus area, by identifying detailed influencing factors. The process involves brainstorming, categorization and refinement to set comprehensive priorities.

As preparation for the following steps it is essential to have a shared definition of the groups of influencing factors. Therefore, a description is created for each group of influencing factors after the workshop.

3.1.4 Connectivity Analysis

To identify the areas of influence with the greatest impact on the production network, a connectivity analysis consisting of a matrix of direct influence (MDI) and a significance matrix is carried out. The proposed method recommends an asynchronous approach instead of performing the analysis in a workshop, as exchange between the participants is not required which allows more extended experts to participate in this step.

An MDI is used to assess the influence of the grouped influencing factors on each other by evaluating the extent to which the influencing factor in the row influences the influencing factor in the column. Based on the evaluation, the four characteristic values active sum, passive sum, dynamic index and momentum index can be calculated in the completed MDI.

In addition to the behaviour of the influencing factors, the importance of each factor is assessed using a relevance matrix, which identifies the more relevant influence for each pair of influences.

With the two matrices, a connectivity and relevance score is calculated for each influencing factor. Their ranked results are visualized as Connectivity-Relevance-Grid in Figure 2, based on which key factors with high connectivity and high relevance can be identified. Furthermore, other possible key factors with high connectivity but low relevance and vice versa can be determined. (Fink & Siebe, 2016)

When identifying the key factors within a production network, the key factors with a high degree of relevance and a high degree of connectivity should be used for a targeted prioritization and focus on the performance of the production network for the further process. Key factors with high relevance and low interconnectedness should not be neglected as they can have a major impact on the performance of the production network despite their low connectivity. Influencing factors with high connectivity but low relevance can be neglected for the rest of the process, as they influence the other factors but have little discernible impact on performance.

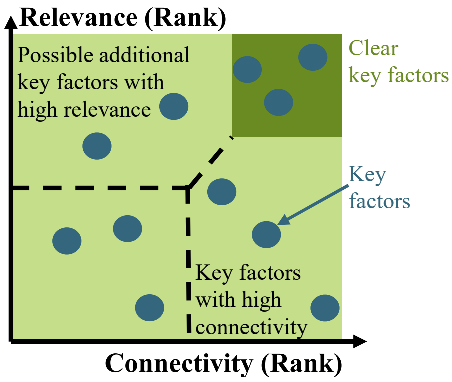

Figure 2: Connectivity-Relevance-Grid based on (Fink & Siebe, 2016).

3.1.5 Creation of Future Projections

Building on the identified key factors, possible states for each are determined and described in the form of future projections. The creation of future projections is a joint task of the project lead and main stakeholders. A variety of information sources are used, including internal information on risk management in the production network, current trends, company reports and external information sources such as scientific reports and publications. Three future projections are developed for each key factor, each representing a positive, a neutral and a negative development of the key factor.

These projections serve an essential role in informing future decisions, as subsequent scenarios are developed and refined based on them. The future projections are deliberately exaggerated in order to describe the projections in as much detail as possible. It is very important that these projections are distinct and unambiguous, reflecting potential developments of key factors without emphasizing the causes or consequences. Each projection for a key factor should cover the full range of possible developments and be compatible with the other key factors. Failure to do so, may result in inconsistencies in the subsequent analysis when establishing consistency between the key factors. (Fink & Siebe, 2016; Gausemeier et al., 1996)

Particular attention should be paid to adapting the descriptions to the production network's specific circumstances in order to avoid an overly general or overly dramatic presentation of the future scenarios.

3.1.6 Consistency Analysis

The main objective of the consistency analysis is to assess the consistency of the future projections for various key factors. Each participant rates the consistency of the future projections between the different key factors. The assessment is done for pairs of key factors and on a scale from 1 (complete inconsistency) to 5 (strong mutual support). It is important to emphasize that this assessment only evaluates the consistency between the respective pairs of future projections and not their probability. The individual consistency assessments are then summarized by averaging to form an overall consistency analysis. Various possible projection bundles can be created on the basis of this analysis, whereby a projection bundle consists of the combination of exactly one future projection for each of the key factors. (Fink & Siebe, 2016; Gausemeier et al., 1996)

The consistency analysis is carried out by all members of the project team and the ratings entered into a matrix. As three future projections are created for each key factor, 3^n projection bundles must be examined as part of the consistency analysis.

