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Investigating Causal Relationships between Disruptions, Product Quality and Network Configurations in Global Production Networks

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Abstract

Companies nowadays act in global production networks. These networks offer advantages such as production close to market as well as the exploitation of low factor costs. However, due to their interlinkage and complex structure, the resulting networks are characterized by a high susceptibility to disruptions. This paper presents an approach, which quantitatively examines the effects of disrupting events in production networks. The main focus of the study is on the question of how product quality is influenced by quality-related disruptions. To describe the analyzed relationships best, a Kriging based metamodel is adapted to the behavior of the developed multimethod simulation model. The results of the investigation are formalized causal relationships between the error probabilities in production networks, the inspection frequencies of the production systems involved, the respective generic network configurations and the observed PPM quality score.

Keywords: Production Network; Quality Control; Metamodel

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1. Introduction

1.1. Motivation

Industrial companies are facing a dynamic competitive environment. Increasing customer requirements and global competition are causing ever more pressure on cost-effective and high quality production processes [1]. To meet these challenges, industrial companies return to core competencies and resort to outsourcing activities [2]. As a result, value-added processes of companies of any size are globally distributed across several partners on supply and distribution side [3]. The resulting global production networks offer advantages such as a close to customer production, an exploitation of low factor costs as well as the possibility to adapt production and products to local market requirements [4]. On the other side, high coordination efforts arise and the network partner’s competitiveness depends not only on himself but on the performance of the overall network [5]. On operational level, the performance of production networks is especially vulnerable to disruptions. Due to the low added value depth of

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production network partners, the cause of disruptions is usually outside the scope of action of one's own company. The disruptions may be noticeable through delays, capacity failures, quality losses, demand deviations, product changes or cost increases. [6,7] The negative effect of the disruption depends on the design of the production processes and it may escalate for partners depending on the configuration of the production network. Taking into account the production target triangle, ensuring a high product quality is of central importance in this context. Therefore, the prevention and handling of quality related disruptions depending on quality assurance strategies and the production networks configuration is a decisive challenge in global production networks [8,9].

1.2. Goal

The aim of this paper is to quantitatively investigate causal relationships between quality related disruptions, quality assurance strategies and product quality in global production networks. The results of the paper should be transferable to as many real world applications and network configurations as possible. Therefore, the approach is based on the consideration of generic production systems and production network configurations. Due to the high complexity of the interactions in a production network, it is difficult to find an analytical solution to the problem. Therefore, multimethod simulation is applied. In order to keep the computing time for the evaluation of the simulation model as short as possible and in order to be able to describe the relationships quantitatively, a Kriging metamodel is trained to the behavior of the simulation model. The results of the paper are recommendations for the design of quality strategies in global production networks. These recommendations are not restricted to a certain structure and therefore independent of the configuration of the production network.

2. Principles

2.1. Operating Global Production Networks

Global production networks serve for cross-company production. They use specific resources and competencies of the partners involved. The production takes place at globally distributed production locations whereby the partners on supply and distribution side are linked to each other via exchange relationships in the form of material and information flows [10–12]. Various tasks of planning and operating production networks can be differentiated [13]. At the strategic level, long-term decisions concerning product portfolio, production strategy, vertical integration as well as geographical distribution of production locations are made. The tasks on tactical level include capacity-, technology- and resource allocation. They are also referred to configuration of the production network. On the side of quality management, quality positioning and quality planning takes place. The operational level includes the actual execution of processes such as order-, transport- and warehouse management. [13] On the quality side, especially quality assurance and quality steering are important [14]. Referring to [15] the tasks of planning and operating global production networks can be negatively influenced by disturbances with different reasons. Scattering, fluctuations and adjustments hamper planning at the strategic and tactical level. At the operational level, disruptions - in other words differences from planned values - are particularly disturbing. They result in order changes, quality defects as well as end product changes. [15] According to studies, German industrial companies that are part of global production networks are the most and the strongest affected by disruptions which result in quality defects [16,17].

