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Information Exchange in Global Production Networks: Increasing Transparency by Simulation, Statistical Experiments and Selection of Digitalization Activities

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Abstract

Today, companies of all industries are part of global production networks. They have a variety of performance relationships with suppliers and customers. Digitalization offers the potential to exchange more information between the partners of global production networks. This may improve operational performance. Especially within the three business processes order management, quality problem solving and engineering change management, a targeted increase in transparency promises a better handling of disruptions and an increase in robustness. This paper presents a simulation-based methodology for modeling production and business processes as well as information exchange in global production networks. Following the principles of Design of Experiment (DoE), screening test plans first carve out the impact of disruptions and information exchange on the performance of the production network. This is followed by the determination of the disruption-robust information exchange using Taguchi-experiments. Starting from the actual state of information exchange, digitalization activities to increase transparency are finally determined. The activities consist of the implementation of digitalization technologies and the stronger linkage of information systems. The paper ends with an application of the methodology to a global production network for plastic-metal components in the automotive supplier industry.

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Keywords: Production; Information; Performance; Global Production Network

Introduction

In recent decades, globalization has led to an interconnection of global procurement and sales markets as well as to increased competition [1]. Industrial companies operate in the form of global production networks (GPN) [2]. GPN bring together partners such as suppliers, production sites and customers. Each partner contributes its specific knowledge to the creation of products and services [3]. In practice, production networks are not designed on a drawing board. They result from opportunistic ad-hoc decisions and lack strategic focus [4]. Often, closed-mindedness and isolation instead of openness and trust are the predominant behavior patterns.

At the operational level, the occurrence of disruptions poses challenges for the partners of GPN. Triggers for these unexpected deviations from planned values are, for example, short-term changes in customer orders, quality problems in production or late product changes [5]. In the majority of the cases, the root-cause of a disruption is not within the company but within a network partner. Therefore, disruptions require joint disruption management in the three core areas order management, quality problem solving and engineering change management. An increased transparency of GPN promises a better handling of disruptions [6]. Companies have high expectations in a transparency increase [7, 8]. Disruptions may be identified and eliminated more quickly. However, the cause-effect relationships between disruptions, the exchange of information and the operational performance of production networks are often unknown in practice. In addition, the choice of suitable digitalization activities such as the introduction of new technologies and the stronger interlinkage of information systems (IT-systems) form a challenging decision problem [6].

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Building upon these challenges, this paper presents a methodology for increasing the transparency of GPN. Simulation and statistical experiments are used to investigate cause-effect relationships and to define a robust target state for information exchange in production networks. Following the target state, digitalization activities are identified and evaluated in order to increase transparency. The exemplary application of the methodology is based on a practical example from the automotive supplier industry.

Principles

2.1. Disruption management in GPN

Global production networks (GPN) are networks in the business sense. The tasks of their management can be divided into the three levels of strategic, configurative and coordinative planning tasks [9]. Coordinative planning tasks include the execution of processes within a short-term time horizon. This approach considers three coordinative planning tasks that must be performed due to the occurrence of disruptions: order management, quality problem solving and engineering change management [10]. Order management is used to plan and optimize order throughput in production [11]. Typical disruptions are customer orders that change at short notice and the failure of machines or planning systems. The elimination of quality problems becomes necessary due to disruptions such as production errors [12]. Engineering change management adapts individual components of products, which have already been released during product development. The triggers for engineering changes are safety or quality adjustments, functional changes or product troubleshooting [13].

Order management, quality problem solving and engineering change management determine the operational performance of the production network. The performance is measured with single key performance indicators (KPIs) which can be linked to indicator systems from the bottom level of the individual production systems up to the production network level [14]. In order management, short lead times and high service levels are to be aimed at. The target parameter for solving quality problems is a low number of faulty parts delivered to the customer. Key figures for engineering change management are short change lead times and the avoidance of engineering change exploitation. A high performant network exhibits a high and stable performance despite disruptions and is called a robust production network [14].

