Journal of Advanced Management Science, Vol. 1, No. 1, March 2013

A Complexity-Oriented Approach to Global Production Network Design

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***Abstract*—The structure of production networks has become more and more complex due to the growth of companies by acquisitions and set ups of production plants to enter new markets. In this paper, we present an approach to design production networks with a minimum level of structural complexity in order to keep up the operability of such networks. The approach consists of three basic elements, all embedded into an optimization algorithm: the capture of structural complexity via characteristic parameters, the determination of causal relations between those parameters and the development of a complexity indicator. Using a data set of a recently conducted industry project, we show that our method is beneficial for the optimization of production networks.**

***Index Terms*—complexity measurement, complexity oriented design, optimization algorithm, production networks.**

I. INTRODUCTION

The economic development of emerging markets in the past years has led to fundamental changes in worldwide production processes. Along with the higher level of labor distribution network structures arose, especially due to new production facilities in Eastern Europe and Asia, that should help to lower production costs. A potential decrease of production costs by embedding new production sites in existing networks can only be lifted if the design of production networks is seen as a constant strategic task where all structures are permanently challenged and optimized [1] and [2].

The enlargement and diversification of production networks can promote the reduction of production costs but also leads to an increased complexity of the production network. By looking at the structure of a growing network, it becomes obvious that mainly the number of possible configuration options increases. This type of complexity that includes the number of elements (e.g. locations, departments, employees) and relations (e.g. interfaces) is called structural complexity. The consideration of structural complexity in the design process of networks using conventional management and design approaches faces difficulties due to incomplete information und missing comprehension of processes within the network [3] and [4].

II. REQUIREMENTS

Three central requirements create the focal point of this article that aims at a complexity-oriented design of global networks. First of all, it is necessary to develop an indicator for the detection of structural complexity in global production networks. This indicator has to be based on parameters that characterize the network configuration unambiguously. Using this indicator, comparisons between different network scenarios can be made in order to find those with the smallest level of complexity. These comparisons build the basis for the optimizations process.

Furthermore, causal correlations between these characteristic parameters have to be analyzed and quantified to consider nonlinear increases of structural complexity while the network is growing. These causal correlations help to improve the significance of the design approach.

Finally, a procedure has to be found that allows finding complexity-oriented configurations of production networks. It should unify the results of the first two requirements and deliver resilient network configurations in order to determine which configuration has the minimal level of structural complexity.

Based on the three requirements, the following research question can be formulated: How can an approach be designed which detects the structural complexity of global production networks and optimizes production networks towards a minimal level of complexity?

III. STATE OF THE ART

The aim of this paper is to define a new way of handling complexity in the design process of global production networks. Two core elements constitute this complexity-oriented design method: the way the complexity of a production network is measured and the design procedure itself. An analysis of existing research results shows the state of the art in measurement techniques and design approaches.

A. Approaches for Complexity Measurement

In daily life, the term “complexity“is used for things that appear difficult, nontransparent and incomprehensible [5]. The two main characteristics of complex systems are a wide range of behavioral patterns and a high degree of uncertainty which can exist combined or separately [6].

Manuscript received September 15, 2012; revised December 28, 2012.

doi: 10.12720/joams.1.1.29-34

There are two different levels of complexity that have to be distinguished: structural and functional complexity [7]. Structural complexity is related to the amount of elements and relations as well as different kind of states. Its measure is the variety, the amount of distinguishable states of the system [5]. Functional complexity describes how a system handles complexity by situation-based variations. The goal is to find ways to handle the complexity of the environment. Functional complexity rises from the gap between problem solving requirements and problem solving potentials due to cognitive and capacitive barriers or resentments [7] and [8].

This paper focusses on the network configuration defined by the number of elements and relations of a production networks. Therefore, the measures presented in this article capture the structural complexity.