2.2. Managing Quality Related Disruptions

Quality is a feature that assesses the actual characteristics of a product against its required characteristics [18]. The required characteristics of the product are derived from the customer requirements. The actual characteristics are determined by the control of quality inspection features within the production process. Various quality assurance strategies exist. They differ, for example, from the scope of testing (e.g. random test, 100% test) and the testing point within material flow (e.g. goods receipt control, production test, assembly test, final test). A quality defect occurs, if it is determined that not all quality features are fulfilled during the quality inspection [19]. Quality defects can be eliminated as part of the production process by rework or rejects prior to delivery to the customer. A key figure for measuring quality defects from the customer's perspective is the figure Parts Per Million (PPM). It measures the proportion of defective parts delivered per 1 million parts. [20] The measurement is independent of whether the part delivered to the customer does not meet one or more required quality characteristics. Disruptions that lead to quality defects in global production networks have many root causes. The main causes are in machines (e.g. lack of power, defective, poorly maintained), humans (e.g. incorrect operation, lack of qualifications) or material (e.g. wrong material, wrong characteristics). [8,9]

2.3. Simulation and Metamodeling

Simulation is a technique that mimics the behavior of real systems to gain insights into variables of interest [21]. Variables of interest are for example relationships between influencing factors such as disruptions or the configuration of a production network and target figures such as the product quality in the production network. Simulation is particularly helpful when investigations on real systems cannot be carried out in a practical way [22]. In the field of simulation of production and logistics systems, various modeling concepts such as system-dynamic, discrete event-based and agent-based simulation are used [23]. A combination of different modeling concepts in one simulation is called a multimethod simulation. Simulation models can be purposefully investigated for their behavior by means of simulation experiments. In this case, systematic structural and parameter variations of the simulation model are carried out and the changed behavior of the model is determined on the basis of the target variables to be investigated. As models for the simulation of disruptions in production networks have a high complexity and thus place higher demands on the computer performance, a resource-saving implementation of simulation experiments is a basic prerequisite for investigating causal relationship between influencing factors and target figures [24]. Therefore, metamodels are used in various engineering disciplines. Metamodels approximate input-output relationship of influencing factors and target figures of simulation models with significantly less computation time and sufficiently accurate prediction [25]. Simple simulation models can be metamodeled using classical mathematical methods such as linear regression. Simulation experiments of entire production networks describe complex relationships. They are not or only partially known before the analysis. For this purpose, flexible metamodeling methods, such as artificial neural networks (ANN) or Kriging have to be used [26,24]. These methods adjust themselves independently to the complex relationships of influencing factors and target figures. A general recommendation for a single metamodeling method is not possible. Therefore, the quality of the metamodeling method has to be verified by comparing the approximated values and the actual simulation results using statistical key figures [27,28].

3. State of the Art

There is a large number of simulation-based publications dealing with the effects of disruptions in production networks. Schuh et al. (2015) developed a generic system dynamics simulation model, which is able to map disruptions in a production network using parameter variations. The authors considered disruptions caused by customers, suppliers and internal processes by implementing customer demand, replenishment lead time, production lead time and production output as variable parameters. The effects of the disruptions were determined with a cost and performance-based system of indicators [29]. Schmitt & Singh (2012) developed a discrete event-oriented simulation model of a production network to investigate how downtimes and temporary demand peaks influence the order fulfillment rate. For this purpose, a risk profile was drawn up for each location, in which the arrival rate and the duration of a downtime are quantified. In addition, it was analyzed how much inventory should be kept at the individual sites of the production network and how a backup strategy must look like in order to be prepared best for the disruptions [30]. Lian & Jia (2013) used a three-stage supply chain as an example to examine how transport-related disruptions affect the overall profit, the overall inventory, and the demand-related shortfall. Using a generic system dynamics simulation model, they analyzed the effects of delivery delays. The authors also evaluated how volume discount agreements and revenue sharing agreements reduce the negative effects of the disruptions [31]. Persson & Olhager (2002) used a generic simulation model of a supply chain in the telecommunications industry to investigate how quality-related disruptions influence the performance of a production network. The disturbing events are represented in the developed discrete event-oriented model by means of quality levels. A defective part can either trigger a rework process at a quality inspection station or it is scrapped directly. In this context, the authors evaluated the influence of different quality levels on costs and delivery times [32].

