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Towards Increasing Robustness in Global Production Networks by Means of an Integrated Disruption Management

Sina Peukert[a,*], Jonas Lohmann[a], Benjamin Haefner[a], Gisela Lanza[a] *

[a]*Karlsruhe Institute of Technology, wbk Institute of Production Science, Kaiserstraße 12, 76131 Karlsruhe, Germany*

* Corresponding author. Tel.: +49-1523-950-2581; fax: +49-721-608-45005. *E-mail address:* sina.peukert@kit.edu

Abstract

Manufacturing companies operating in global production networks face rising complexities and increasing susceptibilities to disruptions. For coping with disruptions, companies are in need of a holistic, comprehensive disruption management, involving all network actors to find optimal measures. However, today's disruption management approaches are characterized by intuitive, experienced-based reactions, limiting themselves to solely the production or the logistics perspective and hence not permitting an overarching reaction. Therefore, this paper presents an integrated approach to disruption management, combining the production and logistics perspectives. It incorporates DoE and metamodelling methods in a simulation model to enable efficient, robust decision-making in highly complex environments.

Keywords: Disruption Management; Global Production Networks; Simulation; Production Planning and Control

1. Introduction

In recent years, as competitive pressure has risen, companies have increasingly tried to make their globally distributed production networks more efficient and cost-effective [1]. These efforts have, however, led to lower inventories and an associated increased susceptibility to disruptions [2]. Due to the high number of interdependencies and the strong interlinkage of partners in global production networks (GPN), occurring disruptions thereby do not only affect individual partners but rather the entire supply chain [3]. In addition to high costs and interruptions in the plans, they particularly also result in reputational damages and lost revenues [4–6]. The aircraft manufacturer Airbus, for example, suffered a drop in revenues of around 12% in the first quarter of 2018 due to technical problems in its suppliers' engine production and was therefore unable to supply its customers on time [7]. Instead, dozens of half-finished aircraft provisionally had to be stored on the factory premises for several weeks [7].

Even less serious disruptions, such as trucks stuck in traffic jams or machine failures, can lead to line stops and thus have serious consequences [6]. Therefore, in order to mitigate the impacts of a disruption as quickly and efficiently as possible and to hence ensure high network performances despite disruptions, a systematic disruption management is required. In order to allow for a satisfying degree of suppression, it should involve all affected network partners [8, 9]. However, as today's disruption management approaches often merely rely on experience and intuition [10], they focus on the optimization of individual areas instead of including all relevant partners and influencing factors and hence impede robust, network-optimal results [11]. Taking these considerations into account, this paper aims at the development of an integrated disruption management approach to identify the most advantageous responses to disruptions in GPN. It is therefore based on a systematic simulative analysis of the diverse landscape of possible combinations of countermeasures originating from both production and logistics. The approach thereby especially

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incorporates the areas of production and procurement logistics as the potentials of an integrated disruption management can especially be exploited if these two areas are considered jointly [12, 13].

The knowledge of advantageous measures can, under certain circumstances, also have implications on the design and organization of the production network for improving the response to disruptions. Thus different proactive strategies for adapting the system configuration are to be investigated in a further step. By identifying configurations which facilitate the reaction to disruptions, this proactive adaptation intends to reduce the sensitivity of GPN and to thus increase robustness.

Therefore, the remainder is structured as follows: While Chapter 2 outlines relevant fundamentals of GPN, disruptions, robustness and simulation, Chapter 3 summarizes the state of the art in disruption management. Chapter 4 thereupon formulates the overarching objective which is addressed using the approach presented in Chapter 5. Chapter 6 subsequently describes the application of the approach to an exemplary use case, and Chapter 7 concludes with a summary and an outlook.

2. Fundamentals

2.1. Disruption management in GPN and the role of robustness

As a result of the far-reaching structural changes that have taken place in the context of globalization, companies have increasingly begun to organize their production in GPN in recent decades [14–17]. GPN are thereby understood to consist of several, globally distributed, value-adding production units, which are connected to each other via material and information flows and which can be supplemented by suppliers and customers [18]. The central tasks to be completed in GPN can be assigned to the three categories of defining the production strategy, configuring the network footprint, and managing the production network (see Figure 1) [18]. In addition to the definition of business models and the product portfolio, the tasks also include the product mix allocation, capability building as well as supply and order management [18].

