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Target system based design of quality control strategies in global production networks

Tobias Arndt[a,*], Christina Lemmerer[b,c], Wilfried Sihn[b,c], Gisela Lanza[a]

[a]*Karlsruhe Institute of Technology (KIT), wbk Institute of Production Science, Kaiserstr. 12, 76131 Karlsruhe, Germany*
[b]*TU Vienna, Institute of Management Science, Theresianumgasse 27, 1040 Vienna, Austria*
[c]*Fraunhofer Austria Research GmbH, Theresianumgasse 27, 1040 Vienna, Austria*

* Corresponding author. Tel.: +49-721-608-44297; fax: +49-721-608-45005. *E-mail address:* tobias.arndt@kit.edu

Abstract

Increasing globalization drives companies to produce in global networks, where each site acts autonomously according to its individual target system, influenced by specific location factors or its defined specialization. Despite distributed value creation processes, the overall production quality must be ensured. Hence, a simulation-based approach is presented, which allows for designing an optimal across-site quality control strategy by evaluating different quality measures depending on individual target systems of different sites. At first, a categorization of quality measures and an applicable target system model are presented. Secondly, a simulation approach is described to evaluate implemented measures according to defined performance indicators.

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Keywords: Production network; target system; quality control measures; simulation-based evaluation; performance indicators

1. Introduction

In order to gain competitive advantages in an environment of growing global competition and increasing globalization of sales and procurement markets, companies are distributing their manufacturing activities in global production networks [1]. They increasingly focus on their core competences and specialize for example concerning manufactured products, the supplying market or the processes carried out [2]. Hence, global production networks consist of own corporate sites as well as locations of external partners and suppliers exchanging a wide range of materials and services. Therefore, it can be concluded that competition is no longer fought between individual companies but between competing networks [3].

Additionally, depending on the specialization and the respective location factors (e.g. available process technology, factor costs, infrastructure), a strategic role in accordance with the respective company strategy is often assigned to the individual actors in the production network [4]. This role defines a specific target system, according to which each site acts autonomously and defines individual production related improvement actions. This leads to mutual interdependencies, target conflicts and asymmetric information distribution among the different actors [5]. Given this context, the management and control of production networks is a growing challenge for companies [6]. Especially the decentralized decision-making structures and processes, which follow the individual target systems, cause difficulties identifying realizable and expedient control and improvement measures.

The assurance of exceptional production quality along the whole product engineering process in the network leads to special challenges in this context [7]. Despite the involvement of many partners with divergent target systems, the required quality of the final product must be ensured with minimum cumulative quality and testing costs, as such activities are not perceived as value adding by customers [8]. Currently, quality control strategies completely focus on the considered process without adequately regarding the specific site role. Moreover, the impact on the individual target system of each actor in the production network is neglected. Thus, quality control measures may not be implemented after an intra-site analysis, even though they would have a positive effect in a holistic view of the production network. In addition, due to the asymmetric information distribution, redundant measures may be carried out at different sites, which leads to significant inefficiencies in the production network.

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Therefore, this article presents an approach, which enables globally operating companies to design an optimal across-site quality control strategy purposefully by evaluating different quality measures depending on individual target systems of different sites. Hereafter, the relevant state of the art in literature is discussed. The designed methodology is presented in chapter 3. Finally, chapter 4 concludes with a summary.

2. Foundations and state of the art

2.1. Target systems in global production networks

Targets are ideas about desired states of a company that should occur as outcome of implementing measures. In a target system, hierarchical in nature, sub-goals are aligned with overall company targets. The sub-goals may be neutral, complementary or adversarial and can be operationalized using Key Performance Indicators (KPI) as compressed metrics [9]. Target systems of individual actors in production networks are influenced by the strategic orientation of the company and activities for coordinating the supply network. Within a company's target system, different hierarchy levels are distinguished. At the highest level, corporate objectives are defined, then divisional or business unit objectives, followed by objectives of departments, and position or station targets [10]. In order to differentiate target systems on a business unit level especially regarding manufacturing or purchasing as link to other partners in the production network, different plant or site roles are described in literature.