Based on the author's findings, only a limited number of publications investigate the effects of disruptions in production networks using metamodels. Kuei, Madu & Winch (2008) developed a discrete event-oriented simulation model of a generic production network to investigate the extent to which lead times and rework costs depend on demand fluctuations, delivery times, site-related quality rates and the required repair times. The authors evaluated the results with a regression model. The site-related quality rates and the required repair times were identified as critical factors [33]. Padhi et al. (2013) investigated in a discrete event-oriented simulation study how the efficiency of a production line is influenced by employee-related disruptions. The results of the simulation study, which was carried out on an Indian automobile manufacturer, were evaluated using a regression model in order to quantitatively map the influence of employee-related work efficiency on production efficiency [34].

The previous sections show that there is a variety of methodologies and procedures for investigating the effects of disruptions in production networks. However, only few publications dealt with the effects of quality-related disruptions that influence production networks via product quality. In particular, the effects on the end customer's product quality were not examined so far. Furthermore, it should be noted that most of the approaches analyzed were developed using case studies as an example. This limits the transferability of the results to larger and differently configured production networks. Moreover, a quantitative description of the relationships between the input variables and the resulting target figures is very limited in this area (see also [34]). To summarize, there is no approach to date that fully meets the defined requirements of this paper for a systematic analysis of the effects of quality-related end-customer-based disruptions in production networks using a quantitative method creating transferable results.

4. Methodology

The proposed methodology for a quantitative investigation of causal relationships between quality related disruptions, quality assurance strategy and product quality in global production networks consists of five steps. The first step includes the characterization of production processes. The characterization serves as a specification for the implementation of modules for the simulation of global production networks. These modules are implemented in the second step in an event discrete and agent based simulation software. They are also aggregated and parameterized to an overall production network simulation. As a third step, a test plan is set up and simulation experiments are run with the model in order to determine the relationships between the variables with the lowest possible number of experiments. In the fourth step, the results of the simulation experiments are used to feed and train a metamodel to the behavior of the simulation model. After the validation of the metamodel, the relationships between quality related disruptions, quality inspection frequencies and product quality are visualized and interpreted using analysis diagrams in the fifth step.

4.1. Characterization of production processes

At the beginning of the methodology, typical features and properties of production processes in production networks are abstracted. The features serve as guidelines and specification for the subsequent simulation. The production processes to be simulated should be aligned to a typical make-to-stock production in the automotive supply industry. The corresponding production processes are characterized by a customer-anonymous order triggering and a consumption-oriented determination of production plans. The simulation should model the production of standard products without any customer-specific variants. The product under consideration has a comparatively slim structural design. The procurement type is characterized by a large proportion of external supplier parts. It is also the aim to map material flow-oriented, tactless series production and series assembly in the simulation.

4.2. Implementation of simulation modules and aggregation to production network simulation

Following the production process characterization, modules are designed to simulate production processes, production sites, customers and transports in production networks (see Fig. 1). The modules are implemented using the simulation software AnyLogic 8.1.0©. As part of the implementation, predefined simulation blocks (e.g. delay, queue, hold) are combined and linked with one another following the specifications of the production processes characterized before. If necessary, the blocks can be extended by individual Java code in order to be able to simulate production processes as accurately as possible. The resulting simulation modules are based on the principle of multi-method modeling and combine elements of agent-based simulation and discrete event-oriented simulation. Production sites and customers represent agents. Internal processes within production sites and customers, such as the order process or manufacturing processes, are controlled by discrete event-driven process chains. The simulation model developed can be configured by a large number of parameters. These are for example: machine uptime, processing times, resource availability, quality test frequencies, stock levels as well as the number and linkage of production sites and customers. The possibility to re-configure the simulation model is deliberately exploited in the subsequent step of experimental design, in order to be able to determine causal relationships via parameter variations of the simulation model.

4.3. Simulation studies

The key figure to be investigated in this paper is the PPM quality index described earlier. Since the interactions between quality related disruptions, quality assurance strategies and network configuration are examined, a systematic variation of eight corresponding parameters takes place. Therefore, a test plan is created using the statistical software JMP 13©. Due to the reason that a computer experiment is performed, a space-filling Latin Hpercube Design is used for the test plan. For influencing factors such as the average error probability and the frequency of testing at individual production steps of the production sites, steady values in the interval of $[0, 0.25]$ or $[0, 0.75]$ are used. Influencing factors such as the number of production steps at a production site and the size of the production network are allocated to discrete factor levels in the interval $[1, 10]$. According to Law, the number of experiments should be about 10 times higher than the number of factors to be examined [35]. Therefore, a total number of 100 experiments with different combinations of the influencing factors is determined. Each experiment requires one simulation run. During each simulation run, the varied factors are recorded as influencing variables and the PPM quality values is recorded as the target variable.