3.1.7 Creation of Raw Scenarios

Due to the large number of projection bundles, it becomes necessary to reduce them. If at least one combination within the scenario bundle is evaluated as inconsistent, it is excluded from further consideration. Here, the use of support through algorithms is essential. The probability of the projection bundles occurring deliberately plays no role here, as this process is more about thinking ahead than making concrete predictions. In a second step, the remaining projection bundles are sorted according to their consistency values. The consistency value of a projection bundle is the sum of the consistency ratings of all the future projections contained in this bundle.

3.1.8 Future Space Mapping

To effectively communicate the results and provide a quick overview of the structure of the resulting raw scenarios, the raw scenarios are presented graphically as part of the future space mapping. Various display options may be suitable, such as diagrams, portfolios, biplots, shapes, colours and symbols, which can be used flexibly depending on the application. (Fink & Siebe, 2016; Gausemeier et al., 1996).

3.2 Derivation of a Simulation-Based Strategy

The methodically prepared qualitative scenarios by themselves are not sufficient to comprehensively analyse the complex and dynamic interactions between the various key factors of a production network and evaluate future strategical decisions. Simulations can be used to convert these qualitative scenarios into quantifiable estimates by depicting complex interactions over time and thus supporting decisions. In addition, a simulation model allows to quantify the effects of changing variables on the overall system by conducting multiple experiments. Figure 1 showcases the proposed approach for integrating the developed scenarios into simulations of the production network for creating a holistic simulation-based strategy which is loosely based on (Shannon, 1998). Note that the extended group of experts from chapter 3.1 is replaced by simulation expert(s) which may also be a member of the main stakeholders or experts. The following chapters introduce the involved steps in more detail.

3.2.1 Modelling of Base Production Network

In the first step of modelling and evaluation, the base model of the GPN is created by identifying the relevant variables and specifying their relationships. A graphical representation of the simulation model and its results can facilitate communication with internal and external stakeholders. It is important to maintain a simple structure of the simulation to avoid losing focus. Collecting the relevant information and data is the most time-consuming aspect of modelling (Kunz et al., 2023). Therefore, it is advisable to involve the relevant parties early on and begin to consider collecting information on the network even before the final scenarios are determined.

Continuous verification and validation (V&V) must be employed in the creation of the simulation model. The simulation results must be plausible and the simulation model checked for its representativeness for the real production network in relation to the defined target. This usually involves the integration of main stakeholders and key experts of the production network.

3.2.2 Modelling of Scenarios and Countermeasures

Once the base simulation model is verified and validated, the scenarios and countermeasures are implemented to enable the comparison of the base network, with scenario and countermeasures, also see (Peukert et al., 2023). The exact implementations may vary depending on the specific network, scenarios and software but it is advised to realise them as modules for each key factor which can then be reused across scenarios.

Feasible countermeasures are collected throughout the entirety of the proposed process as they come up and included here. To enable users to influence the severity and timings of scenarios and countermeasures, the creation of a suitable interface is key. An appropriate visualisation of the scenarios' results is key for understanding and discussing them (Feldkamp et al., 2020). V&V should be employed throughout this process.

3.2.3 Identification of Potentials for Increasing Resilience

Using a suitable interface, simulation expert(s), main stakeholders and other key experts are able to test the scenarios by changing variables including effects and timings. Users have the opportunity to test different strategies and their impact in preparation or response to these scenarios. This is an iterative process where new solutions may arise during the assessment and are implemented and tested again. Depending on the project goals, this exploration may additionally involve optimization algorithms.