From the internationalization motives of globally operating companies, Weber derives four types of sites: resource-oriented, market-oriented and innovation-oriented locations as well as lead plants [11]. Resource-oriented sites produce high lot sizes and a low number of variants. They focus on minimizing production costs while considering time and quality efficiency. Market-oriented sites aim at fulfilling regionally specific customer requirements. They are located in major sales regions, because a customer-oriented expertise is important. Innovation-oriented sites aim at developing innovative products, manufactured as prototypes or in small series. Research and development expertise as well as high capabilities of local suppliers are required. Lead plants have executive functions regarding products or core processes, so they are mostly located in industrialized countries.

Ferdows classifies site roles based on the site competence and the strategic goal of the site [12]. As site competence, he defines the scope of technical activities beyond production, such as procurement activities, supply network management, or process and product development. Related to the strategic goal, three main objectives are differentiated: low production costs, capabilities and knowledge as well as market proximity. Offshore and source factories focus on low-cost production with higher site competences at the source factory. The main objectives of lead and outpost factories are capabilities and knowledge. In lead factories, new products, processes and technologies for the entire company are continuously developed. The main task of outpost factories is to collect information about customers, suppliers and competitors. Finally, the strategic goal of server (low site competence) and contributor factories (high site competence) is market proximity in order to serve national or regional markets.

Vokurka and Davis classify factory types according to existing production facilities in standardizers, customizers and automators [13]. Standardizers produce high volumes with low product, material and customer diversity. Their facilities are set to standard output and markets. In contrast, customizers manufacture low volumes but in high diversity of variants for many different types of customers, which requires high process flexibility. Automators produce high volumes but with high product diversity at the same time.

Wiendahl, Reichardt and Nyhuis define six types of factories according to the perception of the market: high-tech, low-cost, variant flexible, customized, responsive, and volume flexible factory [14]. Innovative products and technologies at the highest process quality characterize the high-tech factory. Due to the high proportion of innovations delivery times, costs and variant diversity are not in focus. In the low-cost factory, mature products are produced in high lot sizes and few variants with the objective of continuous cost reduction. The variant flexible factory has the strategic objective to supply the market demand with customized products. Due to the high variety of products, the focus is on changeability and learning speed of the factory. Quality plays a subordinate role. The customized factory is an extended form of the variant flexible factory, but the focus is the manufacturing of customized products, with the aim to satisfy the customer in terms of cost, time and quality requiring a high degree of changeability. The responsive factory focuses on the dimension of time, in particular in minimizing the lead-time. By high-performance logistics, rapid availability of the products at the customer can be ensured. The volume flexible factory can serve the fluctuating demand by varying lot sizes. For this purpose, a high degree of flexibility and a low level of automation are necessary.

2.2. Quality control in global production networks

The topic of quality control in global production networks is a relatively young research field. Robinson and Malhotra note in their literature analysis that the work so far separate between intra-organizational quality management and inter-organizational coordination in production networks and state the necessity to integrate these parts [15]. Fish demonstrates in a case-based analysis the positive influences between quality management and coordination of production networks and identifies measures from product development to service. Improved lead times, flexibility and delivery reliability by reduced process variation as well as a reduction of stocks and unnecessary transport (transport of defective parts) by lower scrap rates are discussed as main positive influences [16].

Liu and Hipel present a decision model for selecting optimal quality control strategies for supply chains of complex products [17]. The approach consists of a framework model, the House of Supply Chain Quality (HSCQ), based on the concept of the Quality Function Deployment (QFD) methodology. Affected modules or components are combined with suitable but unspecified quality measures. The resulting quality control strategies are characterized using the described methodology. In the roof of the HSCQ, interdependencies between the strategies are identified. The HSCQ is converted into a multi-criterial mathematical model and extended to a hierarchical system, so that a HSCQ can be created for each actor in the production network. The approach provides a qualitative framework for the strategic planning of quality control strategies. However, it remains on an abstract level and is highly dependent on subjective assessments.

Zu and Kaynak present a conceptual framework that relates the underlying factors of production in networks with the use of quality management approaches [18]. Their findings suggest that rather than imposing one generic quality control strategy on all suppliers, companies need to choose different mechanisms for different suppliers based on the attributes of individual suppliers. The proposed solution contains an agency theory-based approach. The effects of different quality measures in relation to individual target systems and site roles in a production network are not discussed.

2.3. Simulation of production networks

According to Kaczmarek, the importance of the structurally similar depiction, that enables an actor-specific evaluation, is particularly significant for the modeling of production networks [19]. Therefore, a suitable approach to include the specifics of individual target systems is the so-called agent-based simulation [20]. In agent-based models independent agents act based on predefined rules both with each other and with their environment. A typical characteristic is an unbalanced distribution of information, so that each agent has only limited problem-solving skills, with which the agent pursues its own goals. Since multi-agent systems have no central evaluative control instance, all calculations are performed locally and asynchronously using a decentralized data storage. Therefore, agent-based simulation is particularly suitable for systems, which consist of autonomous entities, and is hence already been widely used for the operational planning of production networks [21].

Giannakis and Louis present a theoretical framework for an agent-based risk-management approach in demand-oriented networks. Information of the supplier is combined in KPI and compared with reference values to detect deviations. In such cases, consequences are calculated by means of an integrated simulation environment and appropriate measures to minimize the risk are proposed [22]. However, these measures only refer to ordering and inventory policies of the respective company. Internal and external quality control measures are not considered in the model. Long proposes an integration of agent-based distributed simulation and supply chain operations reference (SCOR) model, which allows for a modelling of a production network in different hierarchical levels and a rapid mapping of a production network into the structure model of a multi-agent system [23].

Overall, the presented approaches show, that agent-based simulation is well suited to depict the characteristics of real production networks. However, currently no approaches use agent-based simulation to evaluate benefits of different quality control measures in relation to individual target systems in a global production network.

3. Methodology

The presented methodology addresses these issues. In a first step, the developed target system concept for modeling individual site roles in global production networks is described. Secondly, a categorization and evaluation concept of quality measures is presented. Based on this, a simulation-based approach as a combination of discrete-event and multi-agent simulation is described. It allows for designing an optimal across-site quality control strategy by evaluating the benefit of different discrete combinations of quality measures according to defined performance indicators depending on the described individual target systems of different sites.

3.1. Target system model

As described, a company or an individual site pursues different production related targets. In the described approach, they are distinguished in eight target dimensions: (1) Costs, (2) Time, (3) Quality, (4) Sustainability, (5) Process knowledge, (6) Product innovations, (7) Flexibility, (8) Proximity to markets. The existing approaches in literature to differentiate site or factory roles are analyzed with regard to the differentiation of the defined target dimensions in order to derive a consistent site role model. Figure 1 shows final site role model, which differentiates four basic dimensions, based on the classifications of [11] and [13].

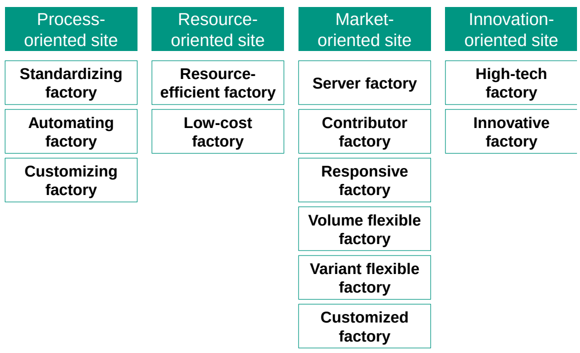

Fig. 1. Target system model

The classification of Vorkuka and Davis is consolidated in process-oriented sites. They can be characterized by a strong focus on their individual process knowledge and describe different targets regarding the dimensions costs and flexibility. Resource-oriented sites are based on the internationalization motive of gaining access to economic production factors, which include labor, material, energy and capital. One main goal is cost leadership as a stable competitive advantage, so that the importance of cost is very high in resource-oriented sites. Low-cost plants are therefore one major sub-group of resource-oriented sites and include source and offshore factories defined by Ferdows [12]. Plants focusing on any other resource than capital are subsumed under resource-efficient factories, where the target dimension of sustainability is of high importance.