According to Klaus, complexity can be described as the type and amount of relations between elements called connectivity. Differentiated from that, the variety of elements is called complicacy. This distinction means that complicacy always causes complexity whereas complexity can also exist with a low level of complicacy (equal elements in a system) [9].

Kornwachs and Lucadou use densities as tools to measure complexity. One defined measure is the connection density, the other the structural density. The connection density is defined as the ratio of the current relations of a system and the maximum number of relations of a system of one kind. The structural density results from adding up all the connection densities for the different kinds of connections and dividing it by the total number of different kinds. If all possible relations are realized, the structural density will be 1. If no relation is realized, the structural density will be 0 [10].

The term “entropy“describes the content of information and the degree of chaos in state spaces or event spaces. The measure is based on the concept that the order of a system is higher if certain states occur with higher probabilities than others. Shannon finds that the entropy of a system depends on the number of events and the distribution of its probabilities. If all probabilities except for one with the value “1“have the value zero, entropy will be zero. If all events have the same probability, the maximum entropy depends on the total number of events [11] and [12].

Existing measures for complexity deliver a good starting point, but do not cover yet different aspects of the specific complexity of production networks. For the purpose of this paper, we will therefore develop our own complexity indicator based on the ideas of Klaus as well as Kornwachs and Lucadou.

B. *Approaches for the Design of Global Production Networks*

Several approaches for designing global production networks have been developed in the past decades. This paper focusses on relevant work in the recent years.

The method of Merchiers supports the evaluation procedure for the design and selection of different network structure alternatives. The approach of Merchiers targets the maximization of the company’s cash flow. The fundament of the evaluation is the cost structure of a production network. According to Merchiers, savings result from reductions of the degree of value-add while keeping up the network structure (outsourcing) and from changes of the network structure itself. The evaluation procedure is divided into three levels (module level, site level and network level) and for each level a specific cost structure is defined. It is embedded into a testing sequence in which the financial feasibility, the allocation of production sites and different network structure alternatives are tested [13].

Ude develops an approach for the evaluation of globally distributed value networks that is used as a support tool for decision-making. Due to a multi-dimensional target system, it can be used to design the system regarding several targets. The procedure contains multiple steps: the qualitative support tool for desicion-making is based on a simulation model for quantitative evaluations. The simulation model is generated by adding predefined network modules and evaluating them according to quantitative measures. The multi-dimensional support tool for decision-making is based on qualitative evaluation criteria. Combining both steps, a ranking of network configurations can be found that can be tested for robustness using sensitivity or scenario analysis [14].

Within the project POWer.net, Lanza et al. develop a software-based planning und optimization method for versatile value networks. A special focus is put on an interdisciplinary approach combining production, logistics and organization. The project defines three focal points: the determination of the need for transformation, the evaluation of transformation enablers and the concept for a continuous monitoring of networks. The need for transformation is determined by so called transformation drivers that cause changes of the network structure. With these transformation drivers, derivations above the limits given by target values of the network can be detected. The second focal point refers to adaption actions of the network configuration in terms of production capacities, logistic relations or the structure of the organization. These actions are subsumed in the term transformation enablers. After necessary changes in the network configuration are done, transformation drivers have to be monitored permanently to detect the need for adaptions in the future. All three focal points are embedded into a control loop for versatile value networks [15].

Many approaches for the design of production networks focus on monetary targets such as costs or revenues, as presented in Merchiers’ approach. Others like Ude broaden the view on production networks by the use of multi-dimensional target systems and a way to compare different scenario alternatives. The permanent need for adaption is described by Lanza et al. who implement a routine to periodically check for necessary structural changes of production networks. Even though Ude and Lanza et al. address the complexity of production networks in their approaches, they do not implement a way to handle it in the design process. Using techniques of the above mentioned approaches, this paper shows a way for designing production networks under the premise of multiple network parameters and by comparing network scenarios in an iterative process in order to find the scenarios of the lowest structural complexity.