The comprehensive analysis and modelling of the production network and scenarios enables a deeper understanding of the process dynamics and helps to identify and optimize potential bottlenecks and inefficient elements in the production chain. More informed strategic decisions can be made based on the explored solution space.

4 APPLICATION AND RESULTS

The proposed approach is implemented for a practical case study in a part of the production network of a large German company. The following chapters give an overview of the results of this application and the lessons learned.

The case study examines a major product line in a German healthcare company. Production is distributed across three locations in Germany, the United Kingdom, and China. Some products are exclusive to one site, while others are produced at multiple locations.

4.1 Forecasting Scenarios

In the first stage, the fundamental scenarios to increase resilience are determined following the approach outlined in section 3.1.

4.1.1 Project Description

During the initial stage of the project, the project lead and main stakeholders defined its context and objectives. The project's results are intended for internal use within the company. They aim to include a methodical elaboration of the main influences on the production network by internal experts and a transparent representation of the same.

Furthermore, it is considered crucial to test potential resilience-enhancing measures through simulation-based analyses to inform the planning of various projects. Alternative countermeasures within the possibilities of the production should be demonstrated for the developed scenarios and quantitatively and objectively evaluated. The alternative scenarios should relate to network capacity and demonstrate various capacity related options.

The depth of the scenarios should be based on industry scenarios and appear plausible and not too generic within the production network. With a time horizon of five years, it is particularly important to disregard unplanned everyday situations within the production, such as machine breakdowns, or new product developments. Rather, the focus should be on unforeseen future situations that have not been adequately considered and for which no countermeasures have been developed yet. This strategic focus aims to ensure the long-term resilience of the production network and identify potential risks at an early stage.

The acceptance criterium for the simulation is a realistic portrayal of the production network. The focus is on the production network with its production sites with modelling up to basic processes. Inputs for the simulation are market conditions, existing orders, delivery times, production capacity, and lead times. Its outputs are the production capacity, production volumes, and lead times. The results should be visualised in graphs. Furthermore, the members of the extended group of experts from process planning, purchasing, supply chain management and production planning are determined at this stage.

4.1.2 Scope Analysis

As described in section 3.1.2 a careful definition of the specific processes and focus areas is required to further specify the scope of the analysis. The processes are derived from an overview of the production network, while the focus areas are defined through discussions with the main stakeholders. In the process, potential risks in other global companies with comparable production networks were considered, as well as specific product-related risks.

The key focus areas identified are *geopolitical factors*, the *supply chain,* and *production operations*. In this context, geopolitical factors refer to capacity-dependent influences within the network. The supply chain includes all factors between the sites, while the production operation includes all internal factors within the sites.

4.1.3 Identification of Influencing Factors

The identification of influencing factors is based on a workshop including the extended group of experts as described in chapter 3.1.3. Ten people from the company and university participated in the workshop which was conducted as a hybrid event. The participants were assigned to the respective focus areas according to their expertise. Overall, nine unique influencing factors are identified and duplicates such as 'availability and productivity of employees' assigned to a single focus area, see Figure 3 for a summary.

The identified and clustered influencing factors were then described in more detail by the project lead in close coordination with the main stakeholders. For example, 'Reliability and quality of suppliers' is specified as 'The reliability and quality of suppliers are of fundamental importance. A global company is dependent on its suppliers for materials and services, so close co-operation and evaluation of suppliers is necessary.'

Design Field of Production Network		
Geopolitical Factors	Supply Chain	Production Operation
Political Stability A	Logistics D	Employees G
Trade Policy B	Suppliers E	Production Site H
Raw Materials C	Market Factors F	Operating Resources I

Figure 3: Resulting grouped influencing factors (grey) allocated by focus area (light green).

4.1.4 Connectivity Analysis

The connectivity analysis was conducted using the collected and specified influencing factors. The members of all groups filled out a MDI and relevance matrix, the results of which are summarized in Figure 4. The key factors with high relevance and connectivity are trade policy, suppliers, and operating resources.