As described, market-oriented sites aim at fulfilling regionally specific customer requirements. Therefore, they are characterized by a high importance of the target dimensions time, proximity to markets, quality, and product innovations. Since the strategic goal of server and contributor factories is market proximity, they belong to market-oriented sites. According to [14], in responsive factories low cycle times and a short time-to-market are of high importance, so that they can be assigned to market-oriented sites. Volume flexible factories have a flexible production of a broad range of volumes as their main goal and hence focus on the target dimension flexibility. They can be seen as market-oriented sites, because their main objective is to react on fluctuations in market demand. Variant flexible factories also focus on the target dimension flexibility and additionally on product innovations. As product variety is a particularly important goal for market-oriented sites, variant flexible factories can be assigned to this typology. Since this type of sites is also characterized by a high level of customer orientation, customized factories are also assigned here. In difference to a customizing factory in the dimension of process-oriented sites, customized factories follow the concept of mass customization of products, whereas customizing factories aim at providing highly individual processes.

For innovation-oriented sites the target dimensions quality, time, process knowledge, product innovations and proximity to markets are of high importance. Innovative technologies and the highest process quality characterize high-tech factories. Hence, this type of plant is assigned to innovation-oriented sites. An innovative factory is rather focusing on product innovations, so that this factory type must also be distinguished among innovation-oriented sites.

3.2. Categorization and evaluation concept of quality measures

In the presented approach quality control strategies are defined as consisting of an inspection strategy and the implementation of measures to improve process quality. Therefore, the categorization and evaluation concept includes these two dimensions. The quality measures are evaluated against the current situation, which is analyzed based on the methodology presented by Haefner et al. [24].

First, the structure of the production network relevant for the regarded product group has to be recorded. This includes all internal sites, external suppliers and customers involved in the value-adding process as well as the transportation processes in between. For each site all relevant production, internal transportation and quality-related processes, such as inspection, rework and scrap processes, are recorded together with their respective performance indicators. These include cycle times, setup times, availabilities, failure rates and inventory for production processes as well as time, distance and frequency for transportation processes. For quality-related processes, indicators such as inspection times and costs, rework costs as well as scrap rates are recorded. If the supplier structure for the regarded product group is too complex, e.g. due to many links between various parts or system suppliers and own factories, it could be advisable to select only those suppliers, which manufacture a particularly critical part or system for the quality of the final component. The criticality can be based on the importance for the proper functionality of the final product, but also on a high value share compared to other supplied parts.

Subsequently, quality control loops link the existing quality processes with their respective inspection characteristics to the causes of failure. This can also be done across sites or companies. An extended risk priority number (RPN_{ext}) then evaluates each quality control loop [25].

$$RPN_{ext} = S * O * D * V * R \tag{1}$$

In addition to the original RPN, defined in the Failure Mode and Effects Analysis (FMEA), the RPN_{ext} contains indicators for the increased value of the product until the discovery of the failure (V) and the replacement time (R). In accordance with the original RPN, which includes the severity of the failure (S), the probability of the occurrence of the failure (O) and the probability of detecting the failure (D), all indicators are rated from 1 to 10.

Based on this analysis, quality improvement measures can be categorized according to five fields of action and five impact dimensions, as shown in Figure 2. Depending on the evaluation of the quality control loop, an improvement measure can reduce the probability of failure occurrence, the replacement time, or the quality related costs. These measures can affect each object of the production network structure: the production process at an internal site, a supplier, a customer or the transportation relations in between. Exemplary measures are depicted in Figure 2.