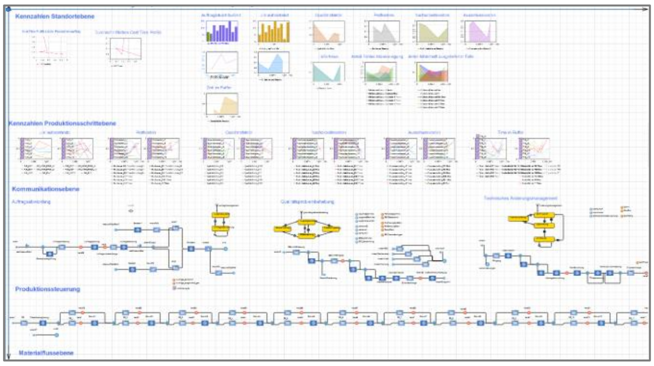

Figure 1: Screenshot of the implemented simulation model

4.4. Training and validation of metamodel

Also the development of the metamodel takes place with the statistical software JMP 13©. For this purpose, the influencing factors and the target variable are stored in the software. The next step is to use the stored simulation data as training data to adapt the Kriging metamodel. The Kriging metamodel is based on a Gaussian kernel. In this case, the prediction takes place using a Gaussian correlation structure in which all points of the experimental space are correlated to each other. Alternatively, an artificial neural network (ANN) is trained as a metamodel. The ANN has a hidden layer with a total of three hidden nodes and is activated via a hyperbolic tangent function. The validation of the metamodels is based on their predictive accuracy. On the one hand, graphical jackknife forecasts are

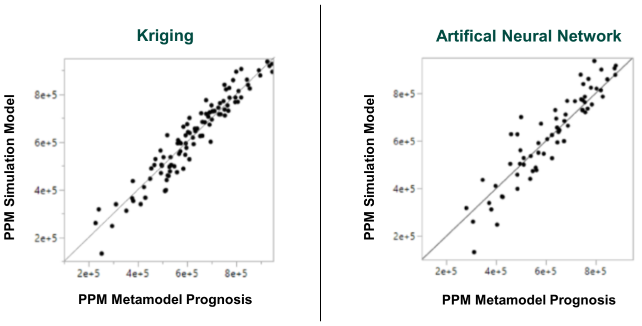

Figure 2: Validation of metamodel using Jackknife-Prognosis-Plots

plotted. On the other hand, the mean absolute deviation (MAE) between the predicted PPM values and the actual PPM values of the simulation model is calculated. As it can be seen in Fig. 2, both metamodels show a high correlation between the simulation model data and the metamodel predictions. Both the Kriging and the ANN metamodel predict the PPM target variable with high accuracy. Scattering is slightly lower in the metamodel generated by Kriging. This is also reflected in the mean absolute deviation. It is 3.75% when using the Kriging method and 3.99% when using the ANN. Therefore, the results of the Kriging method are used in the further course.

4.5. Result interpretation and conclusion

In order to interpret the causal relationships, the shares of the individual influencing factors on the total variance of the target figure PPM are first determined. The share of an influencing factor is a measure of the strength of its impact on the PPM quality score. In addition, an illustration of the directions and the courses of the effect relationships takes place with the help of an analysis diagram (see Fig. 3). The analysis diagrams describe how the PPM value behaves with a variation of the corresponding factor, if all other factors are fixed to the values marked by the dashed vertical lines. The graphs also show the confidence intervals of the curves as well as the strengths and directions of the influences by purple arrow symbols. According to the results, the average error probability of individual production steps has the greatest influence on the target size PPM. The size of the production network and the number of production steps per production site also have a major impact on the PPM target figure. As a central result of the methodology, it can be concluded that a higher test frequency reduces the number of faulty parts delivered to the customer only up to a threshold that depends on other factors. A much greater reduction of the PPM value is achieved by improving the error probability. In addition, it can be stated that quality assurance at the end of a production networks value-added process is most important. Quality defects close to the customer have a more serious effect compared to quality defects at the beginning of the network's value-added process. These results are independent from the actual configuration of a global production network.