2.2. Information exchange and digitalization activities

Within disruption management, the partners of GPN exchange information. The information exchange is not necessarily aligned with the production processes. It can be both chronologically leading and lagging. A phenomenon that describes the necessity for a broad and synchronized exchange of information is the bullwhip effect known from production logistics. It describes the fact that if the flow of information is small and not temporally coordinated, orders from suppliers show greater fluctuations than actual sales to customers. [15]

The information being exchanged between the partners of GPN can be differentiated according to its types and characteristics. Types of information are transaction information (e.g. delivery call-off, shipping note), status information (e.g. machine status, inventory level), master information (e.g. bill of material, technical drawing) and planning information (e.g. sales forecast). Characteristics are represented by the quantity (e.g. no access, limited access, full access), the timeliness (e.g. monthly, daily, real-time) and the accuracy (e.g. unsatisfying, satisfying, high). [16]

Depending on the information being exchanged within business processes, different digital maturity levels are distinguished. “Analogous” business processes are carried out with no or little support by information systems. “Digitalized” processes are supported by information systems. “Digitalized automated” processes are automated on the basis of available information and replace human planning tasks. The highest level “Digitalized self-controlled” processes are characterized by an intensive information exchange in real time. [17]

Digitalization activities are an enabler to gather, store, evaluate and exchange more information in GPN (see Fig. 1). New technologies such as barcode, smart label, mobile data capture, optical character recognition (OCR), radio-frequency identification (RFID), speech recognition and various chip card variants as well as methods for electronic data processing such as electronic data interchange (EDI) may be used. Databases and IT-systems could be connected stronger. IT-systems related to order management are for example Enterprise Resource Planning (ERP) and Manufacturing Execution (MES) systems. They serve for company-wide planning, control and monitoring in procurement, production and sales. Warehouse Management Systems (WMS) and Transportation Management Systems (TMS) support order management. ERP and MES systems also support quality problem solving. However, Computer Aided Quality Systems (CAQ), which collect, analyse, document and archive quality-relevant data, are specially designed for this purpose. Product lifecycle management systems (PLMS) address engineering change management. Systems that specifically support disruption management are subsumed under the term Supply Chain Event Management System (SCEM).

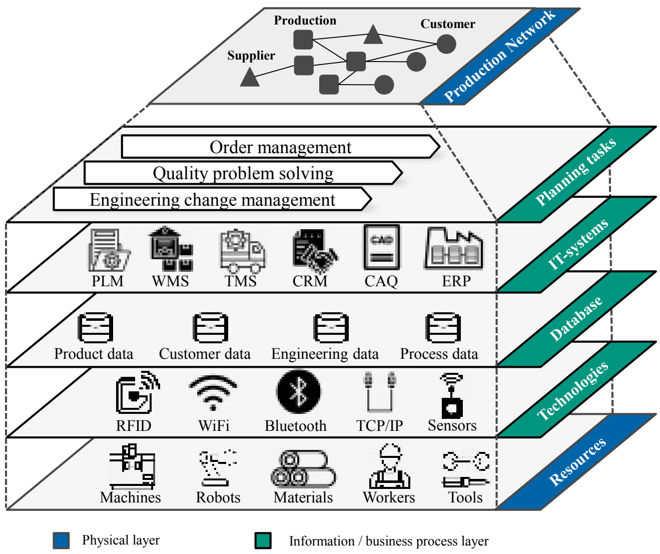

Figure 1. Digitalization activities for information exchange in GPN.

2.3. Simulation, statistical experiments and decision theory

Simulation and statistical experiments are promising methods for determining cause-effect relationships between input variables and target figures. Decision theory supports the selection of measures to enhance information exchange.