Particularly on the network management level, disruptions such as machine failures, quality deficits, personnel failures, material bottlenecks or transport bottlenecks might occur from time to time which need to be overcome for maintaining operations [8, 19, 20]. Thereby, disruptions are defined as

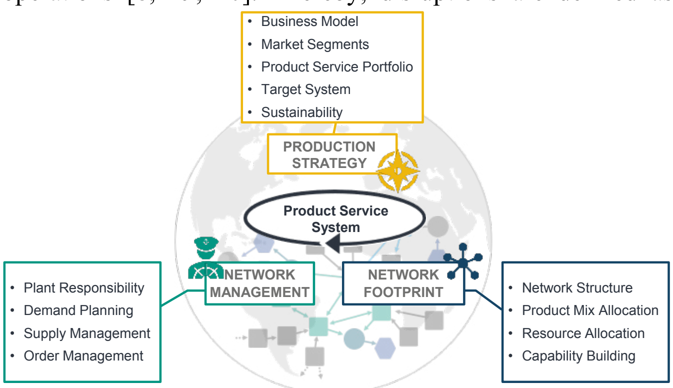

Figure 1: Core tasks in global production networks

unforeseen, unintentionally occurring events, whose effects – without taking any further measures – lead to deviations between actual and planned values and thus to the non-achievement of at least one key performance indicator (KPI) [9, 20]. While many authors concentrate on external disruptions that result from the global environment (state, market, nature) and are therefore difficult to influence, the present paper focuses on disruptions induced internally in the production network or system. They could include machine failures, lack of employees or insufficient material quality. This containment is supported by the fact that according to [21] only less than 30% of the disruptions are induced externally.

In order to allow for a stable and high performance and thus a high robustness of the production network despite disruptions, an efficient disruption management is indispensable [9]. Generally, one can thereby distinguish between reactive and preventive disruption management [22, 23]. While the latter aims at avoiding disruptions (e.g. by additional maintenance) from a long-term perspective [24], reactive disruption management is designed to best deal with disruptions that have already occurred [20]. Within this paper, this encompasses the elimination of disruptions as well as the minimization of their consequences [25]. By taking appropriate measures, both aim to return to the target process as quickly as possible. In doing so, performance losses shall be minimized and the robustness of the GPN shall be increased. Examples of reactive measures are express transports, additional shifts or overtime, rescheduling activities or the use of jumpers [20, 25, 26].

2.2. Representation and analysis of production networks, disruptions and countermeasures

Due to the complexity and dynamics inherent in production networks, simulation is an adequate means of representing and unveiling dependencies/relationships in GPN [27]. Simulation can thereby be defined as the replication of a system with its dynamic processes in order to gain insights that can be transferred to reality [28]. In order to thereby especially illustrate disruptions and to identify correlations between disruptions, countermeasures and the performance or robustness in GPN, discrete-event simulation (DES) is particularly suitable. The reason for this is that DES allows for the modelling of system state changes as different discrete events over time [29, 30].

For modelling as many different scenarios as possible and for gaining far-reaching insights into the interrelationships between the respective objects of investigation, DoE has proven to be adequate [31]. Based on systematic parameter variations, the suitability of certain measures in response to various disruptions can hence be adequately assessed.

However, experimental designs for the investigation of interrelationships in GPN can – like in the present case – become very large and complexity increases with each additional parameter. Therefore, it is appropriate to investigate more complex interrelationships for significant factors by means of metamodels [32]. Per definition, metamodels are auxiliary models that approximate underlying, more detailed simulation models with a satisfying degree of accuracy and hence allow for the analysis of complex relationships in acceptable computation times. The approximation is thereby based on mathematical methods such Gauss process regressions, kriging or neural networks. [33–35]

3. State of the art

Resulting from the risen susceptibility to disruptions described above, disruption management has increasingly become a major research focus for production networks in the last few years. However, an analysis of the existing body of literature reveals that the available approaches largely neglect an integrated consideration of production- and logistics-related aspects in disruption management. Instead, the approaches exclusively focus either on disruption management in production [20, 36–40] or in logistics [8, 41–43]. Robustness aspects are only covered insofar as individual authors – to some extent – evaluate the suitability of particular measures as a reaction to certain disruptions by means of robustness features [8, 42]. Apart from that, however, robustness indices are primarily considered independently from the topic of disruption management. They rather refer to topics such as robust planning [44] and less to robustness as a feature of a production system [9] or even an entire network.

Moreover, the existing approaches of reactive disruption management currently do not consider combinations of measures. Rather, they often only investigate exemplary disruptions and measures [20, 36, 41, 42] with the help of simulations [38, 39, 45], optimization models [37, 46], data analytics [32, 40, 41] or graph theory [20, 47]. These, however, do not exploit the expected potentials of a holistic and comprehensive disruption management and thus do not allow for a profound robustness evaluation within GPN. What existing approaches furthermore leave aside is the derivation of adjustments of the network footprint (planning level) in order to support the reaction within the network management.