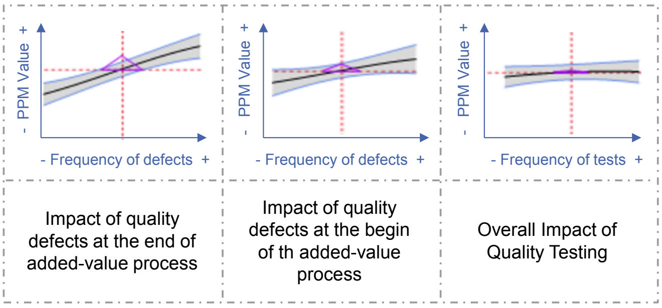

Figure 3: Result interpretation using analysis diagram

5. Application to Industrial Use Case

The methodology for investigating causal relationships between quality related disruptions, product quality and configurations of global production networks has been successfully applied to an industrial use case. For this purpose, a production network from the automotive supply industry which has brush holders for electric motors as a product (see Fig. 4) has been mapped. The first step of the production process of the brush holder contains the punching and deburring of a contact lug at a Tier 4 supplier of the production network. Subsequently, the production of a plastic body by means of plastic injection molding takes place at a Tier 3 supplier. The brush holder is then transported to a Tier 2 supplier, which assembles electronic components such as brushes, torsion springs, thermal switches and stirrup wires. Finally, the delivery of the finished brush carrier to a Tier 1 supplier takes place. The Tier 1 supplier assembles the brush holder with other components such as the stator, rotor, armature and commutator to an electric motor. The internal processes of the Tier 1 suppliers are not part of the consideration. The value stream for the production of the brush holder was recorded in cooperation with the industrial partners and, if necessary, extended by suitable assumptions (see Fig. 4). Subsequently, the simulation model implemented in AnyLogic© was configured and parameterized according to the recorded value stream. In addition, parameter variations were carried out in the course of simulation studies. Experts' assessments on changeable quality-related input variables such as error probabilities and test frequencies of the individual process steps served as a basis. The results of the simulation coincide with the metamodeling results and were considered plausible by the industrial partners. The Tier 1 supplier makes sourcing decisions related to the upstream subcontractors of the brush holder. He is considering using the results of this research in his future supplier development strategy. Motivated by the research results, he is also considering a restructuring of his policies for controlling error prevention costs and quality appraisal costs within the production network.

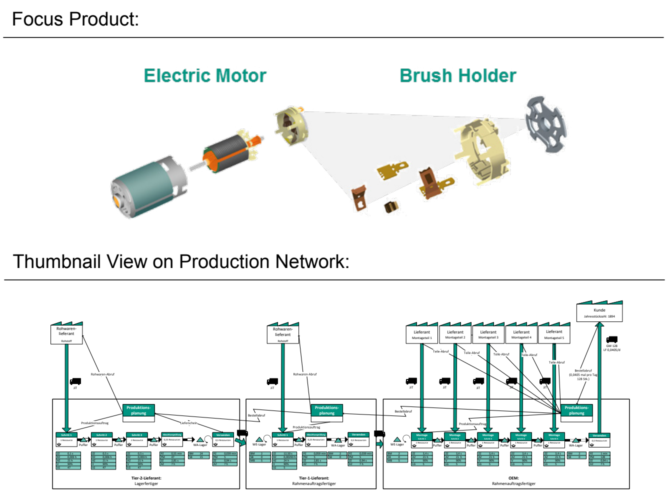

Figure 4: Application of methodology to a production network for the production of electric motors brush holder

6. Summary and Outlook

The objective of this paper was to present a methodology for systematic investigation of causal relationship between quality related disruptions, quality assurance strategies and product quality in global production networks. The proposed methodology includes a five step procedure which deploys simulation and metamodeling techniques as a key element. The results help to formulate guidance for quality management strategies in global production networks. The results also demonstrate, that metamodeling techniques can be successfully applied to the analysis of causal relationships between influencing factors and target figures in global production networks. Future research work will focus on a more intensive investigation of the simulation model. The impact of many other disruptions belonging to the areas of order management and engineering change management will be investigated. As announced in a previous paper [36], it will also be investigated to what extent a more intensive exchange of information between the production networks partners improves disruption management.

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