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Robustness-oriented analysis, (re)design and management of supply chains

PhD Thesis Booklet

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1. Introduction and objectives

Efficiently managed supply chains represent one of the most important prerequisites for the success of today’s manufacturing enterprises, sometimes even for their survival.

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 therefore, they are vulnerable to the turbulences occurring in their supply chains.

To be able to keep or to increase their 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 several supply chains, and as a result, supply networks emerge.

More and more supply chains spread over continents which fact itself makes their proper functioning more vulnerable. Just think of 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.

All the above tendencies highlight the importance of the robust functioning of supply chains and networks.

Until recently the efficiency aspects of production were put into the foreground, as to be considered and strived for, sometimes even exclusively. The vulnerability of production structures received much less attention, and consequently, by now, it is usually beyond its acceptable degree. The frequently changing and uncertain environment which manufacturing companies are facing nowadays, requires robustness at every level of the production hierarchy, including the level of supply chains and networks. The COVID-19 pandemic gave fresh momentum to the research activities related to supply chains’ robustness. The present war in Ukraine further emphasized the importance of the topic. In the cyber-physical era, the complexity of supply chains may increase in parallel with the opportunity to realize more robust systems (Monostori 2018). However, the question arises, what level of complexity is required to achieve a certain degree of robustness while, naturally, keeping the efficiency aspects in mind as well (Monostori 2016b). In other words, how to balance the aspects of robustness, complexity and efficiency.

These questions represent scientific challenges, and their answering may be of significant interest to the production industry. Beyond the importance of the topic, the result of an extensive literature survey gave additional motivations for the research:

- Most of the related papers deal either with the robustness or the complexity of supply chains, and only relatively few publications can be found which jointly assess them. In this regard, the intentions were to contribute to this line of research addressing a more comprehensive treatment of supply chains, moreover, to consider the aspects of robustness, complexity and efficiency together.
- The investigations rarely focus on the structural and the operational robustness and / or complexity at the same time. In this respect, the plans were to make a clear distinction between the two kinds and to exploit their complementary natures in improving the performance of supply chains.
- In many cases, the characterization of supply chains' robustness and complexity relies on qualitative or relatively simple quantitative measures. Regarding this point, the introduction and use of quantitative measures for describing structural and operational properties of supply chains in respect of both robustness and complexity were intended.

The main objectives of the research were to explore the complicated interrelationships of supply chains' robustness, complexity and efficiency, to underline the importance of striving for an appropriate balance between them, and to show that the search for balanced solutions is not a hopeless undertaking.

The worldwide economic growth and the expanding needs of the increasing population in the past decades have resulted in a vast consumption of goods. Global production networks have emerged, with large streams of raw materials, components and products all over the world. In parallel with these developments, growing concern can be observed about the sustainability, from economic, environmental and social aspects alike.

Environmental sustainability is considered as one of the most important recent challenges humanity faces. Companies' commitment to take the environmental consequences of their functioning seriously into account has become essential, which statement is valid for whole supply chains as well.

An additional significant objective of the research was to investigate how to achieve trade-offs between the economic (e.g. profit) and the environmental (e.g. CO_2 emission) aspects of supply chains' sustainability.

2. Preliminaries

2.1. Robustness and complexity of supply chains

In the literature, especially in the past years, growing number of papers have been published dealing with robustness and / or complexity of supply chains.

The robustness of supply chains is assessed and the supply chain vulnerability index (SCVI) based on graph theoretical considerations is introduced in Wagner and Neshat (2010). The randomized local rewiring (RLR) approach is presented in Zhao, Kumar, and Yen (2011) for robustness evaluation of original and modified (rewired) distribution networks. It is pointed out that the robustness of the investigated distribution networks can be significantly affected by appropriate changes in their topologies. The graph theoretical approaches are characteristic in numerous other publications as well, e.g. in Gutiérrez-Pérez et al. (2013); Bates, Angeon, and Ainouche (2014); Nakatani et al. (2018); Tan, Zhang, and Cai (2019).

A significant portion of the papers focusing on complexity of supply chains propose information theoretical considerations, i.e. to associate supply chains' complexity with the expected amount of information needed to describe their states. Entropy-related assessment of complexity is the frequent method in this line, see e.g. Sivadasan et al. (2006); Huaccho Huatuco et al. (2009); Isik (2010); ElMaraghy et al. (2012); Cheng, Chen, and Chen (2014).