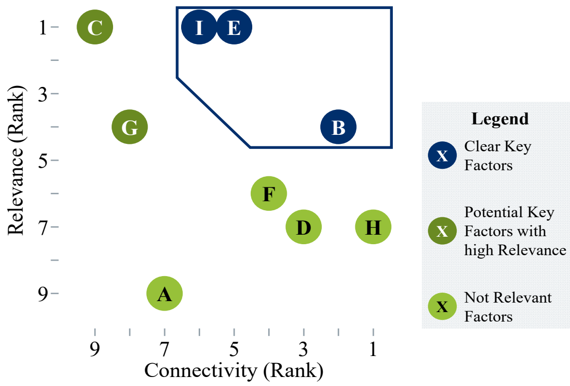

Figure 4: Results of the connectivity analysis visualized as Connectivity-Relevance-Grid by rank. Labelling based on Figure 3.

As stated in section 4.1.4, we considered influencing factors with high relevance but low connectivity, such as access to materials and raw materials (C) and productivity and performance of employees (G). However, we ultimately excluded them from further analysis because the focus of the analysis is on the connectivity of influential factors, and these two factors are already part of existing strategic considerations and measures.

4.1.5 Creation of Future Projections

Future projections are generated by outlining a positive, neutral, and negative scenario for each key factor. Special consideration is given to the unique circumstances of the production network to prevent an overly general or exaggerated presentation. Table 1 provides an example of the three projections for the key factor 'quality and performance of suppliers'.

Table 1: Projections for the key factor 'quality and performance of suppliers' with one positive, one neutral, and one negative development.

Quality and Performance of Suppliers	+	Improved supplier quality through transparent exchange of information. The innovative strength of suppliers leads to new and improved products and services that further optimise production processes.
	○	Continuous supplier optimisation for stable production. The innovative strength of suppliers remains constant, continuing to provide the same quality of products and services that help to maintain current production levels.
	−	Impairment of production plans by unreliable suppliers due to internal or external factors. A lack of innovation among suppliers means that they are unable to keep pace with changing requirements and technologies.

4.1.6 Consistency Analysis

The consistency analysis is performed for the key factors along with their descriptions. A matrix of projections ranging from total inconsistency (1) to strong mutual support (5) is evaluated by the participants of the initial workshop. The averaged results are presented in Table 2.

The range of values and relative consistency of the evaluations suggest a well-developed set of key factors and their projections. The medium values, ranging from 2 to 4, are mostly independent of each other. The main focus for further analysis is on the pairs with high connectivity as this indicates a highly connected and complex dynamic of the key factors.

Table 2: Resulting influencing factors allocated by key factors. Positive projections indicated by plus, neutral by circle and negative by minus symbols.

	KF	Raw. Mat.			Suppl.			Op. Res.		
Key factor (KF)	Dev.	+	○	−	+	○	−	+	○	−
Raw Materials (Raw. Mat.)	+									
	○									
	−									
Suppliers (Suppl.)	+	4,7	2,3	1,5						
	○	2,2	3,8	4,2						
	−	2,5	4,0	1,0						
Operating resources (Op. Res.)	+	3,5	2,3	4,0	4,0	2,7	2,0			
	○	1,5	4,0	1,8	1,8	4,7	4,2			
	−	1,8	3,7	2,0	2,0	3,8	4,8			

4.1.7 Creation of Raw Scenarios

In the next step, raw scenarios are created from the key factors and their consistency. An algorithm is used to create projection bundles that combine future projections of each key factor. In this case, there are 27 projection bundles (3^3). Any bundles with an evaluation consistency smaller than 3 are considered inconsistent and excluded from further analysis. Based on this, ten realistic projection bundles remain. The six projection bundles with the highest consistency score contain predominantly positive or neutral future projections. This suggests that the extended expert group is generally optimistic about the future development of the key factors.

4.1.8 Future Space Mapping

To infer future spaces and effectively communicate the acquired results they are visualised in this step. A scenario map, which is common in scenario planning, is not suitable in this case as the projection bundles cannot be arranged in a meaningful way. Instead, each key factor is indicated by a symbol coloured according to the projected development, see Figure 5.