Simulation is a problem-solving method that depicts systems (e.g. production networks) with their dynamic processes (e.g. disruption management with variable information exchange) in an experimental model in order to gain knowledge that can be transferred to reality. Different types of simulation exist. For the simulation of logistics and production networks, discrete-event and agent-based simulation are particularly suitable. [18]

Simulation experiments enable an investigation of the simulation model behavior by carrying out simulation runs under systematic parameter variation. Depending on the test design and the statistical model, different issues regarding the effect of factors on a target figure can be proven. Statistically significant cause-effect relationships between factors can be verified by full factorial experiments and linear statistic models. Linear statistic models can also be used to determine factors with a large influence on a target figure within screening experiments. So-called Taguchi-experiments differentiate factors into stochastically noise factors and controllable factors. They determine an optimal, robust setting of the control factors in order to minimize the noise factors. When carrying out experiments, test plans must be constructed that are as small as possible on the one hand and reveal all relevant effects on the other side. The statistical validation of the revealed effects is ensured by significance tests and hypothesis tests. [19, 20]

Multi-criteria decision theory provides methods for determining the best alternative from a multitude of possible alternatives when considering several criteria. Multi-Attribute Decision Making (MADM) determines a compromise solution within a discrete set of feasible alternatives. In reality, decision makers do not know exactly about their preferences regarding an alternative. Outranking approaches address this problem by focusing on structuring and supporting the decision-making process. The most used outranking methods are the Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE) and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). [21]

3. State of the Art

Transparency increase in global production networks (GPN) is addressed by four research areas with different objectives.

One area of research examines the fundamental relationships and advantages between information exchange and performance in supply chains. This research makes use of empirical research methods and evaluates data from company surveys or case studies using hypotheses testing or structural equation models. It describes general relationships between supply chain visibility and supply chain integration as well as (financial) performance of supply chain partners. [22–24]

A second research area deals with the development of KPI-systems either for measuring the robustness of production systems [14] or for measuring transparency in supply chains [16]. The relationships between the single performance indicators are modelled analytically.

The third research area analyses the relationships between information exchange and disruptions, either with a focus on order management, quality problem solving or engineering change management. Non-empirical methods such as simulation are applied. The system behavior is analyzed with a high degree of detail. The majority of research focusses on order management. [12, 13, 25]

The fourth research area recommends the use of certain digitalization technologies or software systems to increase transparency in supply chains. For example, the use of RFID and cloud technologies for Track & Trace in order management has been intensively investigated. Besides, SAP Advanced Planning and Optimization (SAP APO) and SupplyOn systems were compared with regard to their value in increasing the visibility of supply chains. [26–28]

Further literature can be allocated to the research areas. However, to the authors' best knowledge, previous research has several shortcomings. Order management, quality problem solving and engineering change management are the core processes of disruption management. But they have not yet been investigated in an integrated manner with respect to a transparency increase. Cause-effect relationships between the large number of influencing factors to be taken into account on the side of disruptions and information exchange have not yet been systematically determined. In addition, there is a lack of research that recommends digitalization activities for improving transparency in the areas of quality problem solving and engineering change management.

4. Methodology

The proposed methodology to increase transparency in global production networks (GPN) consists of three steps: (i) the simulation of disruption management in GPN with respect to variable information exchange, (ii) the investigation of cause-effect relationships as well as the definition of a target picture for the information exchange using statistical experiments and (iii) an approach to put the target picture for a high performant and disruption robust information exchange into practice by identification and comparison of digitalization technologies and stronger interlinkage of IT-systems.

4.1. Simulation of disruption management in GPN

In order to simulate disruption management in GPN, preliminary work is carried out. It supports the implementation of standardized reusable simulation modules which only have to be reparametrized according to the industrial use case.

First, typical features and characteristics of production systems are defined in order management, quality problem solving and engineering change management. A characteristic of order management is, for example, the "type of order triggering" with the characteristics "make to order" and "make to stock".