A promising approach is to consider supply chains as complex adaptive systems (CASs). The underlying assumption of CASs, a paradigm for analyzing the structure and dynamics of large systems, is that the adaptability of systems creates, but at the same time, also resolves complexity. A CAS is, in fact, a multi-agent system in which "a major part of the environment of any given adaptive agent consists of other adaptive agents, so that a portion of any agent's efforts at adaptation is spent adapting to other adaptive agents" (Holland 1995). Supply networks are recognized as CASs, because they are emerging, dynamic, self-organizing and evolving (Choi, Dooley, and Rungtusanatham 2001; Surana et al. 2005; Pathak et al. 2007). For managing systems of this type, appropriate balances between control and emergence (Choi, Dooley, and Rungtusanatham 2001), on the one hand, and between simulation and theory (Surana et al. 2005), on the other, are to be strived for.

Network science is also of high relevance when addressing complexity of supply chains and networks (Cui, Kumara, and Albert 2010; Kito and Ueda 2014). Topological classes of assembly supply chains are introduced in Modrak and Marton (2012).

Relatively few papers can be found which jointly assess supply chains' robustness and complexity, as it is indicated in Olivares Aguila and ElMaraghy (2018).

Three supply chain design characteristics, namely density, complexity and node criticality, are identified in Craighead et al. (2007). Density relates to the geographical positioning of nodes within the supply chain, which can be measured, e.g. by the average distance between them. Complexity is considered as the sum of the number of nodes and the number of connections in the supply chain. Node criticality is the importance of a node, which is context-specific and relative to the significance of other ones within the supply chain. In the referred paper, qualitative propositions are formulated, concerning the influence of the above design characteristics on the severity of supply chain disruptions.

In Ivanov and Sokolov (2013) the examination of complexity in light of robustness, adaptability (flexibility) and economic performance is identified as an important future direction. In Cardoso et al. (2015) a multi-product, multi-period mixed integer linear programming (MILP) model is used for analyzing the effects of various disruptions on eleven indicators in five supply chains with different complexities. In an empirical study (Bode and Wagner 2015), relationship between the supply chains' structural complexity and the frequency of supply-side disruptions is found.

2.2. Environmental sustainability of supply chains

Modeling approaches for sustainable supply chain management are reviewed in Seuring (2013). The following main modeling categories are identified and analyzed: 1) life-cycle assessment based models, 2) equilibrium models, 3) multi-criteria decision making, and 4) the analytical hierarchy process. It is underlined that the environmental aspects dominate the social ones, and the cost minimization is the most frequently considered element of the economic dimension.

A mixed integer programming mathematical model for determining the locations of distribution centers (DCs) in green supply chains is given in Li et al. (2008). The impacts of the crude oil price on the transportation mode options and on the DC locations are also investigated.

In Xu, Pan, and Ballot (2012), cooperative game theory is used for allocation of transportation cost and CO_2 emission in pooled supply chains given by the horizontal cooperation among several independent supply chains in a retail logistics network in France. A reduction of 25.98% in the transportation cost (including the carbon tax) is reported on.

The combination of a genetic algorithm and a convex optimization method is proposed for joint optimization of logistics infrastructure investments and subsidies in a regional logistics network in China, with CO_2 emission reduction targets (Zhang et al. 2018).

3. Summary of the research work and presentation of the theses

I conducted the research in four successive phases. Each phase was started with a comprehensive literature survey to identify some open questions and to set the aims of my related activities.

I developed models and solutions, the applicability of which was demonstrated by using three types of data, i.e. real (industrial) and artificially generated ones, and data taken from the literature. The arsenal of the employed methods included graph theoretical analysis, optimization techniques and supply chain simulation.

I put emphasis on publishing the results of each phase also in peer-reviewed, international journals.

In this section, the research work accomplished is summarized according to the phases, and four related theses are presented.

3.1. Structural robustness and complexity of supply chains

Numerous definitions of supply chains’ robustness can be found in the literature, not to mention such related concepts as resilience, agility, responsiveness, flexibility and changeability. Differences and contradictions between the definitions given even for the same term (robustness is no exception), and overlaps between the various ones exist.

For the above reasons, I formulated the following comprehensive definition of supply chains’ robustness: “In the general sense, a supply chain is robust if it is able to comply with the most important key performance indicators (KPIs) 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” (Monostori 2016b).

Figure 1 illustrates this concept, also indicating the possible outcome when the new stable state resumes with an even higher KPI.