The future space is grouped according to its influence on the capacity of the production network, consistent with the previously defined project goals. If all projections are positive (bundle 1), the capacity flexibility is high. For bundles with one neutral projection (2A, 2B, and 2C) or two neutral projections (3A, 3B, and 3C), the capacity flexibility is medium to high. If all projections are neutral (bundle 4) or negative (bundle 5), the capacity flexibility is low to medium.

This differentiation allows for precise adjustment of the specific capacity needs, based on which different strategies for increasing resilience can be assigned. In a future space with limited to moderate capacity flexibility in the production network, resilience can only be improved by effectively overcoming the challenges within the network. Increasing the resilience in future spaces with high capacity flexibility is not essential as the production network already encompasses an inherently high flexibility to react to unexpected situations. Therefore, the further focus is on increasing resilience for the future space with medium to high capacity flexibility. These projection bundles are the foundation for the subsequent steps that demonstrate ways to enhance resilience in production networks supported by simulation.

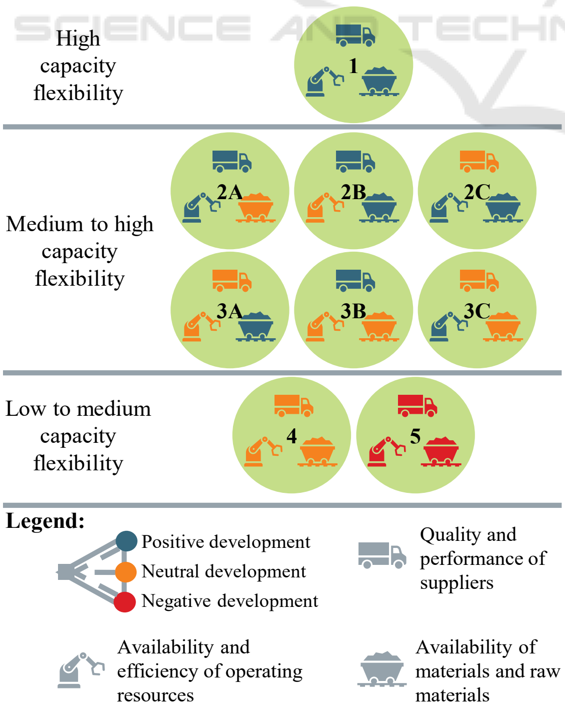

Figure 5: Future Space Mapping for the developed projection bundles.

4.2 Integration of Simulation-Based Capacity Analysis

This section outlines the systematic implementation of the approach for integrating simulations into the scenario planning, as described in section 3.2. This includes conducting a simulation-based capacity-analysis and the derivation of strategies for increasing resilience.

4.2.1 Modelling of Production Network

The production network was modelled in Plant Simulation using discrete-event simulation network due to existing licensing and the ability to build on previous modules and experiences.

The simulation is structured in **three levels**. On the *process level*, variables and objects which depict critical production processes such as bottlenecks or unstable processes are managed. This covers specific aspects which focus on single steps and activities of the production process. The *site level* is broader and introduces variables and objects which impact the lead times of the entire process flow, shift systems or supply cycles of each specific site. At the *network level* the sites and suppliers are connected to each other. Variables of higher levels are influenced by lower levels, e.g. the lead time for the specific site depends on the critical processes within the site. This can also lead to delayed deliveries at the network level which underlines the complex relationships between levels and sites. Figure 6 provides an overview of the simulation model at the site level.

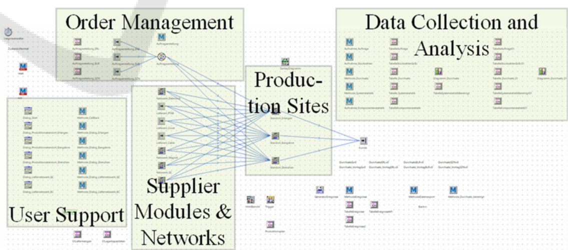

Figure 6: Overview of simulation model at network level.