Besides, elements of production networks such as products, resources, warehouses, transports, production sites, suppliers, and customers are defined. Disruptions are gathered that occur at the network elements. For example, a resource can be a processing machine of a network partner. Typical disruptions at processing machines related to order management are machine breakdowns. A typical disruption in quality problem solving is the production of bad parts.

As further preparatory work, a system of performance indicators is set up. It evaluates the performance of order management, quality problem solving and engineering change management. To set up the system, individual production-related key performance indicators such as the throughput time of orders are first defined on machine level. The indicators are then linked to an indicator system starting from the production line level to the site level up to the network level.

While previous work has focused on the physical layer of the production processes, the focus is now on the overlying information exchange layer. Business processes are modelled for order management, quality problem solving and engineering change management. The processes describe the operational reaction of network partners to disruptions. Transaction-, status-, master- and planning-information that is being exchanged between the partners is specified for each process. Depending on the type and characteristics of the information, different process variants are distinguished.

Finally, the implementation of the simulation takes place using the JAVA-based and object-oriented software AnyLogic®. Based on the preliminary work, discrete-event and agent-based simulation modules are designed. Discrete-event simulation maps the production processes, the occurrence of disruptions and the performance indicator system. The agent-based section simulates disruption management and the exchange of information. Since AnyLogic® offers the advantage of an object-oriented simulation, modules only have to be defined once and can be used several times by individual parametrization. AnyLogic® offers a comprehensive module library for implementing the simulation which can be extended using own JAVA code.

4.2. Investigation of cause-effect relationships and target picture for information exchange

The aim of the statistical experiments is to use the simulation model to determine significant cause-effect relationships between disruptions, the types and characteristics of information exchange as well as the performance of the production network (see Fig. 2). A three-step procedure is chosen. For performing the experiments, the AnyLogic® simulation is linked to Minitab® and Matlab® interfaces.

The aim is to first demonstrate the relationship between information exchange and performance in general. Therefore, parameters on the side of information exchange are varied with a two-step full-factor test plan for each of the three business processes order management, quality problem solving and engineering change management. The results of the simulation runs are analysed with a regression analysis and a linear description model to examine the main effects of the information exchange on the performance of the business processes. For this fundamental proof of cause-effect relationships a significance level of 5% is chosen.

If a cause-effect relationship has been proven, disruptions as well as types and characteristics of the information exchange with largest influence on the performance are revealed within the second step. The starting point of the statistical experiments is a Plackett-Burman screening test plan. As before, the results of the simulation runs are statistically evaluated with a linear description model and a stepwise regression.

Finally, a robust parameter setting is determined for those types and characteristics of information exchange that have a major influence on the performance of the production network. The robust parameter setting reflects the target picture and specifies which information should be exchanged in which quantity, timeliness and accuracy in order to minimize the negative effects of disruptions. The determination of robust information exchange is conducted using a Taguchi-test. The disruptions are regarded as stochastic noise factors that cannot be controlled. The types and characteristics of information exchange serve as control factors. The rule "smaller is better" is chosen as signal-to-noise ratio.

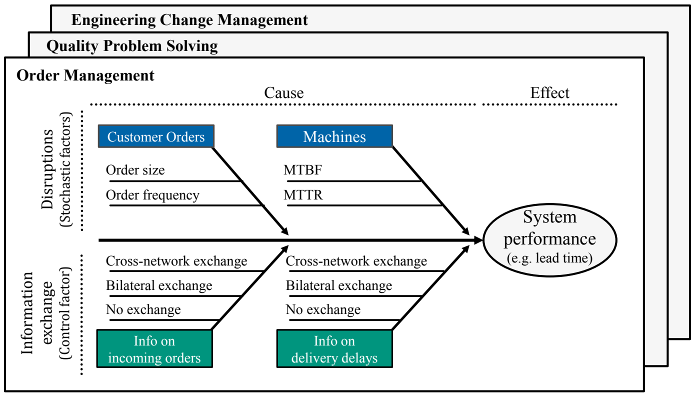

Figure 2. Parameters for investigating cause-effect relationships.