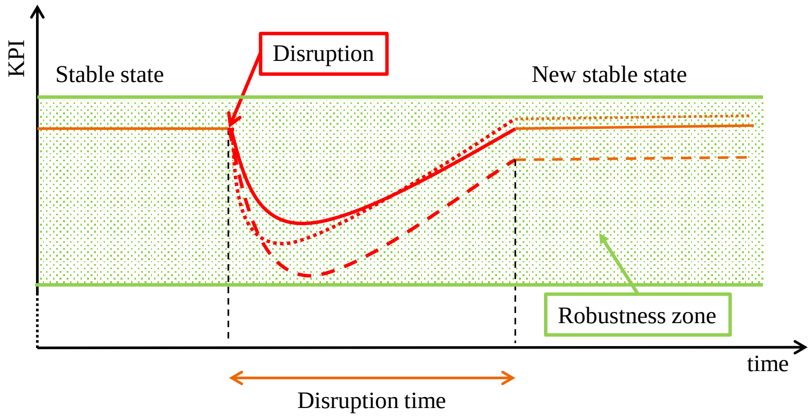

Figure 1. Supply chains' robustness in the general sense (Monostori 2016b).

Naturally, not only one KPI can be influenced by a given disruption, moreover, the time that is required to reach an acceptable new stable state (disruption or recovery time) can depend on which KPI is taken into account.

The application of graph theory is reasonable to characterize the structural properties of supply chains and networks. The elements (e.g. customers, DCs, factories, suppliers) of a chain / network can be modeled by the vertices (nodes) of a graph, while the connections between the elements (e.g. supplier-buyer relationships) by its edges. In this specific field, directed graphs are preferred to undirected ones.

I explored and introduced graph theoretical measures for the characterization of the structural complexity and robustness of supply chains and networks, e.g. the number of the nodes, the number of the edges, the average degree of the nodes and the entropy of the graph, as complexity measures, and the maximum of the normalized betweenness centrality and the factor R, as robustness measures.

The appropriateness of the measures for this purpose was shown on structures of two types, which I analyzed from both complexity and robustness points of view:

- A supply network consisting of OEM enterprises and their first-tier suppliers producing a given part (based on a real industrial case from Japan),
- Multi-tier supply chains (taken from the literature).

The practical applicability of the quantitative approach for analyzing supply chains both in their design and functional phases is straightforward. The values of the robustness and complexity measures can be determined, graphically represented and compared for different scenarios of the considered supply chain. The approach can be an important part of managerial decision support systems for (re)designing supply chains.

Thesis 1: I formulated a comprehensive definition of supply chains' robustness. I explored and introduced graph theoretical measures for the characterization of the structural complexity and robustness of supply chains and networks, moreover, I jointly analyzed the structural complexity and robustness of supply chains and networks. I concluded that – as is to be expected – the increase of the structural complexity – in tendency – increases the structural robustness, however, appropriate caution is needed when steps of strengthening the complexity with the aim of enhancing the robustness are taken, because otherwise it may happen that only the unnecessary complexity increases. A realistic target can be to attain the desired level of robustness with a still acceptable degree of complexity.

The results summarized in Thesis 1 are based mainly on Sections 2 and 3 of the dissertation. The most important related publications are as follows: Monostori (2016b); Monostori (2018).

3.2. Structural and operational robustness and complexity, as well as efficiency of supply chains

My research was extended to the operational robustness and complexity of supply chains, which I also characterized with quantitative measures. Whereas for the description of the structural properties the use of the graph theory proves to be the most adequate modeling approach, here the statistical methods and simulations can be advantageously applied.

I pointed out that there is a pressing need to investigate the interrelationships of robustness, complexity and efficiency of supply chains in order to support decisions related to their design and management.

I set up a methodology for the holistic evaluation of supply chains (including the aspects of robustness, complexity and efficiency), which consists of the following steps:

1. Definition of the supply chain's environment, together with the disruption(s) and KPI(s) to be considered.
2. Description of the supply chain to be analyzed (e.g. product(s) to be produced / delivered, supply chain's structure, capacities of its elements, inventory

management policies, production planning and scheduling methods, means of transportation, etc.).

3. Quantitative characterization of structural properties of the supply chain in respect of both robustness and complexity, based on graph theoretical analysis.
4. Quantitative characterization of operational properties of the supply chain also from robustness and complexity points of view, either by analyzing parameters collected from the real system or by supply chain simulation.
5. Determination of efficiency measures relying on analytical computations or simulation.
6. Investigation of the appropriateness of the achieved performance. In the negative case go back to Step 2. In order to drive the whole process, searching and optimization techniques can be used.

I developed a framework for evaluating robustness, complexity and efficiency of supply chains (Figure 2).