The model contains **three functional base modules**. The *supplier module* contains external and internal procurement which are simulated as simple module for uncritical suppliers or as complex networks. It acts as supply component for the production modules and provides them with components such as raw materials, semi-finished goods and other materials. The *production modules* model the production sites with networks including the individual production processes. The *functional modules* enable the configuration of scenario parameters with a dialog window and visualizes simulation results and reports.

The order management facilitates the redistribution of orders across the production network by providing them to the relevant production sites which then initiate the production processes. The production networks order the required components from the supplier modules and networks where varying delivery concepts such as supermarket or just-in-sequence are implemented.

A set of fixed-value tests demonstrates that the simulation accurately mirrors the production network, with a maximum deviation of only 13% for the combined network, also see Figure 7. Averaged over an entire fiscal year (FY) the simulation deviates by 0.42 %.

In addition to the fixed value tests, the simulated production network is verified through a review in which the management, client, and supplier of the simulation model checked the model's inherent consistency and specification fulfilment. Further V&V techniques are difficult to implement in this context as real-world data on the impact of disruptions is scarce (Tan, 2020).

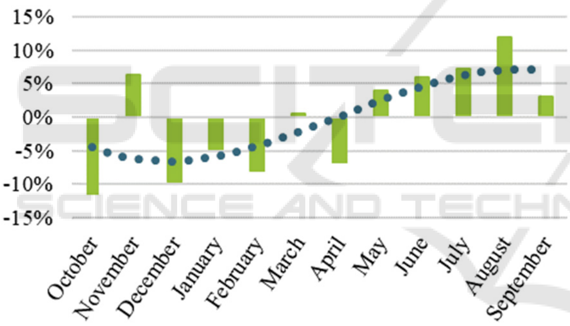

Figure 7: Relative deviation between actual and simulated delivery of products over a fiscal year with blue trend line.

4.2.2 Modelling of Scenarios and Countermeasures

Once the base model of the production network is verified and validated the scenarios and countermeasures are implemented. As described in section 3.2.2, the implementation is based on a module for each influencing factor. These modules are triggered based on the selected scenario and initialize scenario-specific changes.

Out of the implemented scenarios, scenario 3C is presented in detail in the following. Table 3 presents an overview of how the development of the key factors in this scenario is realised in the simulation model. To model the neutral development of the key factor quality and performance of suppliers the delivery of products for one crucial supplier was changed to a normal distribution over a set timeframe to simulate unreliable delivery times. During this, the components are no longer delivered on a daily basis, but follow a normal distribution. The results of this simulation are shown in Figure 8.

The normal distribution of deliveries from a key supplier in the period from the 12th month in FY1 to the 10th month in FY2 has a significant impact on the overall throughput of the production network. The volatile fluctuations are a plausible result of a normally distributed delivery from a main supplier. Once the delivery problems have been resolved, the throughput returns to the previous level with a slight delay. Minor differences between the results of the basic simulation and the scenario simulation are due to the dynamics of the simulation and negligible. The positive development of the key factor 'availability and efficiency of operating resources' has no impact due to the neutral development of the other key factors.

Table 3: Realisation of scenario 3C in simulation model.

Key Factor	Develo-pment	Simulation Model
Availability and efficiency of operating resources	Positive	Increased availability of blocks in production sites
Availability of materials and raw resources	Neutral	Materials and components are produced steadily
Quality and performance of suppliers	Neutral	One crucial supplier delivers the products with a normal distribution for set timeframe.

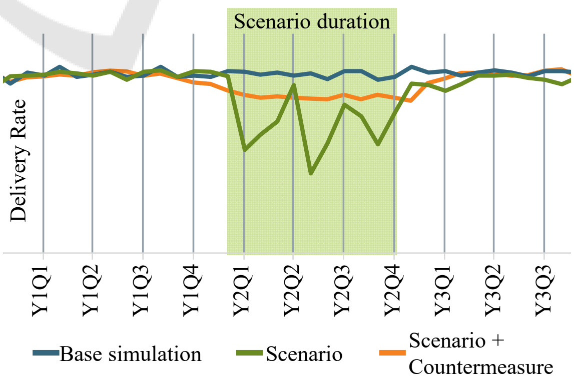

Figure 8: Results of a simulation run for scenario 3C.

In response to the events of scenario 3C described above, a reactive countermeasure is implemented in the form of a second supplier. This additional supplier is now responsible for delivering about ten percent of the critical items. The attached chart in Figure 8 shows that this measure was able to mitigate the negative impact, but not fully compensate for it. Nonetheless, the performance of the production network is able to reach stable condition sooner and is therefore more resilient. However, there are other associated costs, such as increased expenses and existing joint strategic partnerships with the supplier.

The key factors alignment can have varying impacts which are considered in the simulation, e. g. instead of changing the rate of deliveries, the quality of products can be varied, changing the rate of rework, to characterize the development of the suppliers. This step also involves visualising the results and creating an interface to allow a simple manipulation of variables.

4.2.3 Identification of Potentials for Increasing Resilience

In the final step, the potentials for increasing resilience are evaluated based on the created simulation model by inserting countermeasures for the specific scenarios. This allows observation of the impact of potential measures and the time required to reach a stable condition again.

Members of the project team and other key experts are enabled to make more informed decisions by evaluating the impact of the previously identified scenarios on the production network and trial potential countermeasures, such as increasing safety stock, and observing the impacts, and combinations thereof. This is an iterative process where new countermeasures are devised and implemented into the simulation model.

4.3 Lessons Learned

A number of lessons were learnt during the implementation and evaluation of the case study. It is recommended to involve the extended experts often and at an early stage in order to avoid scenarios that are too specific or too general. This also helps to improve access and quality of data, both of which are crucial for the quality of the results. The consulted experts should come from as many different backgrounds and departments as is reasonable.

The process enabled all parties to gain a more comprehensive understanding of the potential risks to the production network under review. This understanding was deepened by the systematic testing of countermeasures in the developed model.

Users gained an understanding of the system's inertia and reaction speed, and how the production network reacts to different scenarios and possible countermeasures. A flexible interface for adapting the scenarios and countermeasures is key for enabling this evaluation.

In accordance with the project's defined goals, the costs associated with the introduction of certain countermeasures and optimisation algorithms have not been included in the simulation. However, their addition is being considered for future projects.

At this point, it must be emphasized that a simulation model is not able to accurately calculate the future. Rather, it serves to point in the right direction and to understand the production network and its reactions to changes. The implemented scenarios and countermeasures must always be critically examined and V&V performed before measures are put into action.

5 CONCLUSION AND OUTLOOK

The complexity of today's GPNs has made them vulnerable to production disruptions. Therefore, recent focus has shifted from reacting to disruptions to proactive prevention. Existing literature does not adequately address the needs of organisations aiming to increase their resilience.

The proposed approach focuses on increasing the resilience in a three-phase process.

In the first phase the project’s goals are specified. After which the second phase involves the identyfication of the most pertinent scenarios, which are subsequently subjected to simulation. This approach allows for a more focused and efficient allocation of modelling and evaluation resources, directing them towards the most critical aspects of the production network.

In the conducted case study, the involved individuals gained a deeper comprehension of the interactions within the considered production network and the potentials for increasing resilience. They were also able to experiment with the consequences of various preventive and corrective measures, thereby enhancing their decision-making abilities.

Future research should concentrate on conducting additional case studies with the objective of further validating the proposed process and developing guidelines for estimating the associated costs for an implemented countermeasure with reasonable efforts.

ACKNOWLEDGEMENTS

We would like to thank Siemens Healthineers Ag for their continued collaboration and support throughout the project. The research was supported by VDI/VDE grant “BayVFP Förderlinie Digitalisierung” with the funding reference number DIK0279/01.

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