For this reason, this paper proposes a methodology for an integrated disruption management which aims to increase robustness in production networks. Resulting from the identified research gaps, the methodology thereby considers combinations of measures from production and logistics and addresses the interplay between the network management and network footprint level to holistically promote robustness.

4. Objective

In order to pave the way towards an increased robustness by means of an integrated disruption management, three research questions shall be addressed (see Figure 2). For first of all gaining insights into the suitability of certain combinations of measures as reaction to disruptions (question 1), potential disruptions and countermeasures from production and logistics have to be (i) identified and (ii) analyzed. The analysis thereby bases on comprehensive, simulation-based parameter studies and metamodelling techniques. As soon as suitable countermeasures have been revealed, question 2 focuses on adjustments on the network footprint level which might support the implementation of these measures from the planning side. Different proactive strategies (e.g., increased safety stocks) are thereby derived from the beneficial countermeasures and their suitability to support the reaction in case of a disruption is elaborated within the simulation model. Knowing both suitable countermeasures as well as beneficial proactive strategies then allows to foster robustness within the network (question 3).

5. Method for increasing robustness in GPN

The proposed method for increasing robustness in GPN by means of an integrated disruption management consists of four steps which will be outlined in the following.

5.1. Modelling of network, KPI system and robustness index

Step 1 aims at holistically assessing and modelling the network under investigation. Besides the identification of relevant processes from production and logistics, this particularly includes the definition of a KPI system and the development of a robustness index *R*.

In this context, the focus initially lies on the systematic collection and description of relevant, production- and logistics-related objects for all levels of observation. From a production point of view, this specifically comprises different locations, required resources such as employees or equipment (including jumpers and replacement equipment) as well as the production program for the different locations. Apart from product-related production sequences and information on technical dependencies, alternative process sequences are also modelled to subsequently provide scope for action in case of disruptions. If an alternative process sequence is known, a measure can in the event of a disruption hence, e.g., consist of switching work processes, thus creating additional degrees of freedom. From a logistics point of view, relevant suppliers, corresponding delivery times, means of transportation, capacities, frequencies, routes and stocks as well as storage and transfer points must be modelled. Here, possible alternatives should also be provided to increase the scope for action when disruptions require the implementation of a countermeasure.

Subsequently, a system of KPIs is developed, by means of which the performance in the network can be recorded and

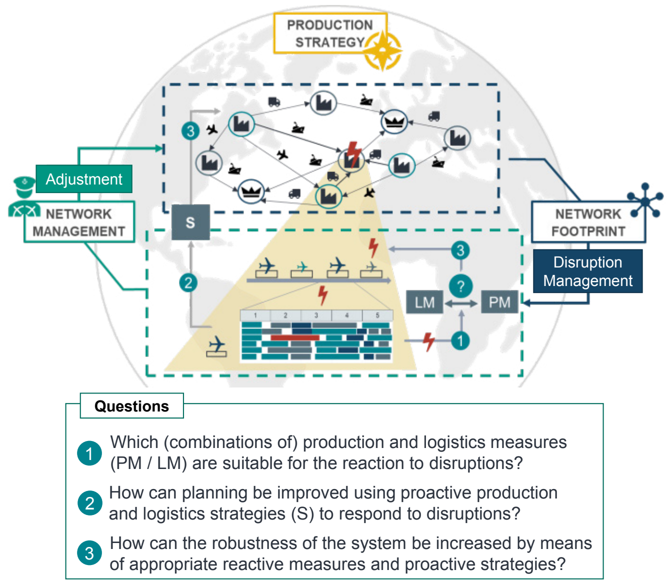

Figure 2: Overview of research questions

measures can be evaluated regarding their suitability for reacting to disruptions. In line with the classic target triangle of time, quality and costs, the KPI system consists of individual key figures related to production and logistics (e.g. adherence to delivery dates, capacity utilization, etc.). These can be interlinked and aggregated across the various levels of consideration for evaluating the network performance. Then, the robustness index *R* is defined for the individual KPIs, which can be used to formulate recommendations for the suitability of certain reactive measures or proactive strategies for coping with the occurrence of different disruption scenarios in step 4. The robustness index is thereby supposed to consider the two robustness dimensions *stability of performance* and *level of performance* and to take the course of time into account.

As a last task of step 1, the target system and the modelled network are parameterized according to a particular use case, hence allowing for the generation of a reference schedule that can be implemented in the simulation model. Since disruptions are initially not considered in this schedule, it reflects a 100% target achievement. This way, KPIs gathered during the reference run serve as benchmarks for evaluating the suitability of different measures/strategies in the case of disruptions.

5.2. Modelling and matching of disruptions and measures

The second step deals with the systematic identification, characterization and modelling of disruptions and measures in production and logistics as a preparation for their examination within the subsequent DoE. For this purpose, disruptions are first collected and then categorized according to the affected area (production/logistics) and the affected resource (e.g. employees, equipment, means of transportation). The search fields thereby either refer to the production network (e.g. suppliers, transports) or the production site (e.g. machines, employees). For each disruption category, the respective disruption effects are then described by means of specific parameters (e.g. quantity, availability, etc.), which can be used to model the disruptions in the simulation model. At the same time, these parameters serve as tools that can be used to also model measures in response to disruptions. In order to provide a framework for representative and realistic disruption scenarios which can be tested within the simulation model, the disruptions are furthermore characterized according to specific properties (e.g. frequency or location of occurrence, duration and intensity of disruption) by means of morphological boxes.

In analogy to the disruptions, countermeasures are also collected and transferred into a comprehensive catalogue that includes production- and logistics-related measures for managing disruptions. The measures are also described and modelled according to their properties so that they can be tested within the simulation model as well. With regard to the properties, a distinction is made between the inputs required for the measure (e.g. resource requirements, lead times, costs) and the effects achieved by the measure. Furthermore, standardized workflows are defined for the measures, hence allowing for their implementation in the simulation model.

By finally matching possible countermeasures to respective disruptions, the number of experimental runs that have to be passed can be reduced prior to the DoE. This way, only plausible combinations of disruptions and countermeasures have to be tested within the scope of the DoE.

5.3. Identification of suitable countermeasures by means of simulation, DoE and metamodelling

Step 3 primarily aims at the identification of cause-effect-relationships between disruptions, countermeasures and the system performance. Simulation experiments are thereby used to make statements about the suitability of certain combinations of measures from production and logistics as a reaction to certain disruptions. For this purpose, the simulation model has first of all to be implemented. In order to thereby keep the implementation effort at a minimum and to guarantee an application-independent usability of the model, standardized modules (such as supplier, production or transport modules) are developed, which can be used and combined repeatedly. Apart from the modules, the KPI system and the disruptions and measures are also implemented. AnyLogic® is thereby used as a simulation software and the modules are verified and validated by different suitable techniques.

Next, the cause-effect-relationships between disruptions, countermeasures and the system performance are determined using the procedure described in Chapter 2 that combines the DoE approach with methods of metamodelling. In doing so, the results of three different types of simulation runs are compared:

1) Reference runs (no disruptions & measures, cf. step 1)
2) Runs with disruptions (no measures)
3) Runs with disruptions & combinations of measures

For runs 2 and 3, a DoE is first conducted, which parameterizes the simulation model for each experiment according to the disruptions and measures that shall be investigated. According to Chapter 5.2, variations of the experimental design thereby include both the disrupted resources and their respective properties as well as the resulting measures. The specific manifestations depend on the selected DoE procedure. An assessment of the suitability of certain combinations of countermeasures as a reaction to disruptions is then carried out based on the data records generated during the simulation runs. As they contain the system performance KPIs and their developments over time, they allow for a suitability assessment and comparison by means of statistical analysis.

Due to the complexity of the topic, however, only a limited number of simulation runs can be carried out. Therefore, the DoE approach is subsequently coupled with the application of metamodelling techniques, by means of which conclusions on non-investigated disruption-countermeasure-constellations and their effects on system performance shall be drawn. For this purpose, the previously generated data sets are divided into a training and a validation data set and the metamodel is adapted to the simulation results via the training data by means of suitable methods such as neural networks (cf. Chapter 2) and a learning algorithm. The validation data set then serves the purpose of ensuring a sufficient coverage of simulation and predicted metamodel results by means of certain metrics and initiates adjustments of the metamodel when necessary. As soon as the results of simulation and metamodel are sufficiently overlapping, the cause-effect-relationships can be interpreted – e.g. by means of response surfaces – and beneficial measures can be identified.

Based on the insights on advantageous measures on the network management level (cf. Figure 2), suitable proactive strategies shall finally be derived that allow for an improved reaction to disruptions by adjustments on the planning side on the network footprint level (cf. Figure 2). A proactive strategy could thereby e.g. consist of an increase in the number of jumpers for the case that jumpers are regarded as highly suitable countermeasure while their utilization rate in the simulation is very high as well. Similarly, adjustments (both increases and reductions) can be undertaken in other resources (e.g. storage capacities, vehicle fleet). These are then combined with each other to create different, potential configurations $K_{1,...,n}$ for the original network (see Figure 3, left). Subsequently, the simulation model has to be adjusted for each respective configuration before the DoE and metamodelling approach are analogously carried out for later identifying the most advantageous network configuration.