4.3. Implementation of target picture using digitalization activities

The Taguchi-tests lead to a target picture for a high performant and disruption robust information exchange in the production network. This target picture specifies the type as well as the quantity, timeliness and accuracy of the information to be exchanged in the production network.

In order to implement the target picture, the necessary digital maturity level "Analogous", "Digitalized", "Digitalized integrated" or "Digitalized self-controlled" of order management, quality problem solving and engineering change management is determined first. If order information such as incoming orders, shipping notification or machine capacities shall only be exchanged weekly and bilaterally between the partners, low maturity levels such as "Analogous" are sufficient. If, however, the information shall be exchanged in real time with various accompanying information such as technical drawings or information on the current machine status, high maturity levels such as "Digitalized automated" or even "Digitalized self-controlled" are required.

The maturity level required in future is then compared with the current maturity level of the business processes. The objective is to determine necessary adjustments. The introduction of new digitalization technologies or the stronger interlinkage of existing IT-systems in the production network are possible activities in order to implement the target picture. If information on orders is currently exchanged by fax or e-mail and the aim is to implement a digitally self-controlled level, digitalization activities such as switching to EDI-based order management or introducing real-time Track & Trace of production and logistics progress must be implemented.

Activities such as the introduction of new digitalization technologies or the stronger linkage of IT-systems can be implemented via various technology alternatives (tracking e.g. with barcodes, RFID or global positioning system (GPS)) or software solutions (EDI, e.g. via SupplyOn, EDIConnect, Dell Boomi). These alternatives must be compared with regard to criteria such as financial and time expenditure or a possible violation of IT-security concerns of the partners in the production network. The TOPSIS method is selected as suitable MADM method for this purpose.

The result of this last methodological step is a recommendation for the implementation of the target picture of an information-transparent disruption management in GPN. It is important to note that the solution space for digitalization activities is extremely large. Therefore, possible technologies and software solutions must be developed and compared on a case-by-case basis.

5. Application to Industrial Use Case

5.1. Production network for metal-plastic composite parts

The presented methodology is applied to a network for the production of metal-plastic composite parts in the automotive supplier industry (see Fig. 3). The part is produced in quantities of up to one million parts per year and installed in an electric actuator which serves as a window regulator or seat adjuster in automobiles. The production network consists of three partners. Partner 1 punches a metal contact lug. Partner 2 produces a plastic body. Partner 3 installs the contact lug and the body with other electrical components to the metal-plastic composite part. The production sites of the partners are located in various European countries. Due to the low exchange of information, the partners struggle with various problems. The bilateral exchange of order information results in a bullwhip effect. Information on quality problem solving is not exchanged since partners compete with each other for other supplier parts and therefore want to maintain their reputation as quality leaders. Information on engineering change management is only exchanged bilaterally between the customer and each partner. A check, whether the specifications of other partners are still fulfilled after changing the product

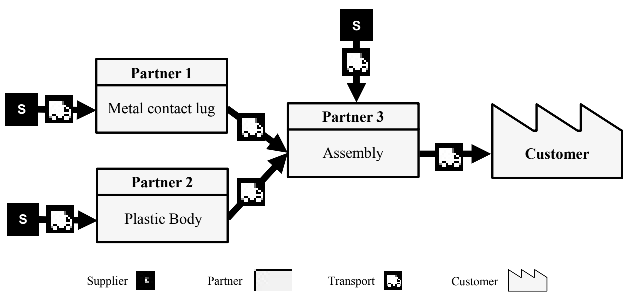

Figure 3. Production network for metal-plastic composite part.

model does not take place. Short lead times and a low number of defect parts delivered to the customer are the most important performance indicators for the network partners.

5.2. Application of methodology for transparency increase

Step 1: Simulation Model

In order to recommend measures for transparency increase, the value stream was recorded with industrial partners and the simulation was parameterized accordingly. The performance system with the KPIs lead times and number of defect parts delivered to the customer has been implemented.