IV. COMPLEXITY-ORIENTED DESIGN APPROACH

The presented method follows the structure given by the three central requirements mentioned above: define characteristic parameters, develop a complexity indicator and analyse causal correlations. In the end, all these requirements are embedded into an optimization procedure for production networks.

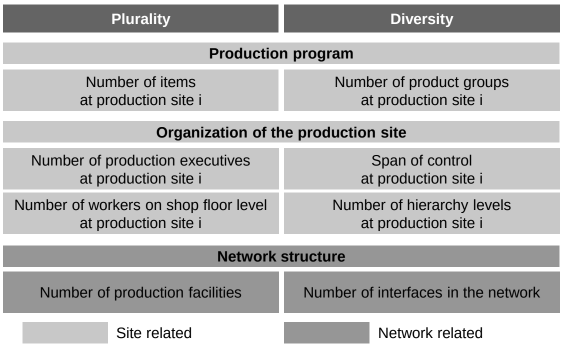
A. Characteristic Parameters

To determine the structural complexity, the plurality and the diversity of complex systems like production networks have to be determined. In those networks, plurality and diversity occur on different levels.

The first level is the production process itself realizing the production program distributed over all sites of the network. The characteristic parameters of the production process in terms of the production program are the number of items (plurality) and the number of product groups (diversity) for each site.

On the second level, the production sites and its organization need to be looked at. Here, plurality arises from the number of employees (number of executives and number of workers on shop floor level) and diversity from the structure of the facility (number of hierarchical levels, span of control).

The third level consists of the network structure itself. It is characterized by the number of production sites (plurality) and the number of interfaces between them (diversity).



Plurality	Diversity
Production program	
Number of items at production site i	Number of product groups at production site i
Organization of the production site	
Number of production executives at production site i	Span of control at production site i
Number of workers on shop floor level at production site i	Number of hierarchy levels at production site i
Network structure	
Number of production facilities	Number of interfaces in the network

▨ Site related

▨ Network related

Figure 1. Characteristic parameters and their levels of appearance

These characteristic parameters are regarded as key factors to indicate the structural complexity of the production network. Fig. 1 presents all characteristic parameters and how they are related to the different levels in a production network.

B. Framework of the Complexity Indicator

The framework for the complexity indicator is created according to the levels of a production network and the two dimensions of structural complexity (plurality and diversity). To integrate all complexity parameters into one indicator, site-specific parameters have to be summed up to network-wide parameters. Furthermore, the distinction between plurality and diversity related parameters leads to two partial indicators that are merged to one complexity indicator for the whole network.

The parameters for span of control and hierarchical levels are set as a constant because it is assumed that no significant differences between different sites of a production network occur. Nevertheless, these two parameters are regarded in the framework for the complexity indicator because structural complexity caused by the number of hierarchical levels and the span of control is expected to rise with an increasing number of sites.

C. Analysis of Causal Associations

Before causal correlations between parameters can be quantified, a qualitative description has to be done to determine whether there exist interdependencies between two parameters or not and in which way the parameters are affected. This preliminary step was done using a causal loop description and is shown in Fig. 2. Assuming an external global production program that has an effect on the local number of items and product groups as well as on the total number production sites, five causal correlations between the characteristic parameters were observed. These correlations were quantified analytically, statistically and by a concept of limited capacity for information processing.

The concept of limited capacity for information processing is the result of an analysis of various research projects following the idea of finding a description which allows an evaluation of the distribution of information processing capacities of executives. It can be shown by psychological analysis working on two parallel tasks increases that the processing time of the task one started to work on later is increased significantly. As a result, the total processing time of parallel work lies above the sum of the separate processing times of the two tasks. It can be assumed that there is a limited capacity of information processing that should be obeyed for the executive to work efficiently [16].