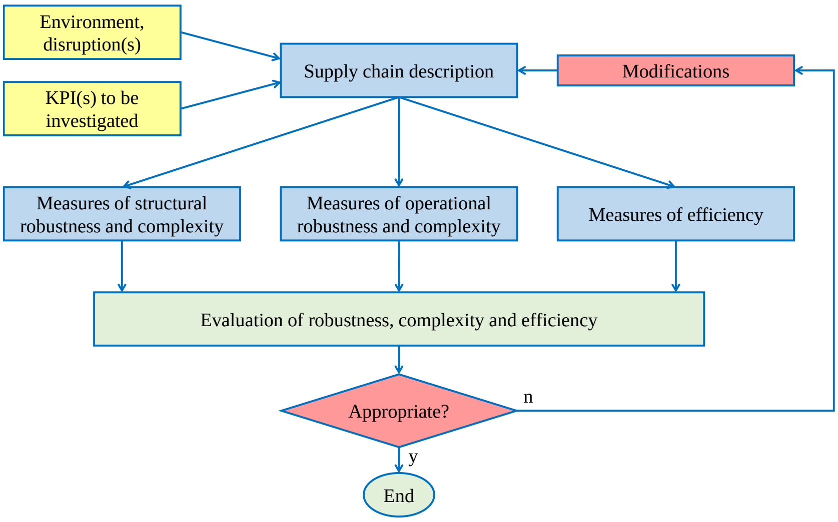

Figure 2. The framework for evaluating supply chains' robustness, complexity and efficiency (Monostori 2018).

In addition to the scientific novelty of the proposed approach which is in line with the main tendencies of supply chain and production network research, it has clear practical relevance too. The latter may even further increase in the era of natural disasters and pandemics.

By applying the methodology and the framework, different supply chain alternatives can be generated, compared from robustness, complexity and efficiency points of view, and offered for the management. This way, more well-founded decisions can be made, taking all the three aspects and the company's priorities into account.

Thesis 2: Beyond the structural characterization, I extended my research to the operational robustness and complexity of supply chains, gave their main quantitative measures, furthermore, I defined and realized a methodology and a framework integrating graph theoretical methods, digital simulation and optimization for the holistic, quantitative analysis of supply chains' structural and operational robustness and complexity, as well as efficiency, and for the support of their (re)design and management.

The results summarized in Thesis 2 are based mainly on Sections 2 and 3 of the dissertation. The most important related publications are as follows: Monostori (2018); Monostori (2021).

3.3. Ripple effects in supply chains

The bullwhip effect, i.e. the amplification of the demand volatility in the upstream direction of the supply chain, is well known for researchers and practitioners of the field. In contrast to the bullwhip effect, the ripple effect, which arises from disruptions at the supply chain elements, generates relatively novel challenges for supply chain managers. Disruptions' negative effects may ripple through the supply chain mainly in the downstream direction, moreover, they can spread to other supply chains as well.

I highlighted the importance of mitigating the ripple effects in supply chains in a way that – at the same time – puts the balance between the aspects of robustness, complexity and efficiency also into the focus.

Thanks to their generality, the proposed methodology and the developed framework can be adequately used for this purpose, which I demonstrated on conceived distribution networks situated in Hungary.

In the case study, the country was divided into regions with demands to be satisfied. The disruption to be considered was a temporarily shutdown of the central DC located in

Budapest. The question was how to balance the aspects of robustness, complexity and efficiency while mitigating the ripple effect of this disruption on the other parts of the investigated distribution networks. With this in view, several strategies were implemented, and their impacts were analyzed. The strategies were as follows: 1) the augmentation of the starting distribution network with additional DC(s), 2) the use of multiple sourcing in different extents, both as structural modifications; 3) the step-by-step increase of the (min-max) inventory policy parameters of the additional DC(s), as operational modifications.

The structural robustness measures of the starting distribution network pointed out that the network structure was extremely vulnerable to potential disruptions at the central DC. This situation could be significantly improved by the structural modifications, which went hand in hand with the increase of the structural complexity measures. Appropriate combinations of the structural and the operational modifications led to distribution network alternatives that represented balanced solutions between the aspects of robustness, complexity and efficiency, and, on the basis of the considered KPIs, could count on managerial satisfaction.

Thesis 3: I provided a procedure for mitigating the negative effects arising from disruptions at the supply chain elements and rippling through the supply chain in the downstream direction (ripple effects), which considers the aspects of robustness, complexity and efficiency simultaneously. I demonstrated its applicability – with the use of the developed methodology and framework – on distribution networks, where by the modifications of their various structural and operational parameters I generated such network alternatives that – besides alleviating the ripple effects – represented balanced solutions between the aspects of robustness, complexity and efficiency. I showed that with appropriate changes in both the structural and the operational complexity of supply chains, the robustness of these systems can be significantly enhanced, while slightly decreasing, sometimes maintaining, rarely even increasing their level of profitability.