Step 2: Cause effect relationships and target picture

As part of the statistical experiments, a total of 1.012 simulation runs were performed on an AMD Ryzen 7 1800X machine with eight cores, 3.60 GHz and 32 GB RAM. In order management, the effect of the two disruptions fluctuating customer demand and machine failures was investigated. In quality problem solving, the frequency of the occurrence of quality problems was subject to the experiments. In engineering change management, the impact of the frequency and the impact of the extent of engineering changes was tested. For order management and quality problem solving, a statistically significant effect between disruptions, information exchange and performance could be revealed. According to the results of the Taguchi-tests, information on incoming orders must be exchanged across the entire production network in order to improve lead times (see Fig. 4). In quality problem solving, the exchange of information related to quality defect complaints and the exchange of information related to quality defect warnings by Partner 1 and Partner 2 have a significant effect on the number of defect parts delivered to the customer (see Fig. 4). In total, lead times can be decreased by up to 4% and number of defect parts delivered to the customer can be decreased by up to 5% by increased information exchange. For engineering change management, a statistically proven relation with the performance indictor lead time could not be revealed.

Step 3: Implementation of target picture

According to the results, the order management should be developed from the current maturity level "analogous" to the level "digitalized automated". The process for solving quality problems is aimed at the level "digitalized". To prepare the implementation, various digitalization activities have been worked out and compared using TOPSIS within workshops with the industrial partners. Since the partners already use SupplyOn platform's functionality for purchasing and logistics, the joint use of additional SupplyOn modules for order management is being sought. In quality problem solving, the need for the introduction of a CAQ system was identified. Since the partners are not building on any existing solution, alternative systems have been compared. Partner 3, is driving the introduction of the CAQ system. As a direct supplier to the customer, he bears the entire quality responsibility of all partners of the production network.

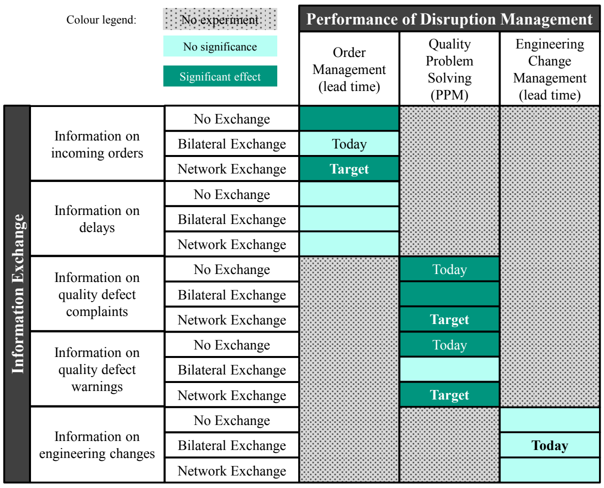

Figure 4. Heatmap of cause-effect relationships for industrial use case.

6. Conclusion

This paper presents a methodology to increase the transparency of global production networks (GPN). First, a simulation model is developed, which maps disruption management in GPN. Subsequently, statistical experiments are used to determine cause-effect relationships between disruptions, information exchange and the operational performance of the network. The experiments help to determine a target picture for the information exchange, too. The approach ends with the identification and selection of industrial-suited measures to implement the target picture of an information transparent disruption management into practice. The methodology is successfully applied to an industrial use case from the automotive supplier industry. Practical digitalization activities to intensify information exchange are determined. They consist of a stronger linking of SupplyOn systems within order management and the introduction of a cross-network CAQ software for quality problem solving. Future research should not only focus on the potential of an increased information exchange for reactive disruption management. Information exchange is the base for anticipatory actions. It enables new forms of collaboration between the involved partners. Therefore, research must answer questions on the potential of collaboration for efficiency increase in GPN.

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