Measures that increase the probability of detections or reduce the increase of value result from a change in the inspection strategy. Hence, they affect the quality control process, including the inspection process itself, scrap and rework processes. Measures regarding a change in the inspection strategy itself can be systematized as shown in Figure 3. For each inspection characteristic potential inspection points in the process, inspection devices, inspection amount and inspection location can be determined. Each possible combination has an impact on the defined target dimensions of each site. A fully automated inspection device is e.g. more expensive, usually faster, more accurate but less flexible than a manual inspection.

	Impact dimensions				
Fields of action	Production process	Control process	Supplier	Customer	Transport relation
Reduction of probability of occurrence	**Poka-Yoke measure**		**Supplier develop-ment**	**External quality contractor**	**Change of transport medium**
Increase of probability of detection	**Inspection planning**				
Reduction of increased value	**Inspection planning**				
Reduction of replacement time	**Safety stocks**		**Supplier integration**	**Safety stocks**	**Change of transport medium**
Reduction of quality related costs	**Waiver of control measure**		**Contrac-tual agreement**	**Contrac-tual agreement**	**Change of transport medium**

Fig. 2. Systematization of quality control measures

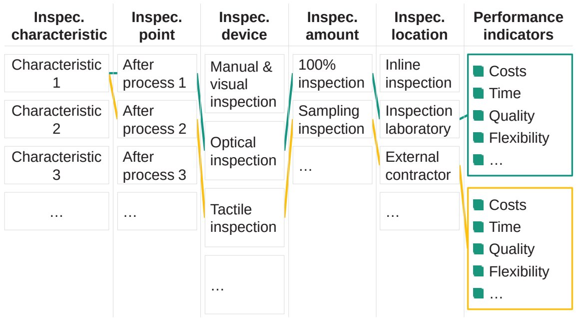

Fig. 3. Systematization of inspection strategies

3.3. Network simulation concept

Based on the presented target system and the categorization and evaluation concept of quality measures, a network simulation is developed in order to evaluate the advantageousness of quality control measures for each site or the entire production network taking into account the individual target systems. This concept is shown schematically in Figure 4. The simulation is created using AnyLogic®, as it not only supports the creation of a discrete-event simulation, but can also realize multi-agent systems, which is essential for modelling individual target systems.

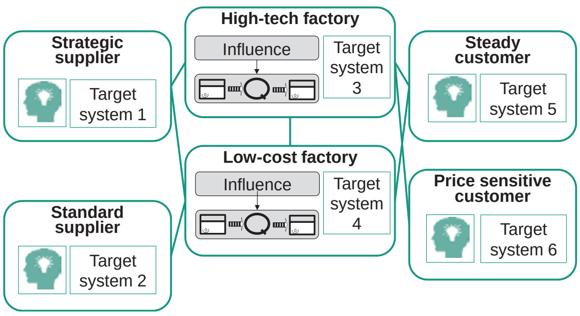

Fig. 4. Concept of network simulation

Previously analysed processes in the production network including production, quality and transportation processes are converted into a discrete-event simulation, implementing the across-site value stream including all relevant quality control loops. For designing alternative inspection strategies, quality control processes are modelled after each potential production process step, taking the restrictions coming out of the systematization presented in Figure 3 into account. This way, alternative strategies and different process configurations can be dynamically evaluated for each individual site.

In order to model the defined individual target systems of all actors in the production network (company internal sites as well as external partners), the defined target system is extended to suppliers and customers and implemented into a software-based agent structure as individual objective functions. Hence, the individual sites can evaluate the performance indicators for each quality strategy with respect to their individual targets. Thus, the influences of individual site roles on the quality control strategy in the production network can be formalized and the influence of different suppliers and customers on the overall behaviour of the network can be determined.