The results summarized in Thesis 3 are based mainly on Sections 2, 3 and 4 of the dissertation. The most important related publication is as follows: Monostori (2021).

3.4. Environmental impacts of supply chains

I developed an approach to achieve trade-offs between the economic and the environmental aspects of supply chains' sustainability. The armory applied in the approach comprises the center of gravity method, (mixed) integer linear programming, constrained optimization, and graph theory based methods.

The approach consists of the following steps:

1. Estimation of the demand and its geographical distribution for the product(s) within the area to be served by the supply chain.
2. Determination of the locations (if they are not known) of the potential DCs (greenfield analysis (GFA)) by the center of gravity (CoG) method.
3. Profit-oriented optimization of the whole supply chain structure, in the general case by mixed integer linear programming (MILP), and in the case of discrete manufacturing by integer linear programming (ILP).
4. Generation of alternative supply chain structures for trade-offs between the economic (e.g. profit) and the environmental (e.g. CO_2 emission) aspects by constrained optimization.
5. Characterization of the different cases from the viewpoints of structural robustness and complexity by using graph theory based methods.

The approach presents a variety of supply chain settings for the management, indicating such important parameters, like different cost factors, revenue, profit, transportation-related CO_2 emission values, and customers' demand fulfillment. Aiming at a comprehensive analysis of the different supply chain settings, the values of some structural robustness and complexity measures are also determined for each of them. As a result, powerful decision support is offered for the supply chain managers, which can be advantageously used in their design and redesign activities.

I demonstrated the applicability of the approach through a case study on a hypothetical, five-level supply chain in Europe. The task was to design the supply chain (or to redesign the existing one), incorporating second- and first-tier suppliers, factories, DCs, and regions with customers to be served, taking not only economic, but also environmental aspects into account. Other KPIs were to be considered, too.

As an economic parameter, the profit earned in the supply chain was chosen, while as an environmental one of high importance, the transportation-related CO_2 emission was involved in the investigations.

It was shown that appropriate balance can be achieved between the considered economic and environmental aspects of sustainability. It is worth noting that trade-offs between these aspects went hand in hand not only with the shortening of the average distance the products and their components have to be transported (as a consequence, relocalization of some suppliers nearer to the factories or even of some factories nearer to the customers may be justified), but also with the increase of the structural robustness and complexity of the resulted supply chain structures.

In a project with a global manufacturing company, I successfully applied the approach to the analysis of its European distribution network and presented network alternatives favorable from economic and environmental aspects alike.

Thesis 4: I developed an approach to achieve trade-offs between the economic and the environmental aspects of supply chains' sustainability. On a multi-level supply chain, I illustrated that with relatively minor relaxations of the expected profit, such supply chain structures can be formed, which not only secure the reduction of the transportation-related CO_2 emission, but also possess increased structural robustness and complexity. I pointed out that the intention to abate the negative environmental impacts foreshadows the relocalization of industry, moreover that the requirements of robustness and environmental consciousness are far from being contradictory ones. Consequently, if the companies – not least as a reaction to the COVID-19 pandemic – restructure their supply chains because of robustness considerations, they can also contribute to the decrease of the environmental burden stemming from their external logistics processes.

The results summarized in Thesis 4 are based mainly on Sections 5, 6 and 7 of the dissertation. The most important related publication is as follows: Monostori (2020).

4. Applications of the results achieved

The results of the research contributed to the success of some significant, accomplished or running projects supported by grant agencies, such as:

- GINOP-2.3.2-15-2016-00002: *Industry 4.0 research and innovation centre of excellence (Ipar 4.0 kutatási és innovációs kiválósági központ)*, November 2016 – January 2021;
- EU H2020, 739592: *Centre of Excellence in Production Informatics and Control (EPIC)*, April 2017 – September 2024;
- NKFIH, ED_18-22018-0006: *Research on prime exploitation of the potential provided by the industrial digitalization (Kutatások az ipari digitalizáció által nyújtott potenciál minőségi kiaknázására (INEXT))*, October 2018 – June 2024;
- NKFIH, TKP2021-NKTA-01: *Research on cooperative production and logistics systems to support a competitive and sustainable economy (Kooperatív gyártó- és logisztikai rendszerek kutatása a versenyképes és fenntartható gazdaság támogatására)*, January 2022 – December 2025.

A part of the results was successfully applied in a project with a global manufacturing company. It served as a door opener project which was followed by other challenging bilateral ones.

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