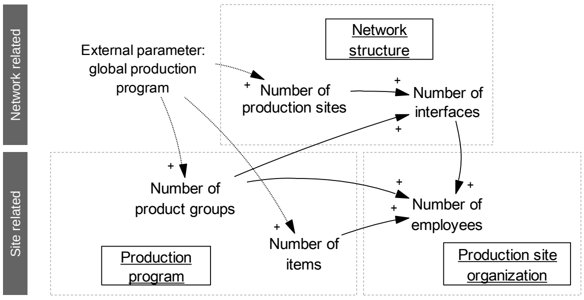


Figure 2. Causal correlations of the characteristic parameters

The next question to answer is what these limits are. Gonzalez and Mark find in their study about the influence of information technologies on the behavior of information processing persons that each executive can work with a maximum of 13 working fields where each field consumes about 35 minutes a day. A working field is defined as a collection of actions that aim towards the same target, having a specific amount of people und resources involved that work within a set time window [17]. According to the parameters of the network design we found, we focus on executives of the production process. These executives have to split their information processing capacity into the three categories we used to distinguish the different levels of a production network: the production process itself, the organization of the production sites and the network structure. The parameters affected by this distribution of the executive's capacity are set to be the span of control of the executive, the number of product groups the executive is responsible for and the number of interfaces the executive has to manage. For our purposes, we assume a standard span of control for the organization of a production site and the company itself because small differences between departments and companies often occur and are hard to measure. We follow the findings of Urwick who set the maximum span of control of an executive to five [18]. According to Hamacher, executives spend about 40 percent of their working time for personnel management. Therefore, we can assume that five working fields are necessary to fulfill the task of leading five persons (according to the span of control) [19]. This leaves eight free working fields that can be distributed on production and interface management. Finally, the concept of limited capacity, illustrated in Fig. 3, delivers the link between the number of product groups, the number of interfaces and the span of control (which is set to constant). From a global perspective towards the production network, one can, in a next step, also distribute the necessary number of executives to the production sites using this concept. The only extension necessary is to sum up the demanded capacity at each production site and the available capacity as the total number of production executives.

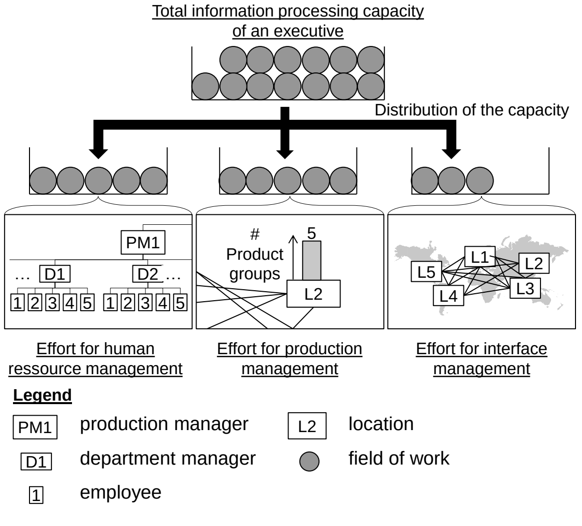


Figure 3. Concept of limited capacity for information processing

Besides the concept of limited capacity, further correlations can be quantified statistically and analytically. Using data from several automotive OEM's, a linear positive correlation of the number of product groups and the number of production executives can be found which supports the conclusion from the concept of limited capacity. Furthermore, this data also shows a declining correlation between the number of items produced and the number of workers on shop floor level. This finding is in accordance with the predictions of many production theories such as the Cobb-Douglas production function [20].

The correlations involving the number of interfaces have been examined analytically. In a production network, the different production sites have to communicate about the products that are produced in each facility. That means that for every product group in each production site, this production site has to communicate with every other site about the specific product group. The outcome is a linear correlation between the number of product groups and the number of interfaces.

A different kind of correlation can be found between the number of production sites and the number of interfaces. Assuming that every production site has to communicate with all sites in the network, this dependency can be quantified with an arithmetic series, a Gaussian totals formula. It results into a disproportional description of the correlation.