5.4. Derivation of recommendations for action

Step 4 evaluates the alternative system configurations tested in step 3 regarding their suitability to effectively and quickly react to disruptions. For this purpose, the alternative configurations are first compared to the initial system configuration (reference case K_0) in terms of their system performance. This way, unfavorable system configurations can be excluded (see Figure 3). The remaining configurations can then be evaluated concerning their robustness. This is based on the robustness index *R* developed in step 1, which reflects the trade-off between stability and level of performance. Building upon the robustness evaluation, recommendations for action can be given which improve the disruption management in GPN through the knowledge of advantageous, proactive strategies and reactive measures and thus lead to an increase in robustness in the network. Besides the quantitative evaluation, qualitative criteria (e.g. effort for the implementation of certain strategies, qualification level) can be considered.

6. Application to an industrial use case

In order to validate the approach and to demonstrate the potential of an integrated disruption management for industrial practice, the presented methodology is currently applied to the production network of an aircraft manufacturer for the production of high-volume single aisle aircraft. The production network thereby consists of one site with several final assembly lines, which is supplied with components for the assembly of the aircraft by various internal and external, internationally dispersed supplier sites. Due to the extreme complexity involved in the fabrication and assembly of these aircraft, the industrial partner expects that the implementation of the integrated disruption management will reveal potentials which might support the reaction to disruptions in the long term. Production and logistics processes as well as KPIs, disruptions and countermeasures have been recorded and implemented in the simulation model. Current research activities focus on the evaluation of first simulation results as well as on the implementation of the metamodel and the identification of strategies and measures to increase robustness.

7. Conclusion

Addressing the need for a holistic, systematic disruption management incorporating all partners in decision-making, this paper introduces a four-step methodology for an integrated disruption management that aims at increasing the robustness in production networks. Building upon the network modelling that incorporates the recording of all processes, disruptions and countermeasures in production and logistics, the development of a KPI system and the elaboration of a robustness index, a modular simulation model is established. Within the scope of this simulation model, suitable strategies and measures that facilitate the reaction to disruptions are derived by means of DoE- and metamodelling-techniques. Thus, an improved robustness in the network shall be achieved. However, as the presented approach is still subject to ongoing work in progress, several aspects need to be further specified before its suitability can be evaluated. In addition to the implementation and evaluation of the metamodels and the development of proactive strategies, this includes, among others, the comprehensive application of the methodology to the use case outlined above.

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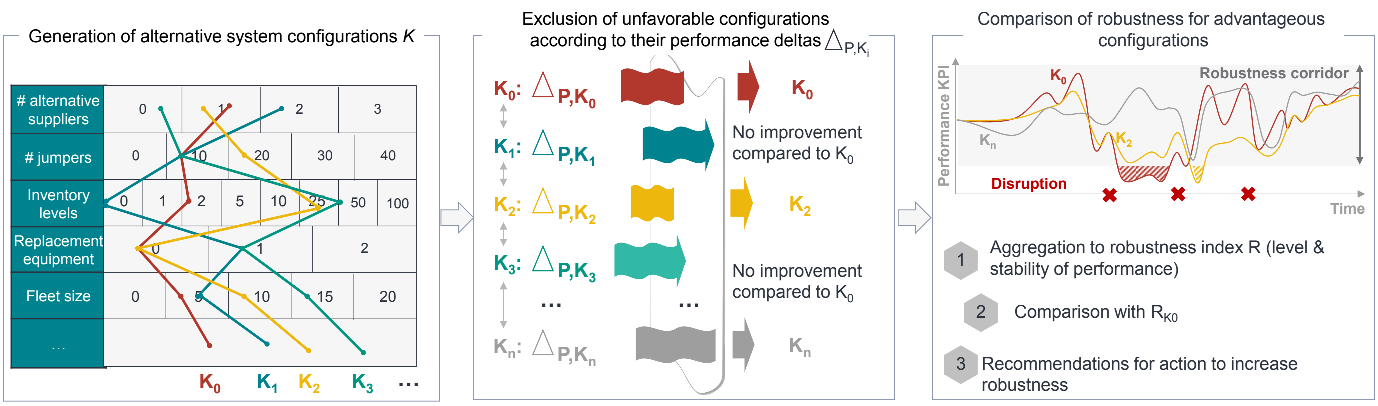

Figure 3: Generation, assessment and selection of advantageous system configurations K_i

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