3.4. Evaluation of quality control strategies

In a last step, a module to systematically evaluate the benefit of potential quality measures against the necessary effort for implementation for each location as well as for the entire production network is presented. For each site, the simulation model provides performance indicators in the defined target dimensions. The number of scrapped parts, reworked parts, as well as the number of inspected parts determine the quality dimension. The dimensions costs and time can be separated in three sections: production process related, quality related and logistics related indicators. The minimum volume flexibility of the location is taken into consideration for the dimension flexibility. The market proximity is determined by evaluating the distance from the site to the location of the next customer. Process knowledge is evaluated using the Overall Equipment Effectiveness (OEE), while sustainability is depending on the level of waste per unit. Finally, the dimension of product innovations is assessed by the amount of new products per time period. From these indicators, the simulation model calculates the benefit of a quality measure in the single dimensions, which are of individual importance to a specific site according to its role. Figure 5 shows a potential visualization of the implementation of a quality control measure for different sites and the network in the exemplary target dimensions quality, time, costs and sustainability.

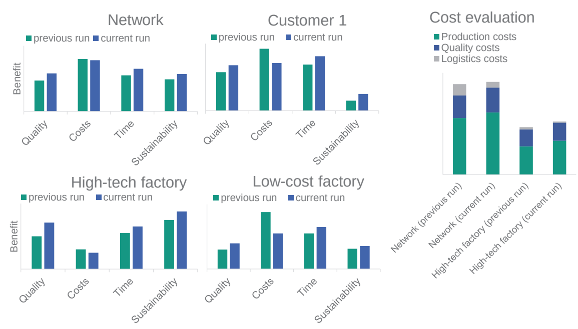

Fig. 5. Evaluation of quality control strategies

In order to test the functionality of the simulation model, a simple case study is executed for an exemplary production network. A quality control measure is implemented at the high-tech factory (see Figure 4), where a production process could be improved. Hence, at the high-tech factory an improvement of the quality level can be observed due to the reduction of occurrence probability, while through the more expensive production process, the benefit in the cost dimension decreases. Since the enhanced process results in a reduction of time and waste per unit, both time and sustainability level increase.

Evaluating the effects on the low-cost factory, the evaluation module shows that the increase in costs has a higher impact compared to the high-tech factory, while the improvement of the quality and sustainability level is not as significant. The reduction of time results in the same benefit at both sites. Evaluating the performance of the entire production network and the benefit for the customer, the same trends as at the single sites can be seen. Since the customer is not that sensitive regarding sustainability, its benefit from conducting the quality control measure is very low in this dimension, the increase in costs even leads to a significant benefit decrease. Besides the performances in the different target dimensions, the overall costs of each single site and the entire network are evaluated. Divided in production, quality and logistic costs, the proportion before and after conducting a measure is visualized. Thus, the advantageousness of conducting the measure can be evaluated.

4. Conclusion and research outlook

The presented paper underlines the importance of production in globally distributed networks, in which each site acts autonomously according to its individual target system influenced by specific location factors or its defined site role. Especially ensuring a high production quality along the distributed value-adding process implicates special challenges in this context. In current literature, there are no methods for multi-criteria evaluation of quality control strategies in production networks with respect to individual target systems.

The described concept enables globally operating companies to systematically design an optimal across-site quality control strategy by evaluating different quality measures depending on individual target systems. First, a target system model is derived from literature, which differentiates site roles according to eight target dimensions. Second, a categorization and evaluation concept of quality measures is presented. This concept is integrated with the target system model into a network simulation as a combination of discrete-event and multi-agent simulation. This multi-method simulation allows for a dynamic evaluation of different discrete combinations of improvement measures regarding the inspection strategy as well as process quality. An assessment module, whereby the benefit of each improvement measure can be evaluated with regard to the individual target system, extends the network simulation.

Further research includes evaluating the concept in a real case study. Sensitivity analysis with regard to internal influencing factors, such as demand behavior of a customer or insolvency of a supplier, as well as external factors such as currency fluctuations have to be conducted. Furthermore, the network simulation could be enhanced by an optimization module, which could either allow for a direct definition of the optimal strategy or an evaluation of the simulation results using statistical tools.

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