An increased number of interfaces also leads to a higher demand in information processing at each production site for which reason the number of production executives has to be increased linearly. Since the number of interfaces refers to the whole network, an average value for the number of interfaces per sites has to be created in order to describe the effect on the number of executives.

D. Procedure for an Iterative Optimization

The preliminary steps that have been taken so far have to be embedded into a method for the complexity-oriented optimization of production networks. Therefore, an iterative process has to be introduced that allows the determination of those optimal network configurations.

The starting point for such an algorithm can be the current network configuration or any other. For this first configuration, all parameters have to be measured and the complexity indicator is calculated. Then, selective changes of the configuration have to be done that aim at reducing the amount of complexity in the production network. All changes will have a direct and an indirect effect on the overall complexity of the network. The direct effect is represented by the changes of the parameters itself, the indirect effects are caused by the correlations and can be determined using the quantified dependencies between the different parameters. To detect the influence of all indirect effects, a specific order of calculation has to be obeyed. First of all, the effects between the number of product groups, respectively the number of production sites and the number of interfaces have to be considered because these also have an influence on the number of executives. In the next step, the correlation between the number of product groups, respectively the number of interfaces and the number of executives can come into focus. The relation between the number of items and the number of workers on shop floor level is not affected by any order of calculations. For the new configuration in which all effects have been considered, the corresponding complexity indicator is determined. If the complexity indicator of the new configuration is lower than the one of the current (or any other) configuration, the new configuration is picked as the new basis. In case the complexity indicator of the new configuration is the same or higher than before, the new configuration is rejected. In any case, further iterative steps have to be done to improve the configuration gradually. If, after a defined number of iterative steps, no further improvements can be observed, it is assumed that a complexity-oriented configuration is found. The complete optimization algorithm is shown in Fig. 4. This configuration represents a complexity optimal design for the current network under given boundary conditions, but cannot be seen as a universal complexity optimum for production networks.

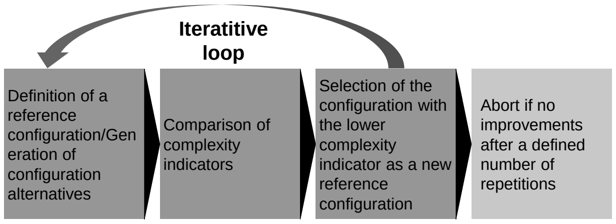


Figure 4. Iterative steps of the optimization algorithm

V. EVALUATION

To test the developed method, we used information from a recently conducted industry project. The collected data could be used to extract two different scenarios and test central aspects of the method for a complexity-oriented design.

A. *Presentation of the Scenarios*

The first scenario represents the already existing configuration of the production network in terms of its product groups, number of items and number of employees. It has been optimized with a software tool to reduce the production costs of the network. The result of this optimization constitutes the second scenario. This scenario has a new structure (new production sites) and represents the overall cost optimized configuration of the network as it has been calculated by the mentioned software tool.

B. *Results of the Evaluation*

The data that was available for the first evaluation of the method is imperfect in a few ways. One core element of the method, the causal correlations, cannot be tested with this data because the two data points technically do not fulfill the requirements. The two scenarios are fundamentally different in terms of their external design parameters such as the global number of production sites or the level of process distribution and distribution of product types. Therefore, the causal correlations found that have also been derived from historically grown networks are not applicable. Nevertheless, the second core element, the complexity indicator can be tested with this data. The second scenario with an increased number of production sites as well as a higher level of labor distribution as well as a higher number of employees results in a higher level of structural complexity. This assumption can be confirmed with the complexity indicator as the value for the second scenario is about 40 % higher than for the first scenario. Further validation currently being conducted requires more information and data points of historically grown networks.

VI. CONCLUSION

From industry partners, we learn that the reduction of complexity becomes a main goal of companies. The presented method for a complexity-oriented design delivers another dimension for the optimization of global production networks besides cost and time driven approaches. In the future, we will enhance this method by further analysis of possible correlations and improvements of the optimization algorithm.

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