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Robustness- and complexity-oriented characterization of supply networks' structures

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Abstract

In the past period the efficiency aspects of production were emphasized, sometimes even overemphasized. As a result, the vulnerability of production structures was put in the background, and consequently, by now, it is usually beyond its acceptable degree. The frequently changing and uncertain environment which manufacturing companies are facing in our days requires robustness on every level of the production hierarchy from the process / machine level, through the system and enterprise levels, up to the level of supply chains and networks. As to the supply networks, the question may arise, what level of complexity is required for achieving a certain degree of robustness while, naturally, keeping the efficiency aspects in mind as well. In order to be able to give appropriate answers to this question, it is indispensable to quantify the robustness and complexity of supply chains and networks. Structural (static) and operational (dynamic) robustness and complexity are distinguished in the paper, which focuses on the structural aspects. A complex network approach is used for this purpose, namely the structural – both robustness and complexity – nature of the networks is described by applying graph theoretical concepts. Appropriate, quantitative graph measures are introduced and their applicability for characterizing the robustness and complexity of supply chains and networks is investigated by using structures of three types, namely real and artificially generated ones, and structures taken from the literature. Finally, it is illustrated how a decision support system based on the approach described in the paper can contribute to the design and redesign of supply chains and networks striving for an appropriate balance between the robustness, complexity and efficiency aspects of the problem.

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1. Introduction

Efficiently managed supply chains represent one of the most important prerequisites for the success of today's manufacturing enterprises, sometimes even for their survival in the frequently changing and uncertain environment.

Striving for cost efficiency, companies streamlined their operations, by outsourcing auxiliary activities, introducing just-in-time, just-in-sequence and lean management concepts. The enterprises usually work with low level safety stocks, and as a consequence, they may be vulnerable to the turbulences occurring in their supply chains.

In order to be able to keep or to increase their appropriate market share, companies are forced to change their product portfolios more frequently, or even to comply with the individual requirements of the customers. The growing number of product variants – parallel with the low stock levels – makes their dependence on their suppliers even stronger. To make the situation more complicated, most of the enterprises simultaneously participate in a number of supply chains, and as a result, supply networks emerge.

More and more frequently, supply chains spread over continents which fact itself makes their proper functioning more vulnerable. Let us only refer to the related consequences of the volcano eruption in Iceland, 2010, or the earthquake in March 2011 and the following tsunami in Japan, or other natural catastrophes, such as floods, not mentioning some political uncertainties.

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All of the above tendencies highlight the importance of the robust functioning of supply chains and networks. A logical assumption is that the robustness of the supply chains can be increased by including, e.g. more suppliers, transport lines, distribution centers; in one word, by increasing their complexity. These steps, however, usually include some extra costs. Therefore, a key question is how to balance between robustness, complexity and efficiency aspects in the design and management of supply chains and networks.

2. Robustness and complexity of supply chains and networks

In the literature various definitions are given for the *robustness* of supply chains, moreover, some related concepts (resilience, responsiveness) are also in use [1]. In the paper the more comprehensive formulation introduced in [2] will be applied: "In the general sense, a supply chain is robust if it is able to comply with the most important key performance indicators (KPI) set towards it, at an acceptable level (i.e. remaining in a predefined robustness zone) during and after unexpected event(s) / disruption(s) which caused disturbances in one or more production or logistics processes". Fig. 1 (a further developed version of the figure in [3]) illustrates this concept, also pointing to the possible outcome when the new stable state goes on with an even higher KPI.

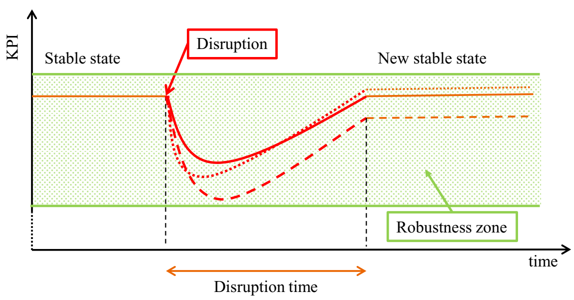

Fig. 1. Delineation of supply chains' robustness used in the paper.

In the paper the concept *vulnerability* [3] is considered as a kind of feature opposite to the robustness, i.e. the more vulnerable a supply chain, the less robust it is.

In the past years, handling *complexity* gained significant attention also in the production related literature [4,5]. Serdarasan distinguishes necessary and unnecessary complexities of supply chains on the one hand, and current and potential complexities, on the other [6]. By necessary complexity we mean the complexity level that the customer / market is willing to pay for and what would provide a significant competitive advantage. Unnecessary complexity brings no or not enough benefits for the company / supply chain, which would compensate for the additional costs. Fig. 2 summarizes the main approaches to dealing with supply chains' complexity.

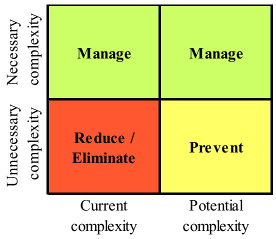

Fig. 2. Approaches to dealing with supply chains' complexity [6].

In the context of supply chains, both in the fields of robustness and complexity, we can speak of *structural* (*static*) and *operational* (*dynamic*) types. In course of structural investigations, the size of the network, its elements and the linkages between them are put in the focus, while operational investigations deal with the dynamic processes occurring in the supply chains, assuming unchanged structures [7,8,9].

Theoretically, the robustness of a supply chain can be influenced by changing its structural or operational properties. Remaining at the structure, generally, it is expected that the increase / decrease of the structural complexity – in tendency – should go hand in hand with the similar changes in the structural robustness. The challenge is to achieve the required level of robustness with the lowest possible level of complexity. The objectivity of the process for evaluating the different scenarios can be significantly enhanced by using quantitative measures of the structural robustness and complexity.

In contrast to most of the papers dealing with the structural properties of supply chains and networks, either from robustness or complexity point of view, here an attempt is made to characterize supply chains and networks from both the aspects of complexity and robustness.

3. Graph theory based measures for describing the structure of supply chains and networks

It is straightforward to use graph theoretical concepts for characterizing the structural properties of supply chains and networks. Elements (e.g. factories, warehouses, points of delivery) of the chains / networks can be represented by the vertices / nodes of the graph, while the connection of two elements (e.g. a supplier-buyer relationship) by its edges. For describing the relationships in the given field, directed graphs are more adequate than undirected ones.

3.1. Fundamental complexity measures of graphs

The most natural complexity measures are the *order of the graph* (the number of the vertices / nodes, n) and the *size of the graph* (the number of the edges, m). The number of edges incident to vertex v is the *degree of the vertex, deg(v)*.

Perhaps, the measure based on Shannon's information theory [10], which considers the similarity between the vertex degrees in a graph, is one of the most frequently used measures of the graphs' complexity [11,8]. The *entropy of a graph* derived accordingly is as follows: