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

PhD Dissertation

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Contents

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.

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 (Ivanov and Dolgui 2020; Belhadi et al. 2021; El Baz and Ruel 2021). The present war in Ukraine further emphasized the importance of the topic. In the cyber-physical era (Monostori et al. 2016), 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 2016). 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 (Lanza et al. 2019) 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.*

All the above are reflected in the structure of the dissertation:

Section 2 outlines some key concepts and challenges based on a comprehensive literature analysis of previous works, such as risk categories, bullwhip and ripple effects, robustness in other disciplines (especially in biology) and at the different levels of manufacturing, supply chains' robustness and connected terms, the conflicts between efficiency and robustness, and the relation of complexity and robustness. The timeliness of the research related to handling supply chains' robustness and complexity together, considering both structural and operational points of view, not forgetting efficiency either is justified by identifying the research gaps in this field.

In Section 3, graph theoretical measures are given for characterizing the structural robustness and complexity of supply chains and networks. Their appropriateness is shown on structures of two types, namely real two-level structures from Japan and multi-level ones taken from the literature. Measures for assessing supply chains' operational robustness and complexity that can be determined by statistical methods and / or by simulations are also highlighted. Lastly, a methodology and a framework are introduced for the holistic, quantitative evaluation of supply chains' robustness, complexity and efficiency.

A case study on conceived distribution networks is described in Section 4, indicating that with the use of the methodology and the framework, the envisioned balance between the three aspects can be achieved while mitigating the ripple effect.

Concentrating on supply chains' sustainability, related concepts are summarized in Section 5, emphasizing the significance of striving for trade-offs between the different sustainability dimensions of the field. Some previous ways to incorporate CO_2 emission reduction into the (re)design of supply chains are outlined, and the main steps of the approach proposed for this purpose are described.

The applicability of the approach is illustrated in Section 6 on a hypothetical multi-level supply chain, in the form of a case study, showing how an appropriate balance can be achieved between the investigated aspects of the economic and environmental sustainability dimensions. It is also highlighted that the balanced supply chain structures possess increased structural robustness and complexity.

Section 7 introduces the results of an industrial project on the analysis and potential restructuring of the European distribution network of a global manufacturing company. In addition to giving the cost-optimal solution, it is demonstrated how the optimal network structure depends on the parameters of the considered cost factors, i.e. the facility and the transportation costs. The consequences of the possible restructuring of the network on the transportation-related CO_2 emission are also treated.

Finally, Section 8 summarizes the scientific results in the form of theses and underlines their applications in concrete R&D projects. Wider perspectives, challenges and opportunities are also highlighted.

Acknowledgements, references, and lists of figures, tables, symbols and abbreviations complete the dissertation.

2. Key concepts and challenges

A vast number of publications dealing with different aspects of the design and management of supply chains and networks can be found in the literature. The main goals of this section are to introduce the most important concepts related to the topic of the dissertation, and to clarify in what sense they will be used hereinafter, and, furthermore, to point out the main challenges to be tackled and to identify the research gaps addressed in the work to be reported on.

2.1. Main risks the supply chains face

Supply chains are exposed to *risks* of various types (Chopra and Sodhi 2004). *Demand-side*, *supply-side* and *catastrophic risks* are differentiated in Wagner and Bode (2006):

- *Demand-side risks* include deviations of the actual demands from the forecasted ones, inadequate supply chain coordination, and problems in the products' physical distribution. Possible negative effects of demand-side risks are inefficient capacity utilization, costly shortages or surpluses.
- *Supply-side risks* involve suppliers' unreliability, capacity constraints, changes in the product design or in the technology, quality problems of the supply, and weak logistics performance. Typical negative consequences of supply-side risks are backlogs, late deliveries, and inappropriate functioning of some elements / parts of the supply chains concerned, resulting, many times, in lower level of overall performance.
- *Catastrophic risks* include natural hazards (e.g. volcanic eruptions, hurricanes, earthquakes, tsunamis, floods and droughts), economic crises, social-political instabilities, civil unrests, and even acts of terrorism. Because of the often geographically dispersed nature of supply chains, local problems can significantly affect even remote parts of them, negatively influencing the performance of entire supply chains.

Obviously, the occurrence probability and the potential impact of the given risk are important characteristics. Their product is a widely used measure for risks' ranking (Vilko and Hallikas 2012). Nowadays, two distinct risk categories represent special challenges for the researchers: the *recurrent* (sometimes called *operational*) risks and the *disruptive* ones, i.e. *frequent events with low impact* and *rare events with high impact*, respectively (Tomlin 2006; Dolgui, Ivanov, and Sokolov 2018).

2.2. Bullwhip effect, ripple effect

The *bullwhip effect* (Forrester 1961; Dolgui, Ivanov, and Sokolov 2018), 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* (Ivanov, Sokolov, and Dolgui 2014; Ivanov, Dolgui, and Sokolov 2015; Ivanov 2018), 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.

The bullwhip and ripple effects are related to the recurrent and disruptive risk categories (see Subsection 2.1), respectively. As typical risks, e.g. demand fluctuation in the former, and plant unavailability or severe strikes in the latter one can be mentioned. Both effects can influence critical parameters of the supply chains, e.g. inventory shortages, increased lead times and lost sales may occur. In order to recover from the situation, usually short-term coordination actions for balancing demand and supply are initiated as reaction to the bullwhip event. Fighting against the ripple effect mostly requires middle- and long-term coordination actions and investments.

When dealing with ripple effects, which belong to the disruptive risk category, a particular difficulty arises, i.e. their occurrence probabilities and the magnitudes of their potential consequences are hard to estimate, because little or no empirical knowledge is available about them in a given supply chain.

2.3. The concept of robustness

The concept of robustness can be found in different disciplines. Before focusing on supply chains' robustness, it is worth seeing how robustness is tackled in some other fields of science and technology (Monostori 2018).

2.3.1. Robustness in biology

As to the *biological robustness*: "robustness is a property that allows a system to maintain its functions against internal and external perturbations" (Kitano 2004; Kitano 2007). "To discuss robustness, one must identify system, function, and perturbations. It is important to realize that robustness is concerned with maintaining functions of a system rather than system states, which distinguishes robustness from stability" (Kitano 2007). Biological robustness – according to the kind of perturbation – can be classified as mutational, environmental, recombinational, behavioral, etc. one.

It is argued that robustness is a fundamental feature of evolvable complex systems, and evolution enhances the robustness of organisms, e.g. by increasing their complexity through successive addition of regulatory systems. Trade-offs between robustness, fragility, performance and resource demands can be observed in biological systems at different levels. Bacteria, for example, should be able to swim faster without negative feedback, but this would sacrifice their precision in following a chemical gradient: the use of negative feedback improves the bacteria's ability to follow the gradient, at the cost of reduced swim speed (Kitano 2004).

In biology, the following "solutions" are distinguished to ensure the robustness of a system (Kitano 2004):

- *System control*: negative and positive *feedbacks*, for robust adaptation to perturbations, and for amplification of stimuli, respectively.
- *Alternative or fail-safe mechanisms*: for achieving *redundancy* by several identical or similar components or modules able to replace the one which fails, or by diversity or heterogeneity, whereby a specific function can be attained by other means available in a population of heterogeneous components.
- *Modularity*: for containing perturbations and damage *locally* to minimize the effects on the whole system.

- *Decoupling*: for isolating low level variations from high level functionalities. *Buffers* play a specific role here, e.g. the heat shock protein 90 (HSP90) decouples genetic variations from the phenotype, providing a genetic buffer against mutations.

2.3.2. Robustness in manufacturing

Robustness becomes a more and more important feature at the different levels of manufacturing.

In *product design* robustness is tackled by making the product insensitive to variations, e.g. the environmental variation during the product's usage, the manufacturing variation, and the component deterioration (robust design or Taguchi method [Taguchi 1986]).

A *manufacturing process* is considered robust if it maintains its acceptable performance consistently at a desired level, even if there may be significant and substantial changes occurring in input variables and noise parameters during a given period of time or planning horizon (Mondal, Ray, and Maiti 2014). Naturally, process monitoring and (adaptive) control play a significant role here (Byrne et al. 1995; Teti et al. 2010). A comprehensive list and categorization of approaches to measure and evaluate the robustness of manufacturing processes is given in Mondal, Ray, and Maiti (2014).

For a *manufacturing system*, robustness can be defined as the system's aptitude to preserve its specified properties against foreseen or unforeseen disturbances (Telmoudi, Bourjault, and Nabli 2008).

A fundamental way to increase the robustness of manufacturing systems is to allocate reserves in physical and / or time domains (buffers, inventories or slack times). Another group of approaches relies on different (robust, reactive, predictive-reactive, proactive) scheduling techniques.

Distributed, decentralized control solutions – from their nature – offer higher robustness level for the system. The agent-based, holonic manufacturing systems (HMSs) consist of autonomous, intelligent, flexible, distributed, cooperative agents or holons (Van Brussel et al. 1998; Valckenaers and Van Brussel 2005; Monostori, Váncza, and Kumara 2006). The basic approach can be augmented with coordination and control mechanisms inspired by biological systems (i.e. food foraging behavior in ant colonies) supporting the execution of process plans properly under changing conditions, by continuously forecasting the workload of the manufacturing resources and the lead times of the products (Valckenaers and Van Brussel 2005).

The concept of biological manufacturing systems (BMSs) aims to deal with dynamic changes in external and internal environments based on biologically-inspired ideas such as self-growth, self-organization, adaptation and evolution (Ueda 1992; Ueda, Vaario, and Ohkura 1997; Ueda and Vaario 1998). It belongs to those, more and more frequently adopted approaches which use analogies taken from the biology to develop more effective and robust products and systems.

In Váncza et al. (2011) the importance of the cooperation between different entities at various levels of manufacturing for realizing more robust and responsive systems is underlined.

2.3.3. Robustness types

The concept of robustness can be categorized by using its different characteristics:

- Robustness *in the small* versus robustness *in the large* depending on the – problem specific – magnitude of the perturbations.
- A similar distinction is made between *local* and *global* robustness, i.e. whether the whole uncertainty space or a relatively limited part of it is considered in the investigations (cp. local versus global optimization).
- *Active* versus *passive* robustness, i.e. whether a modification in the control is necessary or not, in order to preserve the specified properties.
- *Proactive* versus *reactive* robustness, i.e. whether measures are taken before something disruptive happens or after it.

2.4. Robustness, resilience and vulnerability of supply chains

The concept of *robustness* – the word comes from the Latin *robustus*, meaning strong – appears in different disciplines, e.g. in architecture, economics, biology, computer science, systems and control science, and – naturally – in mathematics (e.g. robust optimization).

As to the robustness of supply chains, various, partly overlapping, partly even contradictory definitions are given in the literature. Some examples are:

- "The ability of a network to cope with changes in the competitive environment *without resorting to changes in the network structure*" (Ferdows 1997).
- "The system's ability to resist an accidental event and return to do its intended mission and *retain the same stable situation* as it had before the accidental event" (Asbjornslett and Rausand 1999).
- "The ability of a supply chain *to maintain a given level* of output after a failure" (Bundschuh, Klabjan, and Thurston 2006).
- "The ability of a supply chain network to carry out its functions despite some *damage* done to it, such as the *removal of some of the nodes and / or links* in the network" (Dong 2006; Dong and Chen 2007).

A more comprehensive enumeration and comparison of definitions of supply chains' robustness can be found, e.g. in Vlajic, van der Vorst, and Haijema (2012).

Another important concept related to the previous one is the *resilience* of supply chains. The word comes from the Latin *resilio*, meaning to rebound. The concept is adopted from the material sciences, where it characterizes materials' ability to recover their original shapes following a deformation. In case of supply chains, it represents their ability to, and the speed at which they can, *return to their normal performance levels* following a disruption (Sheffi 2007).

In the supply chain literature, similarly to the robustness, a variety of resilience definitions are given, emphasizing different aspects, as one can see from the following examples:

- "The ability of a system *to return to its original state* or *move to a new, more desirable state* after being disturbed" (Christopher and Peck 2004).

- “The adaptive capability of the supply chain *to prepare for unexpected events*, *respond to disruptions*, and *recover from them* by maintaining continuity of operations at the desired level of connectedness and control over structure and function” (Ponomarov and Holcomb 2009).
- “The supply chain’s ability *to react to the negative effects* caused by disturbances that occur at a given moment in order *to maintain the supply chain’s objectives*” (Barroso, Machado, and Cruz-Machado 2011).

Though, when comparing robustness and resilience, numerous authors underline the *adaptation ability* of resilient systems as a distinguishing feature, the real situation is not so clear-cut (see a multitude of resilience definitions in review papers, e.g. Bhamra, Dani, and Burnard [2011]; Kamalahmadi and Mellat Parast [2016]).

Additionally, other similar concepts, e.g. agility, responsiveness, flexibility and changeability, to mention only some of them, are also in use (Váncza et al. 2011; Carvalho, Azevedo, and Cruz-Machado 2012; Wieland and Wallenburg 2013; Stricker and Lanza 2014). All, in some respects, relate to the ability of a system to accommodate perturbations without losing functionality.

Without examining in detail the differences between the formulations given even for the same concept in the literature, and the overlaps between the various ones, in the dissertation the term robustness will be mostly used, with the following comprehensive formulation: “*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 2016).

Figure 1 (a further developed version of the figure in Asbjornslett [2009]) illustrates this concept, also indicating the possible outcome when the new stable state resumes with an even higher KPI.

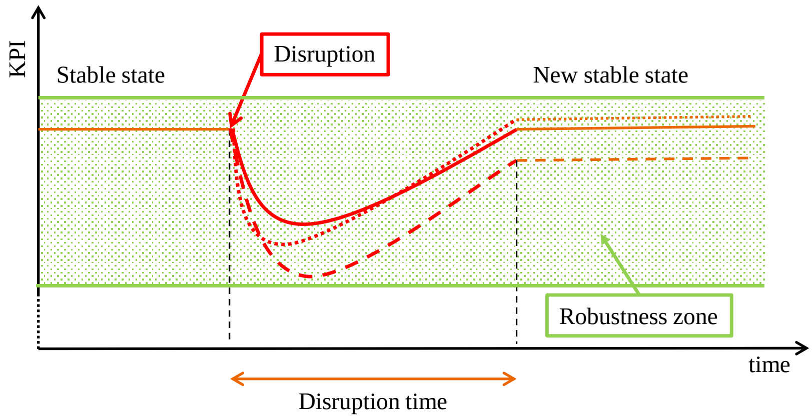

Figure 1. Delineation of supply chains' robustness used in the dissertation (Monostori 2016).

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 *vulnerability* (Asbjornslett 2009) is considered in the dissertation as a concept closely but inversely related to robustness, i.e. the more vulnerable a supply chain, the less robust it is. In this respect, the main *drivers* which act against the robustness of supply chains are as follows (Wagner and Bode 2006):

- *Customer dependence*: Dependence on a dominant customer with a significant proportion of the sales volume. In the presence of a disruption at the dominant customer, the seller firm may be seriously impacted.
- *Supplier dependence*: Dependence on a dominant supplier to which there are only few alternatives. The severity of a disruption at the dominant supplier for the buyer firm is fundamentally determined by the criticality of the item(s) to be purchased.
- *Supplier concentration and single sourcing*: Concentrating the sourcing on a relatively small number of suppliers or even on a single one, the company weakens its ability to involve alternative suppliers in critical situations.
- *Global sourcing*: Globe-spanning supply chains may be faced with increased uncertainty and poorer transparency.

2.5. Efficiency versus robustness of supply chains

For most of the companies *efficiency* is the ultimate goal. As an obvious consequence, their operations are streamlined by applying management concepts such as outsourcing, lean, just-in-time and just-in-sequence. Low level safety stocks are usually aimed at, and this way, supply chains become vulnerable to different turbulences (Monostori 2016).

Efficiency, on the one hand, and robustness, on the other, drive supply chain managers in mostly opposite directions (Table 1).

Table 1. Characteristics of efficient and robust supply chains
(based on Ivanov and Dolgui [2019]).

Criteria	Efficient supply chains	Robust supply chains
Primary goal	Supply demand with maximum profit / at minimum cost	Ensure demand fulfillment also in case of disruptions
Network organization	Centralized, global	Decentralized, local, diversified, segmented
Product design strategy	Standardization, performance maximization at minimum product cost	Postponement to ensure product flexibility, product substitution, capacity pooling
Pricing strategy	Lower margins because price is a prime customer driver	Potentially higher prices caused by the cost of robustness
Manufacturing strategy	Cost reduction through high utilization	Capacity reserves for unforeseen events / disruptions
Inventory strategy	Cost reduction through inventory minimization	Inventory reserves for mitigating risks' potential consequences
Lead time strategy	Lead time reduction, but not at the expense of cost increase	Lead time reserves for handling uncertainties
Sourcing strategy	Supplier selection based on cost and quality, single sourcing	Supplier risk exposure analysis, backup suppliers and multiple sourcing

From Table 1 the conclusion can be drawn that efficiency and robustness pose contradictory requirements towards supply chain design and management. However, the real challenge is to *balance* these opposing characteristics with the aim of a kind of reconciliation. The feature which incorporates both resilience / robustness and efficiency aspects in supply chain management is denoted as *resileanness* in Ivanov and Dolgui (2019). According to this vision, digital technologies and smart operations can contribute to the integration of resilience / robustness and lean thinking.

The increase of supply chains' resilience / robustness usually implies some additional costs. As it is underlined in Fiksel et al. (2015), unnecessary overinvestment in corresponding capabilities can erode profits, therefore, a *balanced resilience* is to be strived for in supply chains to match their portfolio of capabilities to their pattern of vulnerabilities.

2.6. Complexity issues in supply chains

The *complexity* and the question, how to handle it came into the foreground at every level of the production hierarchy, thus also at the level of supply chains and networks (Wiendahl and Scholtissek 1994; ElMaraghy et al. 2012).

Three dimensions of the supply base complexity of a focal company are outlined in Choi and Krause (2006): the number of suppliers, the degree of differentiation among these suppliers (concerning operational practices, cross-border barriers, technical capabilities), and the level of interrelationships between them. The main statement of the referred paper is that although the reduction of the supply base complexity may be cost-efficient, its incautious implementation can negatively impact the focal company's overall competitiveness.

One possible method to cluster supply chains' complexity is to distinguish between *necessary* and *unnecessary* complexities, on the one hand, and between *current* and *potential* complexities, on the other (Serdarasan 2013). The complexity that provides a distinct competitive advantage and that the market / customer is willing to pay for is considered as necessary complexity, while unnecessary complexity – though usually involves additional costs – cannot offer such benefits. Potential complexity, in contrast to the current one, does not exist at the present time, but may occur in the future. To the different clusters various approaches can be ordered, such as to *manage*, *reduce / eliminate*, or to *prevent* as it is illustrated in Figure 2. Necessary complexity needs to be managed, independently of its relation to time (current or potential). Unnecessary, current complexity requires intervention to reduce or even eliminate it as soon as possible. In case of unnecessary, potential complexity, preventive actions may be taken.

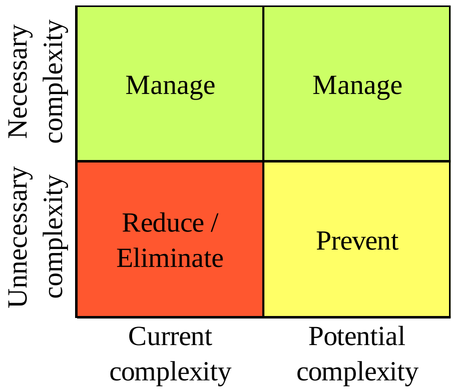

Figure 2. Approaches to dealing with supply chains' complexity (Serdarasan 2013).

Another, highly important categorization is to be mentioned that is applicable in respect of both complexity and robustness of supply chains, namely the *structural (static)* and the *operational (dynamic)* complexity / robustness. When investigating a supply chain from structural point of view, the focus is on its elements and the connections between them. While analyzing operational aspects, the dynamic processes occurring in the supply chain are dealt with, considering unchanged structure (Tolio, Urgo, and Váncza 2011; Cheng, Chen, and Chen 2014; Stricker et al. 2015). The two kinds of complexity and robustness, i.e. the structural and the operational ones, are strongly interrelated. The behavior of the whole system originates from both.

Naturally, by changing structural and / or operational properties of supply chains, their performance – so also their robustness – can be influenced. Generally, it may be expected that – in tendency – a well-aimed increase of the complexity should initiate similar changes in the robustness. However, unnecessary complexity is to be avoided. *In this respect, the challenge – sometimes even the art – is to secure the required level of robustness with the lowest possible level of complexity* (Monostori 2016).

2.7. Some previous ways to consider supply chains' robustness and / or complexity

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.

2.8. Own contributions

The statements and challenges formulated in the previous parts of the section constituted the guiding thread of the research work staying behind the dissertation. Its main steps can be followed in the publications of the author, referring to the most important ones only:

- A complex network approach is introduced in Monostori (2016) for the *structural* characterization of supply chains and networks from both robustness and complexity points of view. Its feasibility is demonstrated on three types of structures, i.e. on real (industrial) and artificially generated ones, and on structures taken from the literature.
- Measures for *operational* robustness are also described and the concept of a framework for evaluating supply chains' robustness, complexity and efficiency is outlined in Monostori (2018).
- An approach to achieve trade-offs between the *economic* (e.g. profit) and the *environmental* (e.g. CO_2 emission) aspects of supply chains' sustainability is introduced in Monostori (2020). On a multi-level supply chain, it is shown how relatively minor relaxations of the expected profit can lead to supply chain structures not only with reduced transportation-related CO_2 emission, but also with increased structural robustness and complexity.
- The paper Monostori (2021) can be considered as a next step in the process of handling *robustness* and *complexity* issues in supply chains jointly. The developed methodology and framework are not restricted to *structural* aspects only, but can deal also with *operational* ones, naturally not neglecting *efficiency* either. Their applicability is illustrated by the results of a case study focusing on the mitigation of the ripple effect in distribution networks.

2.9. Conclusions

In the section, robustness and complexity of supply chains were treated jointly, not restricted exclusively to their structural or operational aspects, but considering both. Moreover, the *complicated interrelationships of robustness, complexity and efficiency* were put into the focus.

For the sake of unambiguity and understandability, relying on a comprehensive literature analysis of previous works, key concepts and challenges related to the content of the dissertation were defined and commented on:

- On the basis of their occurrence probabilities and potential impacts, two risk categories were identified as highly challenging for the researchers: the *recurrent* risks and the *disruptive* ones, i.e. *frequent events with low impact* and *rare events with high impact*, respectively.
- It was outlined that comparing with the relatively well-known *bullwhip effect*, which belongs to the recurrent risk category, in the literature generally less attention was given to the *ripple effect*, a representative of the disruptive risk category.
- *Robustness-enhancing techniques used in some other fields of science and technology* (e.g. biology, manufacturing) were explored and found to be relevant also to supply chains.
- A number of terms connected to supply chains' robustness were listed, e.g. resilience, agility, responsiveness, flexibility, changeability and vulnerability, and furthermore, a *comprehensive robustness definition* was formulated.
- Dealing with the seemingly irreconcilable conflicts between *efficiency and robustness*, the target to *balance their opposing characteristics* was set.
- As to the relation of supply chains' *complexity and robustness*, the challenge to *achieve the required level of robustness with the lowest possible level of complexity* was formulated.
- Finally, *research gaps* were identified, and this way the *timeliness* of the research was justified.

3. Quantitative characterization of supply chains' robustness and complexity

In order to compare different supply chain settings from robustness, complexity and efficiency points of view, the use of objective measures – if possible, quantitative ones – is of fundamental importance. For efficiency there are some generally accepted measures in use, e.g. the profit or the total cost, however this is not the case for robustness and complexity. In this section, such measures are defined. The methodology, the related framework and most of the investigations described in the subsequent parts rely on these measures.

The measures are introduced in the following order:

- *Structural measures of supply chains*, in respect of both complexity and robustness (Monostori 2016).
- *Operational measures of supply chains*, also from complexity and robustness points of view (Monostori 2018; Monostori 2021).

3.1. Structural measures of supply chains

The application of graph theoretical concepts is reasonable to characterize the structural properties of supply chains and networks. The elements (e.g. customers, distribution centers, 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.

3.1.1. Measures for describing graphs' complexity

The *order* of a graph, n and the *size* of a graph, m, i.e. the number of the vertices and the number of the edges, respectively, are natural measures of its complexity. The *degree* of vertex v, $deg(v)$ equals the number of edges incident to it.

The *entropy* of a graph is a more sophisticated measure for graphs' complexity (Modrak and Marton 2012; Cheng, Chen, and Chen 2014). Relying on Shannon's information theory (Shannon and Weaver 1971), it characterizes the similarity between the vertex degrees in a graph, and is to be derived as follows:

$$H_{graph} = -\sum_{i=1}^{n} \frac{deg(v_i)}{m} * log_2 \frac{deg(v_i)}{m}. \quad (1)$$

The entropy value lies in the interval [0, $log_2 n$], it is 0 in edgeless graphs and $log_2 n$ in fully connected ones.

3.1.2. Measures for describing graphs' robustness

The *betweenness centrality* of vertex *v* (also known as *vertex betweenness centrality*) relates to the ratio of the number of the shortest paths between vertices that pass *v* to the total number of the shortest paths in the graph (Holme et al. 2002; Duan and Lu 2014):

$$BC(v) = \sum_{u \neq w \in V} \frac{\sigma_{uw}(v)}{\sigma_{uw}}. \quad (2)$$

Here σ_{uw} denotes the number of the shortest paths between any vertices *u* and *w* while $\sigma_{uw}(v)$ is the number of the shortest paths within this set, which incorporate vertex *v*. *V* is the set of all vertices in the graph.

In the interest of making the betweenness centrality of vertices which pertain to graphs of different size comparable, its values are usually divided by factors related to the size of the given graph. In directed graphs, a suitable normalization factor is $(n-1)*(n-2)$, while in undirected ones $(n-1)*(n-2)/2$. Being directed graphs more adequate to describe supply chains and networks, in this field the former factor is to be used for the determination of the normalized betweenness centrality:

$$BC'(v) = \frac{BC(v)}{(n-1)*(n-2)}. \quad (3)$$

The normalized betweenness centrality of a vertex can take a value in the interval [0, 1]. The higher this value, the more important the given vertex, which means the graph is less robust here.

The *edge betweenness centrality* of edge *e* is also applicable to the analysis of supply chains and networks. It relates to the ratio of the number of the shortest paths that incorporate the given edge, $\sigma_{uw}(e)$ to the total number of the shortest paths in the graph (Holme et al. 2002):

$$BCE(e) = \sum_{u \neq w \in V} \frac{\sigma_{uw}(e)}{\sigma_{uw}}. \quad (4)$$

A relatively new measure of graphs' robustness is *factor R* (Schneider et al. 2011; Zhou and Liu 2014):

$$R = \frac{1}{n} \sum_{Q=1}^{n} s(Q), \quad (5)$$

where *s(Q)* is the proportion of the order of the largest connected subgraph remained after removing *Q* vertices to the order of the original graph. (It is always the vertex with the highest degree in the largest subgraph which is eliminated.) The range of possible R values lies in the interval [*1/n*, ½]. The endpoints are taken in case of star graphs and fully connected graphs, respectively.

Some other graph measures can also be considered for characterizing the robustness of supply chains and networks, e.g. *average shortest distance*, *average path length* and *average clustering coefficient* (Cui, Kumara, and Albert 2010).

3.2. Graph theoretical analysis of concrete supply chain and network structures

The available literature dealing with structural properties of supply chains and networks investigates – nearly without exception – either their robustness or their complexity character. Contrarily, the results introduced in this subsection are derived from a series of investigations where a number of measures of both robustness and complexity nature were determined and analyzed (Monostori 2016). The investigated supply structures were of two types, namely real ones, and structures taken from the literature.

3.2.1. A supply network consisting of OEM enterprises and their first-tier suppliers producing a given part

The structure in Figure 3 is based on real data from Japan (Kito and Ueda 2014). The supply network consists of original equipment manufacturers (OEMs) and some of their first-tier suppliers, i.e. of 11 car manufacturers (A1-A11 assemblers for the final assembly of cars) and of 6 tire suppliers (S1-S6). The data are from 2002. (Obviously, the network illustrated in the figure represents only a small part of the whole automotive parts' supply network of Japan at that time.)

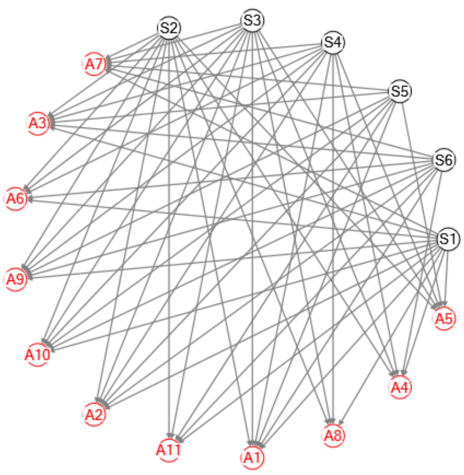

Figure 3. Supply network of tires for automotive OEMs in Japan, 2002
(based on Kito and Ueda [2014]).

In the network of Figure 3 all of the suppliers S1-S6 deliver to a number of assemblers. S1-S3 supply all the 11 OEMs, while S4, S5 and S6 supply 10, 8 and 9 ones, respectively. Assemblers A1, A2, A3, A7, A9 and A10 are supplied by all the 6 tire manufacturers.

The graph which represents this supply network incorporates 17 nodes and 60 directed edges. Dense connections between the suppliers and the final assemblers can be observed.

As to the structure of this supply network, the authors of the referred paper (Kito and Ueda 2014) reported on a remarkable change in it in the period of 2002-2012. Focusing on the relation between the OEMs and the tire suppliers again, in 2012 the structure of Figure 4 came into being.

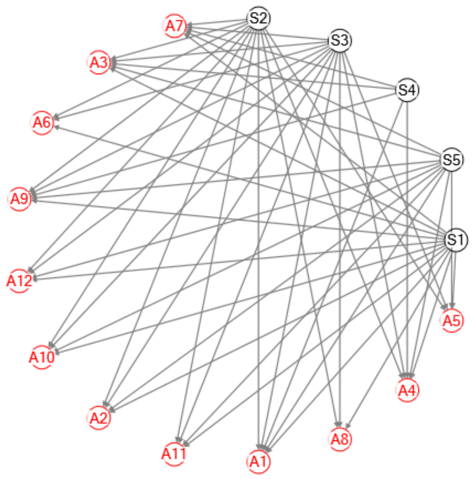

Figure 4. Supply network of tires for automotive OEMs in Japan, 2012
(based on Kito and Ueda [2014]).

Comparing the structures of Figure 3 and Figure 4, one can conclude that the number of assemblers increased from 11 to 12, the number of tire suppliers decreased from 6 to 5, and the number of supplier connections decreased from 60 to 51.

The real data from Japan gave the opportunity for a deep analysis in respect of the structural complexity and structural robustness of these networks. The most important results are summarized in Table 2.

Table 2. Changes in the values of the complexity and robustness measures
in the period of 2002-2012.

Year	No. of nodes	No. of edges	Average degree	Entropy	Max. of the normalized betweenness centrality	Factor R
2002	17	60	3.529	4.012	0.106	0.27
2012	17	51	3	3.913	0.169	0.215

The four columns following the year data contain the values of the complexity measures. The order of the graphs (the number of the nodes / vertices) remained unchanged (17). The size of the graphs (the number of the edges) decreased from 60 to 51 in the investigated period. Accordingly, the average vertex degree changed from 3.529 to 3 (in this respect a directed edge was considered only once). The entropy which measures the similarity of the nodes in the network in respect of their degree, decreased from 4.012 to 3.913. As a summary, all of the investigated complexity measures decreased in the period of 2002-2012. (Except for the number of the nodes, which remained unchanged.)

It is worth noting that in both investigated years nodes S1, S2 and S3 showed the largest normalized betweenness centrality values, but the values in 2012 surpassed the earlier ones by 60%. This means that they became more vulnerable (their robustness decreased). Robustness factor R decreased from 0.27 to 0.215.

Summarizing the above observations, in the 10-year period both the complexity and robustness measures of the investigated network decreased. The results support the statements of Kito and Ueda, who used one special measure (nestedness) for the structural characterization of the same supply networks (Kito and Ueda 2014).

3.2.2. Multi-tier supply chains

An important part of the investigations reported here focused on complexity and robustness analysis of multi-tier supply chains. Each of the concrete structures taken from Cheng, Chen, and Chen (2014) consists of 22 nodes including the one which assembles the final product. The six analyzed supply chains differ only in the number of the edges which varies from 23 to 59, in such a way that a given structure incorporates the previous one as a subgraph (it has been extended with additional edges only).

Figure 5 illustrates the smallest and the largest chains.

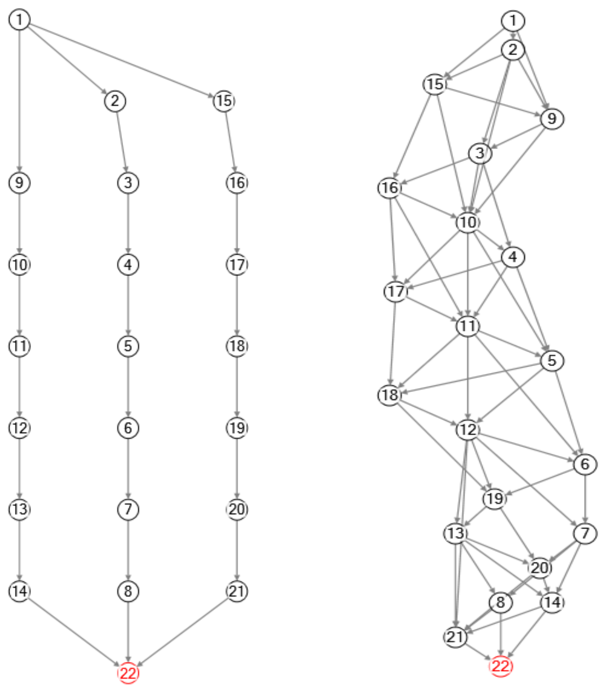

Figure 5. The smallest and the largest analyzed multi-tier supply chains (based on Cheng, Chen, and Chen [2014]).

The results of the investigations are summarized in Table 3.

Table 3. Complexity and robustness measures of the investigated multi-tier supply chains.

No. of nodes	No. of edges	Average degree	Entropy	Max. of the normalized betweenness centrality	Factor R
22	23	1.045	4.447	0.317	0.145
22	28	1.273	4.414	0.415	0.213
22	34	1.545	4.373	0.518	0.254
22	40	1.818	4.379	0.389	0.273
22	47	2.136	4.376	0.412	0.318
22	59	2.682	4.411	0.339	0.376

The described way of generation of the consecutive structures provided an opportunity for investigating the effect of additional links on the structural complexity and the structural robustness measures of multi-tier supply chains.

It is obvious that the average degree of the nodes increases with the inclusion of additional edges. However, if the increased number of the edges does not contribute to a more even distribution of the vertex degrees in the supply chain, in the given step, the entropy does not necessarily go hand in hand with the average vertex degree.

The maximum of the normalized betweenness centrality refers to the most vulnerable node within the structure, and in this sense is a local feature. It is understandable that not every additional edge in the supply chain influences the vulnerability of a given node in the targeted direction.

The best – positive – correlation was found between two global structural features, namely between the average vertex degree (as complexity measure) and the factor R (as robustness measure) (Figure 6).

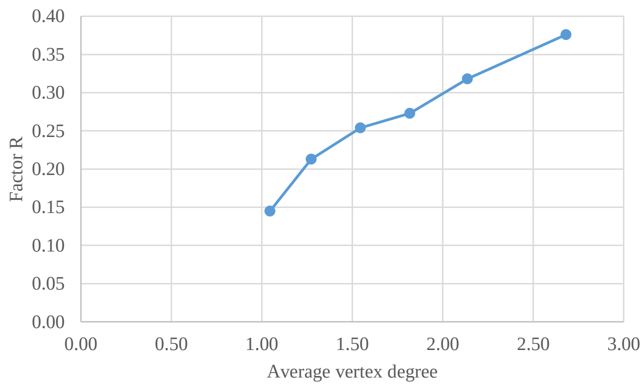

Figure 6. The factor R as a function of the average vertex degree in case of the investigated multi-tier supply chains.

3.2.3. Conclusions

The investigations showed 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*.

The practical applicability of the quantitative approach for analyzing supply chains both in their design and functional phases is straightforward. The values of the introduced 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.

3.3. Operational measures of supply chains

3.3.1. Measures for supply chains' operational complexity

In addition to the structural complexity, there are very important factors which contribute to the complexity of supply chains:

- *Demands*: amounts, volatility, seasonality of the demands for different products in different regions.
- *Products*: number and diversity of products, material types, parts and subassemblies within the supply chain.
- *Factories*: capacities, the applied production planning and scheduling methods and their parameters, types and parameters of inventory policies, sourcing policies and their parameters.
- *Warehouses, distribution centers*: capacities, types and parameters of inventory policies, sourcing policies and their parameters.
- *Transportation*: number and types of vehicles, types of transportation policies.

The above, non-exhaustive list is in harmony with the related literature, see e.g. Bozarth et al. (2009).

3.3.2. Measures for supply chains' operational robustness

In order to quantify the operational robustness of supply chains, some KPIs have to be defined (Figure 1).

Those KPIs of supply chains that characterize either the *delivery speed* or the *delivery reliability* of orders are of high importance (Vachon and Klassen 2002). As examples of the former, the *throughput time* and the *delivery lead time* are to be outlined, while as representatives of the latter, the *delivery tardiness*, the *percentage of late deliveries* and the *service level by orders or by products* can be mentioned:

- *Throughput time*: the average time between the start of an order's production and its completion.
- *Delivery lead time*: the average time between the placement of an order and its shipment to the customer.

- *Delivery tardiness*: the average time between the actual and the contractual delivery times, in case of late deliveries.
- *Percentage of late deliveries*: the proportion of the number of the late deliveries to the number of all deliveries.
- *Service level by orders or by products*: the proportion of the number of the successful orders to the number of all orders placed, or the proportion of the number of the products in the successful orders to the number of products in all orders placed, respectively.

All these KPIs can be used for characterizing entire supply chains, but in case of a more detailed analysis, they are also appropriate for investigating every single supplier-buyer relationship within them.

The measures of operational robustness are the actual values of the KPIs in focus, or rather their closeness to their anticipated / planned values.

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.

3.4. Methodology and framework for the evaluation of supply chains' robustness, complexity and efficiency

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 (Monostori 2018; Monostori 2021).

On the basis of the considerations and challenges highlighted in Section 2, and of the quantitative measures described in Subsections 3.1 and 3.3 for characterizing supply chains' robustness and complexity from both structural and operational points of view, the following *methodology* for the holistic evaluation of supply chains (including the aspects of robustness, complexity and efficiency) is proposed:

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.

The *framework* developed for evaluating robustness, complexity and efficiency of supply chains is illustrated in Figure 7.

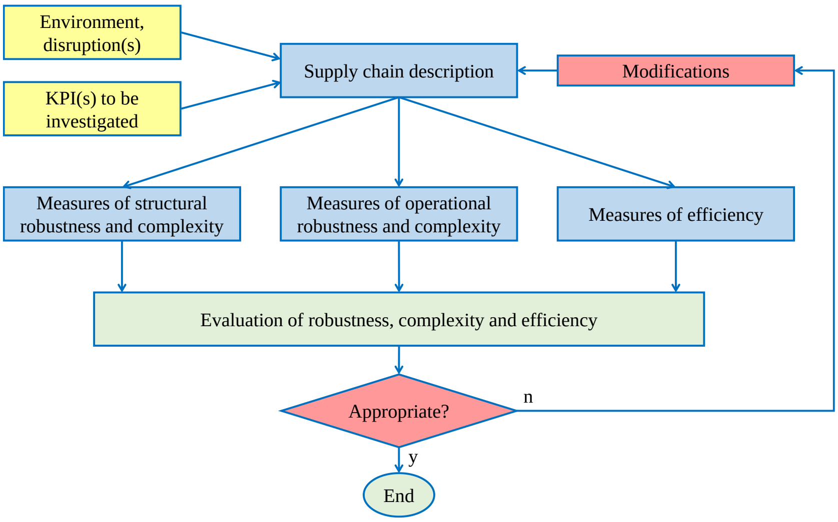

Figure 7. The framework for evaluating supply chains' robustness, complexity and efficiency (Monostori 2018).

The structural measures are computed partly by the NodeXL network analysis tool (https://www.smrfoundation.org/nodexl/), partly by own algorithms. The operational and the efficiency measures are determined by using the AnyLogistix supply chain software (https://www.anylogistix.com/) offering versatile opportunities for the simulation of supply chains. Simulation is a fundamental approach to the evaluation of supply chain settings. On the one hand, it is not feasible to perform experiments in running supply chains, and on the other, it is nearly impossible to include all the small but many times important details of a supply chain in an analytical model.

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.

Here is to be mentioned that the methodology and the framework can be adequately used also for investigating and mitigating the ripple effects in supply chains, as it is illustrated in Section 4.

3.5. Conclusions

Aiming to balance the aspects of *robustness, complexity and efficiency* in supply chains, and, necessarily, to compare different supply chain settings in a reliable way, *measures* – primarily *quantitative* ones – have to be defined. For efficiency there are a number of well-known measures available, however this is not the case for robustness and complexity. In the section, graph theoretical measures were given for characterizing the structural robustness and complexity of supply chains and networks. Measures for assessing their operational robustness and complexity were also highlighted, outlining that in this field statistical methods and simulation techniques are more adequate.

A *methodology* and a *framework for the holistic evaluation of supply chains' robustness, complexity and efficiency* were depicted.

4. Mitigation of the ripple effect in supply chains: Balancing the aspects of robustness, complexity and efficiency

In this section, the applicability of the proposed methodology and the developed framework is demonstrated by mitigating the ripple effect in distribution networks through balancing the aspects of robustness, complexity and efficiency (Monostori 2021).

4.1. General description of the investigated distribution networks

The case study to be reported on here refers to conceived distribution networks situated in Hungary. They comprise 30 regions with demands to be satisfied. In the fundamental setting, the regions are served from a central distribution center (DC) located in Budapest (Figure 8). (In the graph representations in this section, the regions are denoted by R1-R30, the central DC by W1, and the additional DCs by H1 and H2.)

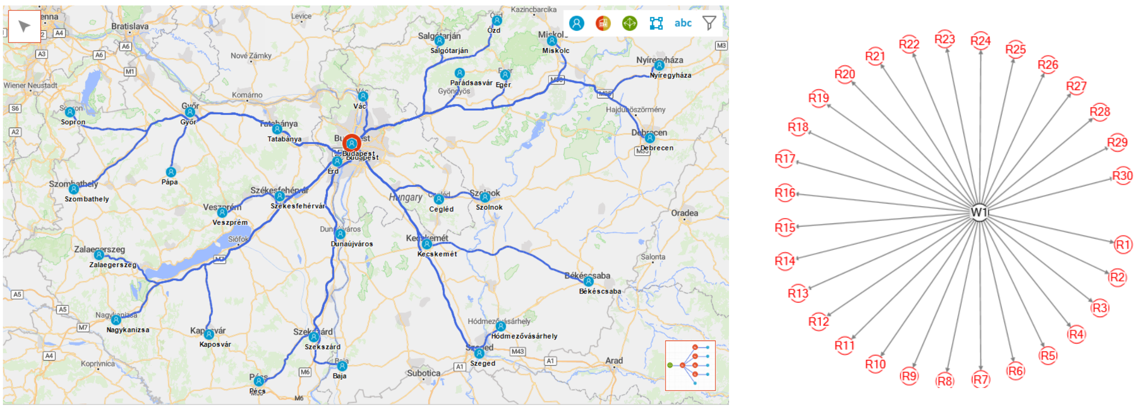

Figure 8. The starting distribution network and its structure in graph representation.

The main operational parameters of the distribution networks are as follows:

- *Product*: mineral water in 2-liter bottle, its cost and selling price are 0.2 and 0.5 USD/bottle, respectively.
- *Demands*: deterministic, constant over time, proportional to the number of inhabitants in the given regions, 0.4 liter/day/inhabitant.
- *Order parameters of the regions*: order interval: 5 days, expected lead time (ELT): 7 days, backorder is not allowed.

- *Parameters of the DCs*: carrying cost: 0.001 USD/m^3/day, initial cost of an additional DC: 1 million USD, the additional DCs use min-max inventory policy (s,S) with a periodic check of 1 day.
- *Transportation*: less than truckload (LTL) policy, trucks with capacity 50 m^3 and speed 60 km/h, with cost 0.05 USD/m^3/km calculated with actual routes (not with straight lines).

The investigated time period is 1 calendar year, with a 1-month *disruption* at the central DC in Budapest (the DC is temporarily closed).

The next two subsections illustrate how structural and operational modifications can result in distribution network alternatives with improved ripple effect mitigation abilities.

4.2. Structural modifications

Obviously, the star structure in Figure 8 is extremely vulnerable. The structure was augmented step by step: first, one additional DC (in Siófok) was added to the network, which was supplied from the DC in Budapest. Three of the regions (Zalaegerszeg, Nagykanizsa and Kaposvár, indicated by squares with horizontal and vertical edges) were served exclusively from Siófok, three other regions (Pécs, Szekszárd and Baja, marked by squares standing on their vertices) from both Budapest and Siófok (in equal ratio, in cases when both of them were functioning), and the remaining 24 regions solely from Budapest (Figure 9, upper part). (Generally, the network structures analyzed here can be described with the triple *a*-*b*-*c* where *a* is the number of additional DCs, each of which supplies *b* regions jointly with the central DC, and *c* regions exclusively.)

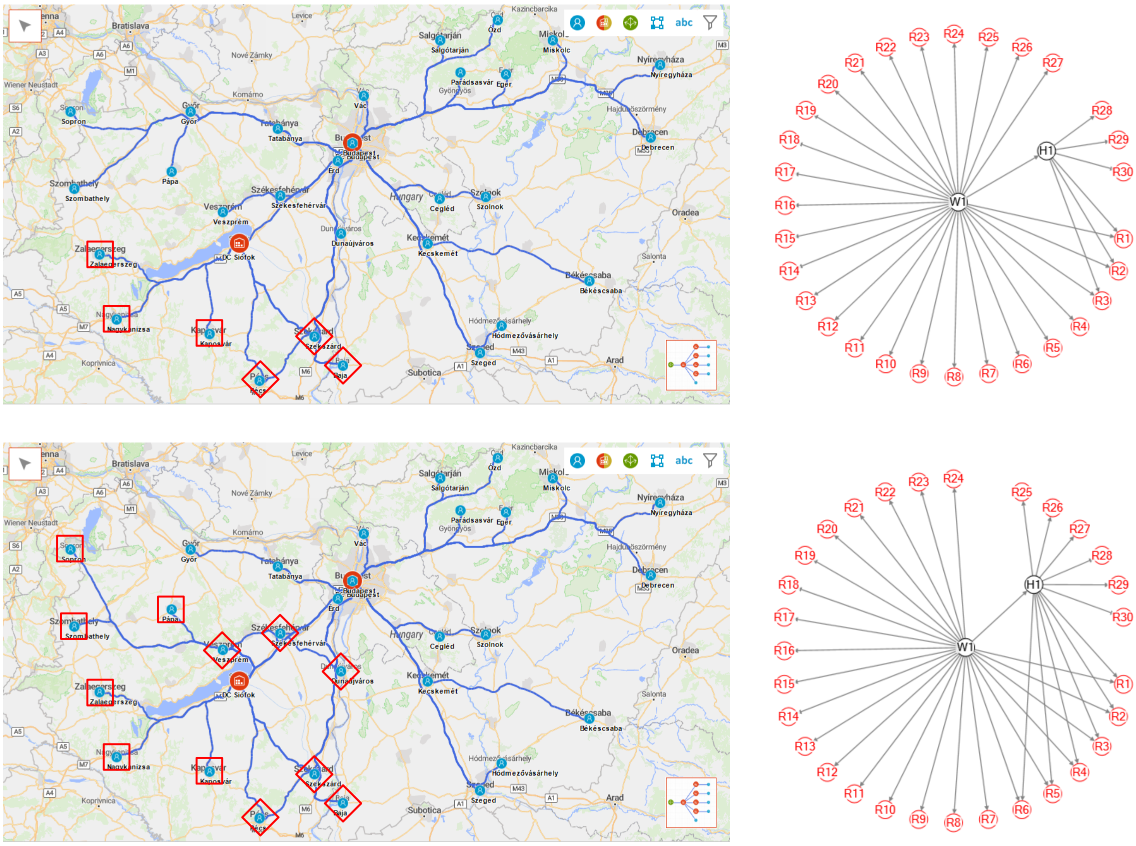

Figure 9. The networks 1-3-3 (upper part of the figure) and 1-6-6 (lower part of the figure) incorporating one additional DC (in Siófok) and their structures in graph representation.

The next network was differentiated from the preceding one only in the numbers of how many regions were served solely by Siófok, and how many by Budapest and Siófok together (similar graphical indications are used as before). These numbers were 6-6 (Figure 9, lower part).

Finally, two other networks were generated both having two additional DCs (in Siófok and in Szolnok). Similarly to the cases with one additional DC, these DCs served some (3 and 6) regions exclusively, and the same numbers jointly with Budapest (Figure 10). (The newly involved regions are marked by squares with dotted edges.)

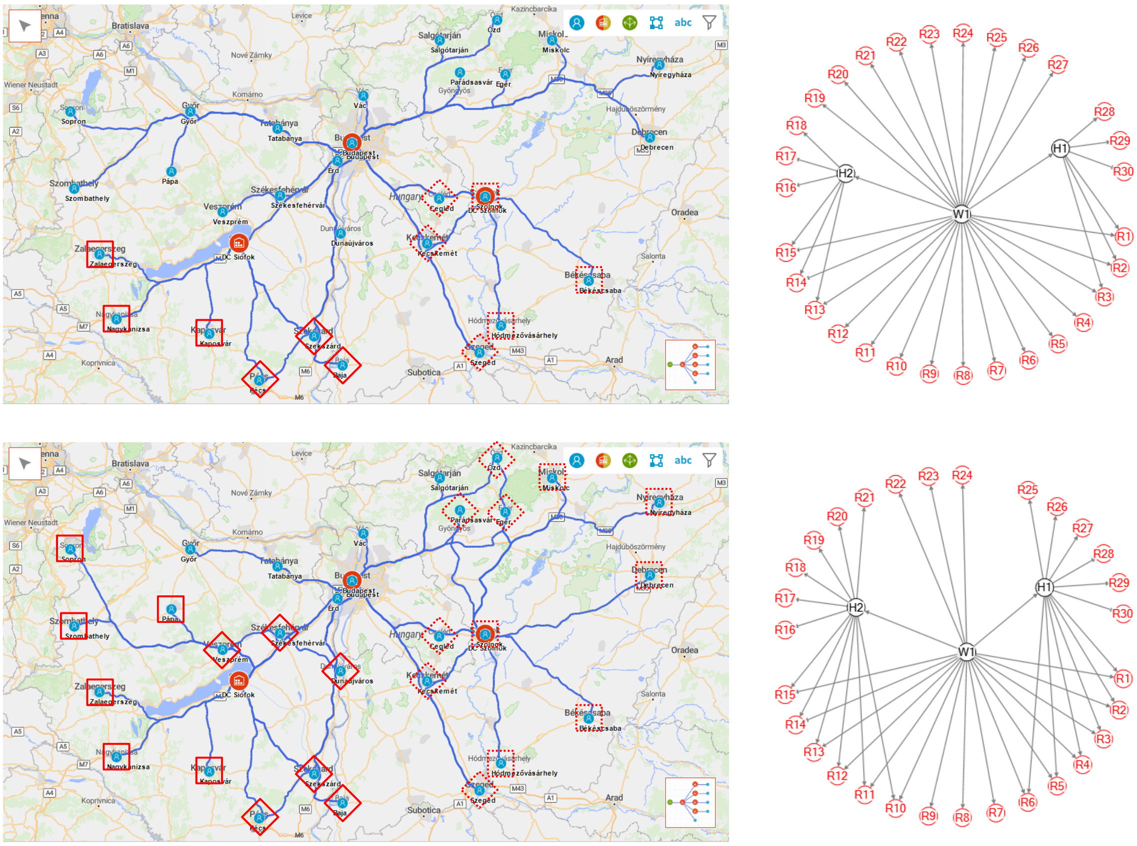

Figure 10. The networks 2-3-3 (upper part of the figure) and 2-6-6 (lower part of the figure) incorporating two additional DCs (in Siófok and in Szolnok) and their structures in graph representation.

Some structural complexity and robustness measures defined in Subsection 3.1 were determined for the five networks (Table 4) by using the framework introduced in Subsection 3.4. As described there, the structural measures were computed partly by the NodeXL network analysis tool, partly by own algorithms.

Table 4. Structural complexity and robustness measures.

Network structure	No. of nodes	No. of edges	Average degree	Entropy	Max. of the normalized betweenness centrality	Factor R
0-0-0	31	30	0.968	3.453	1	0.032
1-3-3	32	34	1.063	3.731	0.958	0.036
1-6-6	32	37	1.156	3.828	0.848	0.043
2-3-3	33	38	1.152	3.965	0.921	0.047
2-6-6	33	44	1.333	4.111	0.716	0.063

Comparing the values of the *complexity measures* (number of the nodes, number of the edges, average degree of the nodes, entropy of the graph (see Subsection 3.1.1)) in rows 2-5 (networks 1-3-3, 1-6-6, 2-3-3 and 2-6-6), with the values of the basic distribution network owning only one, central DC (0-0-0, first row), it can be seen that all measures exceed their initial values. Within the blocks of networks with the same number of additional DCs (1-3-3, 1-6-6 and 2-3-3, 2-6-6, respectively), the increase is monotonous. It is also worthy of note that – as a result of the more and more evenly distributed node degrees in the structures – the monotonous increase of the entropy values is experienced for all the consecutive networks.

Looking at the *robustness-related measures* (maximum of the normalized betweenness centrality, factor R (see Subsection 3.1.2)) in the two right-hand side columns, it can be observed that in case of the networks belonging to the same block, their augmentation with further edges led to growing robustness measures. This outcome is in harmony with the general perception that if a higher proportion of the regions applies multiple sourcing, the networks' robustness increases.

4.3. Operational modifications

The coming part shows how the different distribution networks behave in case of the disruption, taking not only structural but also operational parameters into account.

In the example under discussion, the disruption occurs at the central DC. It causes ripples, its negative effects gradually spread across the whole distribution network, from the central DC, through the additional DCs, and finally to the regions. Obviously, the additional DCs play a crucial role in mitigating the ripple effect, and consequently, a logical way was to concentrate on their inventory levels.

Numerous possible KPIs, e.g. number of bottles sold, costs related to inventory and transportation, revenue, profit, and service levels, were determined through simulation by applying the framework highlighted in Subsection 3.4. As outlined there, for this purpose, the AnyLogistix supply chain software was used. Here, three KPIs are analyzed and illustrated, namely the number of bottles sold and the profit (Figure 11), and the accumulated service level by orders (Figure 12).

The triples in Figure 11 indicate the network structures, as in Subsection 4.2. Altogether 30 cases were considered, 1 in the basic structure, 4, 9, 4 and 12 in structures 1-3-3, 1-6-6, 2-3-3 and 2-6-6, respectively. Within the sets with the same structural complexity, the consecutive cases incorporated enhanced operational complexity, by increasing the parameters of the min-max inventory policy of the additional DCs step by step. In each step, the min (s) and the max (S) parameters were increased by the same amount (500,000 bottles).

As expected, the smallest amount of mineral water was sold in the basic network with no additional DC. The amount monotonically increased within each set, in parallel with the networks' enhanced operational complexity.

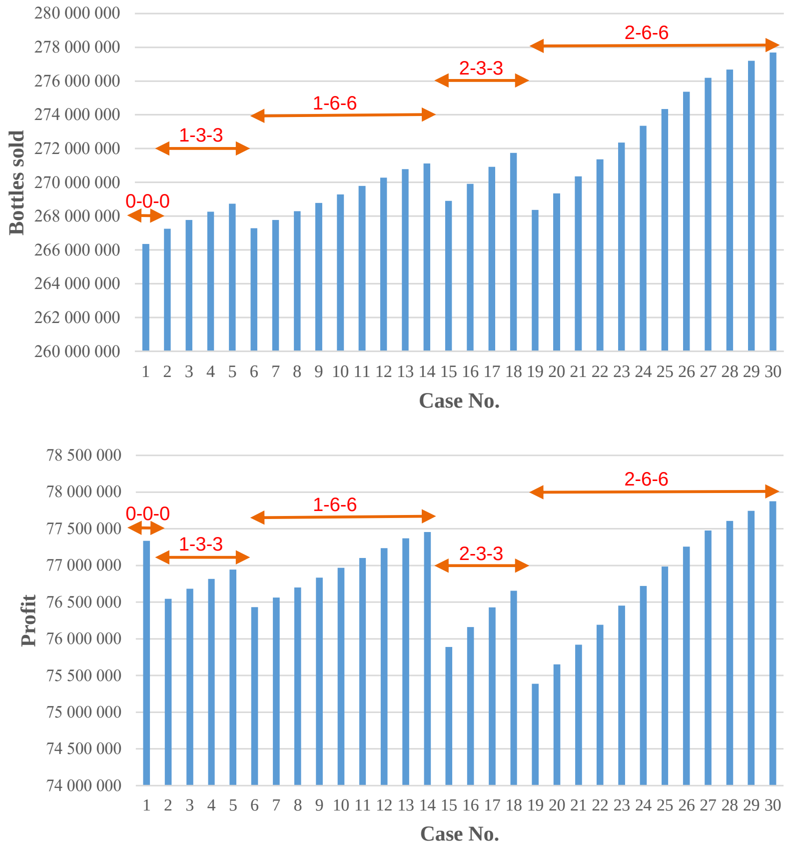

Figure 11. Number of bottles sold and profit (in USD).

Looking at the profit (as efficiency measure), one can see that the inclusion of the additional DCs having initial cost, in most cases resulted in decreased profitability. Generally, this phenomenon is called “the cost of robustness” (Ivanov 2018). However, in the networks with 1-6-6 and 2-6-6 structures, with relatively large inventory policy parameters (Cases 13 and 14, and Cases 27-30, respectively), the profit could even surpass the value yielded by the reference network.

To the service level of a network similar importance can be attached as to its profitability. Considering the 1-year period, the accumulated service level by orders (as robustness measure) increased monotonically set by set, starting with 0.92 (0-0-0, Case 1) and ending with 0.98 (2-6-6, Case 30). As to these two extreme cases, Figure 12 shows the accumulated service levels by orders for the period investigated, assuming the disruption being in March.

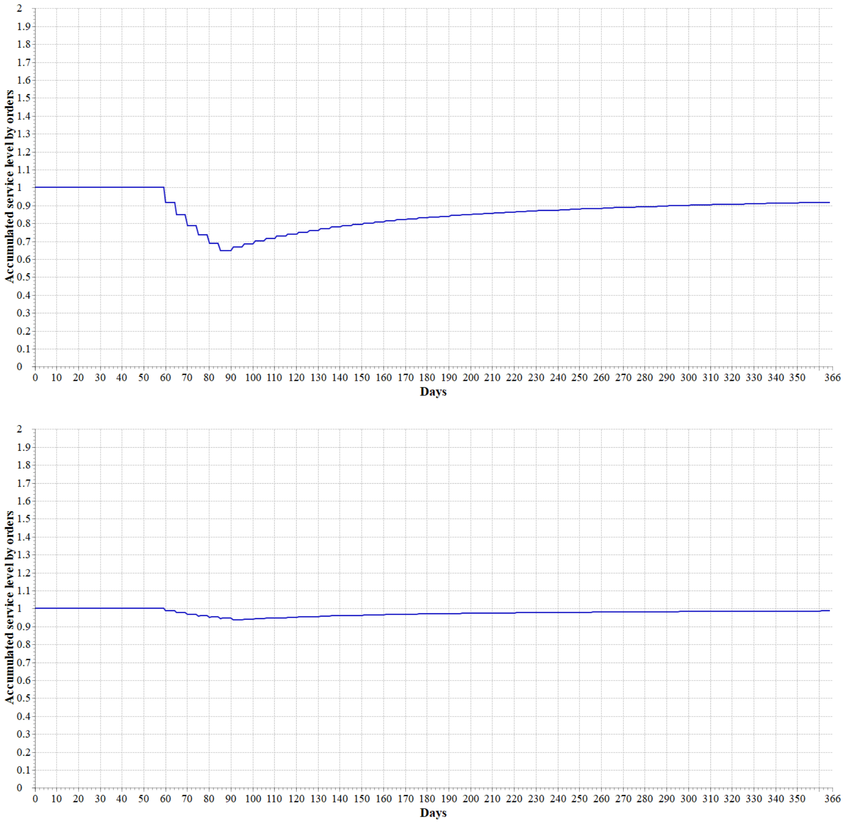

Figure 12. The accumulated service levels by orders for the networks 0-0-0 (upper part) and 2-6-6 (lower part), respectively, the latter with the largest inventory policy parameters considered.

4.4. Interpretation of the results

The disruption considered in the case study lasted for one month at the central DC in Budapest. Throughout that period, no region could be served directly from this DC. Obviously, modifications had to be initiated to alleviate the consequences of the temporary shutdown.

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. For this purpose, 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 (Table 4). 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 (Figure 11 and Figure 12), could count on the management's satisfaction.

4.5. Conclusions

The applicability of the methodology and the framework for the holistic evaluation of supply chains' robustness, complexity and efficiency introduced in Subsection 3.4 was illustrated by the results of the case study, demonstrating how the envisioned *balance between the three aspects can be achieved while mitigating the ripple effect* in distribution networks.

It was shown that *with appropriate changes in both the structural and the operational complexity, the robustness can be significantly enhanced, while slightly decreasing, sometimes maintaining, rarely even increasing the level of profitability*.

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 (Ivanov and Sokolov 2013; Lanza et al. 2019), it has clear *practical relevance* too. The latter may even further increase in the era of natural disasters and pandemics (Monostori 2020). The methodology and the framework can be advantageously used in the (re)design, analysis and management of supply chains, and can be made capable of acting as a digital twin of them.

5. Beyond the profit motive: Environmentally conscious (re)design of supply chain structures

In this section, a novel approach to offer supply chain variants for trade-offs between the economic and the environmental aspects for the management is introduced. Uniquely, the analysis of the structural robustness and complexity of the variants is also part of the approach (Monostori 2020).

5.1. Sustainability of supply chains

As formulated by the World Commission on Environment and Development (WCED) in 1987, *sustainable development* is "a development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (N.N. 1987). While investigating sustainable development or sustainability of any corporate processes, *economic*, *environmental* and *social pillars (dimensions)* are all to be taken into account (Dyllick and Hockerts 2002). As factors in the economic pillar, the profit and other efficiency measures come primarily into the scope. The most frequently mentioned environmental aspects are: carbon footprint, wastes, water and energy usage. As elements of the social dimension, e.g. different employee benefits, such as flexible work scheduling, learning and development opportunities, and healthy working conditions can be mentioned (Dyllick and Hockerts 2002; Seuring 2013).

Sustainable supply chain management refers to the management of the material, information and capital flows, and the cooperation between the companies incorporated in the supply chain, with consideration of the above three pillars of sustainability (Seuring 2013).

5.1.1. Environmental impacts of supply chains

In supply chains, the environmental impact is influenced by a number of actors, e.g. suppliers, manufacturers, consumers, logistics operators, and third parties operating in testing, refurbishing and recycling of the products (Linton, Klassen, and Jayaraman 2007; Quariguasi Frota Neto et al. 2008). Emphasizing the environmental aspects, *green manufacturing*, *green supply chain management* and *green logistics* are usually distinguished, depending on the focus of the investigation (Dekker, Bloemhof, and Mallidis 2012; Hauschild et al. 2014; Jørgensen et al. 2014).

In the past few years, the fight against *climate change* has become one of the most important subjects of international debate. The emission of *greenhouse gases (GHGs)* related to human activities (including, e.g. running of supply chains) was identified as the leading cause of climate change. The Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC) set the goal to reduce GHG emissions on a global scale (N.N. 1997; Scipioni et al. 2010).

5.1.2. Decarbonization of supply chain logistics and its measures

The most visible causer of environmental pollution in supply chains is undoubtedly the *transportation*. About 14% of the total *CO_2 emission* in the world can be attributed to that, moreover, it is a main source of NO_x, SO_2 and PM (particulate matter or fine dust) emissions (Dekker, Bloemhof, and Mallidis 2012). There is a nearly general political consensus that – compared to the pre-industrial level – the increase of the global temperature is to be limited to 2 ºC by 2100, which involves – against the 1990 values – a global reduction in CO_2 emission of 50% by 2050 (McKinnon 2010).

A conceptual framework for measuring and studying environmental impact in supply chains is given in Montoya-Torres, Gutierrez-Franco, and Blanco (2015). Five key parameters that can be addressed at logistics-related carbon-mitigation efforts in freight transportation (which accounts for 80-90% of carbon emissions in logistics) are identified in McKinnon (2010).

Data indicating the energy use (in kWh/t/km) and the emissions of different gases (in g/t/km) can be found for different modes of freight transportation, e.g. in McKinnon (2007); N.N. (2011b); Dekker, Bloemhof, and Mallidis (2012). As an example, the values for heavy trucks are estimated as 0.18 kWh/t/km, and 50 g/t/km, respectively (Dekker, Bloemhof, and Mallidis 2012).

5.1.3. Trade-offs between the dimensions of supply chains' sustainability

By the growing environmental and social awareness of the customers, companies are demanded to consider beyond pure economic goals, issues like environment-friendly production and logistics, and fair labor conditions (Mota et al. 2015).

As an example, – remaining at the main topic of the section – a not negligible number of companies acted proactively and lowered the environmental, e.g. carbon footprint of their processes and products. They succeeded in getting an environment-friendly image, and this way, gained and retained environmentally conscious customers. Moreover, there are companies that even achieved economic benefits from the transformation of their logistics networks to more environment-friendly ones (Quariguasi Frota Neto et al. 2008).

Companies are stimulated by the customers and the legislation to take environmental aspects into account while designing or redesigning their supply chains. An appropriate balance between the economic and the environmental aspects becomes a necessity.

5.2. Incorporation of CO_2 emission reduction into the design and redesign 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 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).

The approach presented here consists of the following steps (Monostori 2020):

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.

5.3. Conclusions

An *approach to achieve trade-offs between the economic and the environmental aspects of supply chains' sustainability* was introduced. 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 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.

6. Achieving trade-offs between the economic and the environmental aspects of supply chains' sustainability

The applicability of the above approach is demonstrated through a case study on a hypothetical, in some respects (e.g. complexity of the product, number of suppliers) relatively simple, five-level supply chain (Monostori 2020). The management's task is 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 (e.g. profit), but also environmental (e.g. transportation-related CO_2 emission) aspects into account. Other KPIs, such as demand fulfillment, are to be considered, too.

6.1. Parameters of the investigated multi-level supply chain with demand estimation

The focal company intends to serve 6 countries in Europe, namely Austria, Czech Republic, Germany, Hungary, Poland and Slovakia, through DCs with a given product (e.g. household appliance). It owns 3 factories and 4 first-tier suppliers that are capable of manufacturing the final "Product" and its two most important components (Part1.1 and Part1.2), respectively. The second-tier suppliers (also 4 in number) are not owned by the company and are able to produce Part2.1 and Part2.2 (see Table 5, for details).

Table 5. Potential delivery connections between the elements of the consecutive levels with the product and components to be transported.

Source	Destination	Product, components
DCs	Customers	Product
Factories	DCs	Product
T1 Bydgoszcz	Factories	Part1.2
T2 Graz	Factories	Part1.2
T3 Szolnok	Factories	Part1.1
T4 Žilina	Factories	Part1.1
S1 Békéscsaba	Tier1s	Part2.1
S2 Debrecen	Tier1s	Part2.2
S3 Grudziądz	Tier1s	Part2.2
S4 Kielce	Tier1s	Part2.1

In the case study, the 6 countries are divided into 25 regions indicated by blue filled circles on the map of Figure 13.

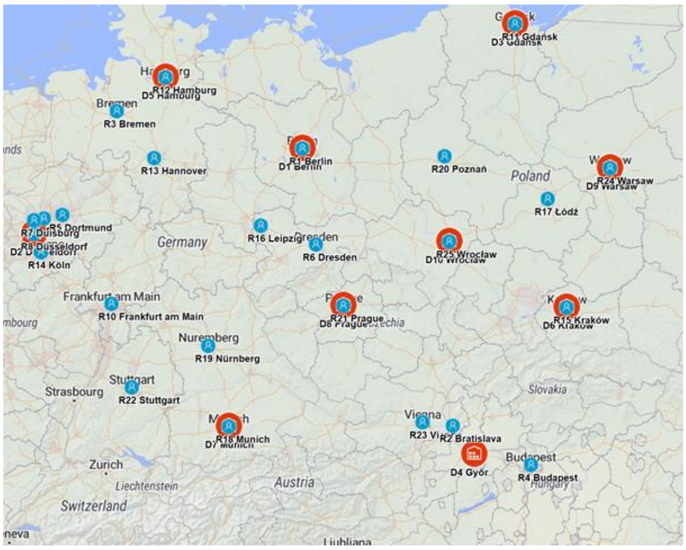

Figure 13. Locations of the 25 regions and the 10 DCs.

Other important parameters of the problem to be addressed here, together with their conceived values are as follows:

- *Product*: household appliance with a selling price of 500 €/pc. (If the specified demand quantity is violated, 300 € penalty is to be paid for each not delivered pc.)
- *Demand*: deterministic, constant over time, proportional to the number of inhabitants in the given regions. Based on the rough estimate for 1000 inhabitants, the total yearly demand for the 25 regions gave 595,899 pcs.
- *Order interval of the regions*: 5 days.
- *Capacities of the DCs, factories, first- and second-tier suppliers*: considered high enough, i.e. they can fulfill the tasks assigned to them.
- *Transportation*: full truckload (FTL) policy, trucks with capacity 40 m^3 and speed 60 km/h, with cost 2 €/km calculated with actual routes (not with straight lines).
- *Transportation-related CO_2 emission*: 1.2 kg/km.
- *Investigated time period*: 1 calendar year.

Table 6 incorporates the bills of materials (BOMs) of the product and of its main components. The production / supply costs and the geometrical volumes of the product and of all the components are also indicated.

Table 6. BOMs, production / supply costs, and volume data.

Product, components	BOM [pc]	Prod. / supply cost [€/pc]	Volume [m^3/pc]
Product	Part1.1: 1, Part1.2: 2	150	0.8
Part1.1	Part2.1: 1, Part2.2: 2	40	0.3
Part1.2	Part2.1: 1, Part2.2: 1	30	0.2
Part2.1	-	5	0.1
Part2.2	-	6	0.05

The cost parameters of the potential DCs are considered to be the same for all of them (Table 7).

Table 7. Cost parameters of the DCs.

DCs	Other cost [€/day]	Inbound proc. cost [€/m^3]	Outbound proc. cost [€/m^3]
All DCs	3,000	2	2

Table 8 and Table 9 incorporate the cost parameters of the factories and the first-tier suppliers, respectively.

Table 8. Cost parameters of the factories.

Factories	Other cost [€/day]	Inbound proc. cost [€/m^3]	Outbound proc. cost [€/m^3]
F1 Chemnitz	4,000	2	2
F2 Linz	4,500	2.5	2.5
F3 Miskolc	3,500	1.5	1.5

Table 9. Cost parameters of the first-tier suppliers.

First-tier suppliers	Other cost [€/day]	Inbound proc. cost [€/m^3]	Outbound proc. cost [€/m^3]
T1 Bydgoszcz	2,000	1	1
T2 Graz	3,000	2.5	2.5
T3 Szolnok	2,500	1.5	1.5
T4 Žilina	2,500	1.5	1.5

6.2. Determination of the geographical locations of the potential distribution centers

In this step, the geographical locations of the potential DCs responsible for fulfilling the demands of the regions are to be determined (GFA). As a usual technique for this task, the CoG method was applied. By using the AnyLogistix supply chain software, the locations of 1, 2, …, 10 DCs were generated, with the requirement that each of them should have at least 100,000 inhabitants. Figure 13 represents the solution for 10 DCs with red filled circles.

As it was expected, by increasing the number of DCs to be determined, the average distance the products travel between the DCs and the regions decreased, especially in the beginning (Figure 14).

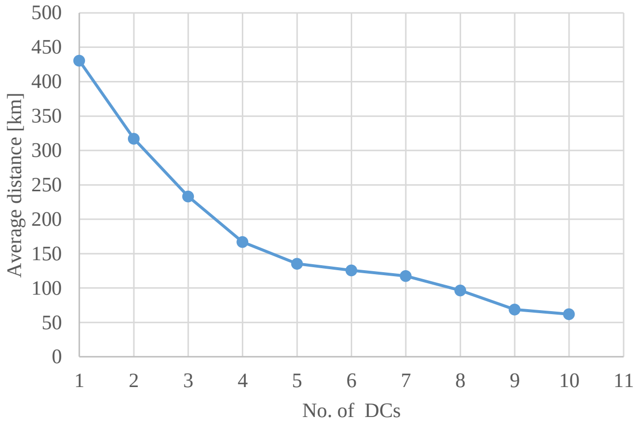

Figure 14. The average distance the products travel between the DCs and the regions as a function of the number of DCs.

However, the CoG method does not take some important factors, e.g. neither the costs of functioning the DCs, nor, naturally, the other levels of the supply chain, into account, so further considerations are needed.

6.3. Profit-oriented optimization of the supply chain structure

The next step is to optimize the whole supply chain by ILP, considering the parameters described in Subsection 6.1. The objective function is the earned profit of the company, which comprises the following terms: revenue, production cost, supply cost, transportation cost, in- and outbound processing costs, other cost, and penalty.

The elements of the different supply chain levels are to be selected from the second- and first-tier suppliers, the factories, and the 10 DCs of Figure 13.

The result of the optimization is a profit of 85.898 M€, with the following supply chain structure: 3 second-tier suppliers (S2 Debrecen, S3 Grudziądz, S4 Kielce), 2 first-tier suppliers (T1 Bydgoszcz, T4 Žilina), 1 factory (F1 Chemnitz), 2 DCs (D1 Berlin, D8 Prague), and the 25 regions. Putting the numbers of the elements in the consecutive levels into a quintuple, starting with the second-tier suppliers, the structure is coded as (3-2-1-2-25).

The achieved result is a relatively lean supply chain structure (Figure 15, Figure 16). The transportation-related CO_2 emission was 17,991 t.

In Figure 15, Figure 16, Figure 21 and Figure 22, the following additional coloring are used: brown for the factories, orange for the first-tier suppliers, and green for the second-tier ones.

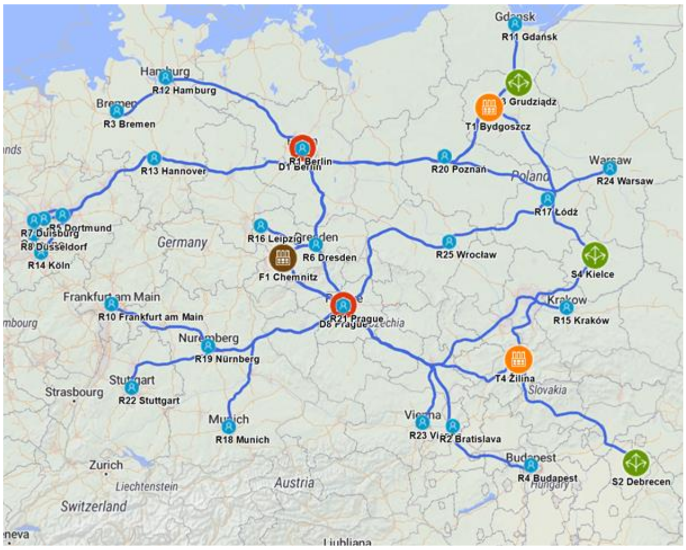

Figure 15. The structure of the supply chain as a result of the profit optimization.

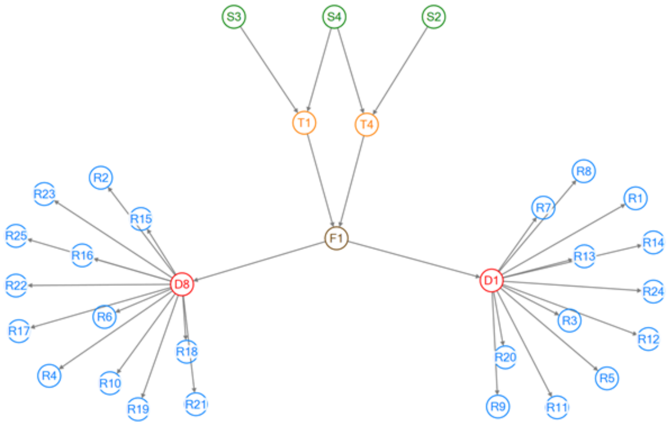

Figure 16. The graph structure of the supply chain as a result of the profit optimization.

6.4. Generation of alternative supply chain structures by minimizing the transportation-related CO_2 emission under different profit constraints

In order to analyze the relation of the profit and the transportation-related CO_2 emission, and this way, to offer a variety of solutions for the management, a series of tests were run, doing constrained optimizations, by setting lower bounds on the profit and taking the CO_2 emission as the objective function to be minimized.

The profit bound was decreased stepwise starting from its optimum value by 2 M€ (by less than 2% of it in each run), in 9 consecutive investigations. With the result of the profit optimization in the previous subsection, altogether 10 cases became available for comparison. Figure 17 and Figure 18 show the main financial indicators.

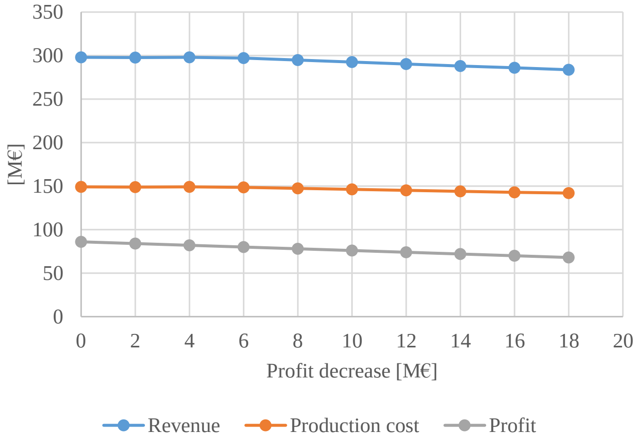

Figure 17. Revenue, production cost and profit as functions of the profit decrease.

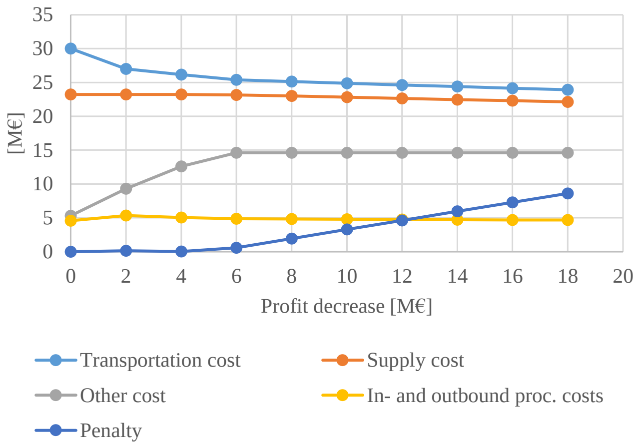

Figure 18. Different cost factors as functions of the profit decrease.

Using the quintuple notation introduced in Subsection 6.3, the following supply chain structures were given in the consecutive cases: (3-2-1-2-25) in the profit optimization case (Case 1), and from Case 2 to Case 4: (2-2-2-4-25), (4-3-3-5-25), and (4-4-3-6-25), respectively. Cases 5-10 resulted in the same structure as Case 4, except that the last structures proved not to be able to serve all the customers under the related profit constraints.

It can be seen in Figure 18 that by the involvement of more elements at the different levels, the other cost increased and the transportation cost decreased gradually, moreover, especially from Case 4 growing penalty occurred, indicating that the goal of CO_2 minimization induced unfulfilled demands.

The above tendencies can be very well followed in Figure 19 and in Figure 20, through the amounts of the transportation-related CO_2 emission decrease, and the values of the demand fulfillment, respectively.

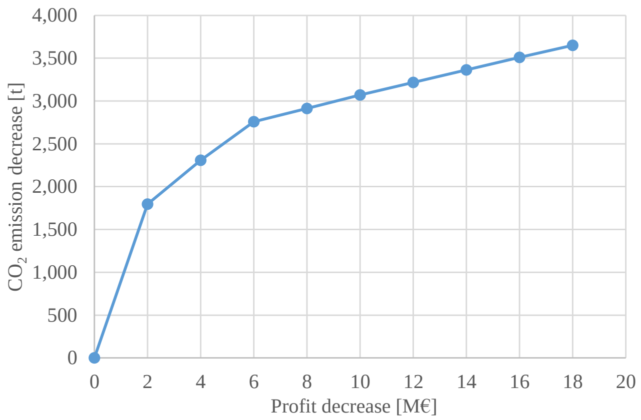

Figure 19. The transportation-related CO_2 emission decrease as a function of the profit decrease.

It is worth to mention that the first 2 M€ decrease in the profit expectation brought 1,795 t, the second further 513 t, and the third one next 451 t decrease in the CO_2 emission (Figure 19).

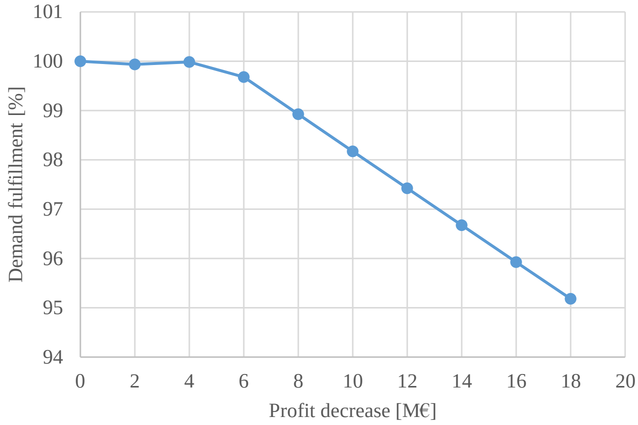

Figure 20. The demand fulfillment as a function of the profit decrease.

Figure 20 clearly shows that from a given point, further decrease of the CO_2 emission could be achieved only through the decrease of the demand fulfillment, and not by the structural expansion of the supply chain.

Figure 17, Figure 18, Figure 19 and Figure 20 present valuable information for the management, i.e. which setting is to be chosen taking the economic, the environmental and the customer satisfaction aspects into account. As a potential candidate, the (4-4-3-6-25) structure of Case 4 is indicated in Figure 21 and Figure 22, which involves all the considered second and first-tier suppliers, factories and 6 from the potential DCs.

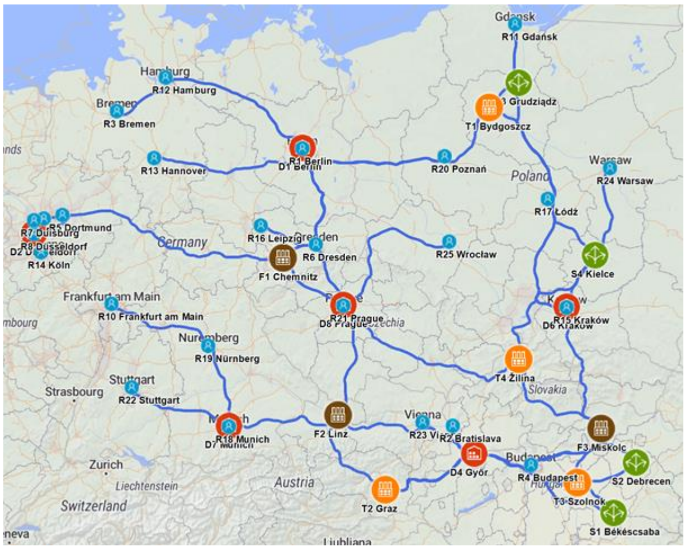

Figure 21. The (4-4-3-6-25) structure of Case 4.

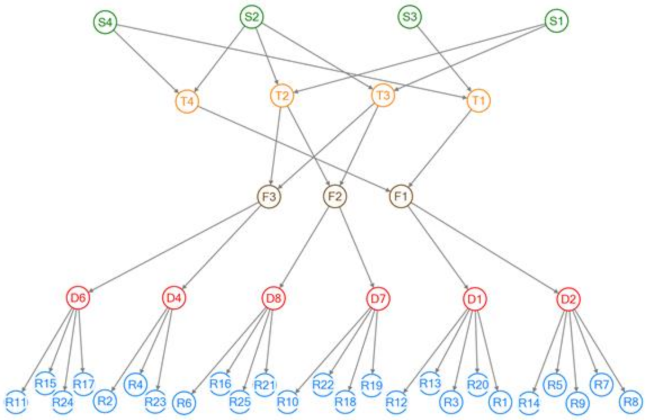

Figure 22. The (4-4-3-6-25) graph structure of Case 4.

6.5. Characterization of the different cases from the viewpoints of structural robustness and complexity

The robustness and the complexity of the different supply chain structures may be of interest to the management. Cases 1-10 of the previous subsections – as results of optimization – can be considered vulnerable, e.g. each region is served by only one DC. A relatively simple solution for increasing the robustness of the structures under investigation is to introduce the opportunity of alternative sourcing between all the consecutive supply chain levels, in order to handle unexpected disruptions.

Similarly to the investigations in Subsections 3.2 and 4.2, 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, were computed for the structures derived here, with the extension of allowing alternative sourcing between the consecutive supply chain levels. The values characterizing the structural robustness and complexity of the different cases indicate that the attempts to minimize the transportation-related CO_2 emission, resulted not only in supply chain structures with shorter distances the products and their components have to be transported, but also in more robust ones with increased structural complexity (Table 10).

Table 10. Values of the structural complexity and robustness measures.

Case	No. of nodes	No. of edges	Average degree	Entropy	Max. of the normalized betweenness centrality	Factor R
Case 1	33	60	1.818	4.203	0.454	0.067
Case 2	35	116	3.314	4.563	0.201	0.114
Case 3	40	161	4.025	4.874	0.149	0.130
Case 4	42	196	4.667	5.029	0.117	0.154

6.6. Conclusions

In the section, the applicability of the approach introduced in Subsection 5.2 for achieving trade-offs between the economic and the environmental aspects of supply chains' sustainability was demonstrated through a case study on a hypothetical multi-level supply chain. 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.

The last point indicates that the intentions to design and manage *more environment-friendly and robust supply chains* are not at all contradictory ones. In the era of environmental problems, and of natural disasters and viral infections endangering global supply chains, it is a positive sign. However, the solely profit-centric thinking in this field is to be changed.

7. Analysis and potential restructuring of the European distribution network of a global manufacturing company

A project with a global manufacturing company provided an opportunity to investigate the applicability of some of the results described in the previous sections in an industrial setting. The company owning a worldwide supply chain had the intention to test whether it could be made more efficient, however, taking the environmental sustainability aspects also into consideration.

The only input which was made available for the investigations was three excel files that had been derived from the company's database. The files incorporated data of a 1-year period, related to the orders from Europe, the Middle East and Africa (EMEA) and their transportation. Each file contained one of the following distinct categories: the direct shipments from Thailand to the EMEA countries, the shipments from Thailand to the company's European logistics center (LC) located in Maarssen, the Netherlands, and finally, the shipments from the LC to the EMEA countries.

The focus of the investigations was put on the logistics realized from the European LC. The following main questions were raised partly at the beginning of the project and partly during its accomplishment:

- Is it appropriate to have only one LC in Europe, and what LC location(s) would be optimal considering the demand with its geographical distribution, and the different cost factors which have influence on the European operation of the company?
- How does the optimal structure of the distribution network depend on the parameters of the cost factors considered?
- What are the consequences of the possible restructuring of the network on the environmental load caused by the transportation?

The main steps of the approach set up were as follows:

1. *Interpretation and analysis of the data* given by the company.
2. *Determination of the potential LCs' locations* (GFA) by the CoG method.
3. *Cost-oriented optimization of the distribution network* by ILP.

4. *Generation of different network structures through cost minimization under various parameters, and their comparisons* concerning:
   - number and locations of LCs,
   - different kinds of costs, and
   - transportation-related CO_2 emission.

Please note that the first three steps above are practically the same as in the approach described in Subsection 5.2.

In the project, the results achieved by using the approach were compared with the baseline situation.

7.1. Specifics of the problem

By filtering and analyzing the data available for the 117,358 shipments realized from the LC, it could be determined that 93.19% of the products (6,883,214 from 7,385,879) were transported by trucks. 19 destination countries were concerned in these shipments.

The demands which were served by trucks were also determined for each of these countries. Germany was found to be the largest market in this sense, with a demand of 2,608,536 products which took 37.9% of the products delivered by trucks from the Maarssen LC.

Mainly because the addresses were included in the related excel file in different ways, sometimes even misprinted, the exact delivery points of the orders within the countries were hard to determine in a reliable way.

The products were computer components and belonged to the same product family. They had various capacities, but similar geometrical dimensions and weights.

Taking the above circumstances into consideration, the following specifications and assumptions were derived:

- Investigations were made on historical data of a 1-year period, related to the deliveries from Maarssen.
- Only truck transportation was considered.
- Countries' yearly demands were aggregated in the capitals.
- Products were considered to be equal.
- 100% service level was aimed to reach.

7.2. Determination of the potential logistics centers' geographical locations

The geographical locations of the potential LCs were determined with the CoG method, by giving different (1, 2, …, 10) values for the number of LCs to be generated, with the requirement that each of the locations should have at least 100,000 inhabitants, similarly to the investigations in Subsection 6.2.

The results of the 10 runs are given in Table 11.

Table 11. The locations of the potential LCs.

No. of LCs	Proposed solutions, GFA
1	Berlin
2	Berlin, Helsinki
3	Berlin, Helsinki, Niš
4	Berlin, Brussels, Helsinki, Niš
5	Amsterdam, Berlin, Bern, Craiova, Helsinki
6	Amsterdam, Berlin, Bern, Craiova, Helsinki, Madrid
7	Amsterdam, Berlin, Bern, Craiova, Helsinki, Madrid, Paris
8	Amsterdam, Berlin, Bern, Craiova, Dublin, Helsinki, Madrid, Paris
9	Amsterdam, Athens, Berlin, Bern, Bucharest, Dublin, Helsinki, Madrid, Paris
10	Amsterdam, Athens, Berlin, Bern, Bucharest, Dublin, Helsinki, Madrid, Paris, Rome

It is no wonder that Berlin – with its proportion of 37.9% in the total demand fulfilled by trucks – came out as the optimal location for a single LC, and it was an element of all the sets of LCs.

The average distances the products travel between the LCs and the capitals are given in Figure 23. The orange line in the diagram shows the average distance the products had to travel from Maarssen to their destinations, namely 891 km in this baseline situation. The

GFA solution with one LC (Berlin) gave 644 km for the average distance, which means a decrease of nearly 28%.

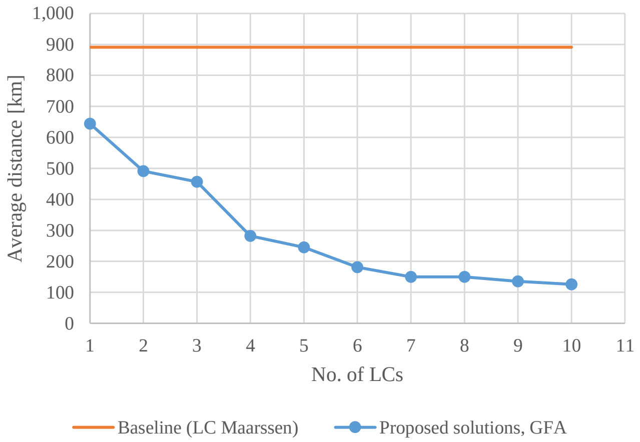

Figure 23. The average distance the products travel between the LCs and the capitals as a function of the number of LCs.

As it was expected, – similarly to the case in Subsection 6.2 (Figure 14) – by increasing the number of LCs to be determined, the average distance the products travel between the LCs and the capitals decreased, especially in the beginning.

To have some idea of the result with 10 generated LCs, the map of Figure 24 illustrates the locations of the 19 capitals and the 10 LCs indicated by blue and red filled circles, respectively.

Figure 24. The 19 capitals and the 10 generated LCs.

However, the CoG method does not take some important factors, e.g. the costs related to the LCs and to the transportation, into account. With the use of additional data, the most appropriate LCs can be selected from the set of 10 LCs, via optimization.

7.3. Cost-oriented optimization of the distribution network

In the optimization process, the following main data – some of them based on assumptions – were used:

- *Products*: computer components with a geometrical volume of 0.005 m^3 in packaged form.
- *Demands*: deterministic, historic, given for the 19 capitals, 6,883,214 pcs in total.
- *Transportation*: FTL policy, trucks with capacity 20 m^3 and speed 70 km/h, with cost 5 USD/km calculated with actual routes (not with straight lines).
- *Transportation-related CO_2 emission*: 1 kg/km.
- *Capacities of the LCs*: considered high enough.
- *Facility cost of the LC in Maarssen*: 8,000 USD/day.
- *Investigated time period*: 1 year.

The facility costs of the 10 potential LCs were estimated by using the gross domestic product (GDP) per capita ratios between the given country and the Netherlands (see Table 12 and Table 13).

Table 12. GDPs per capita in the countries of the potential LC locations.

Potential LC location	Country	GDP per capita, 2019 [€]	Ratio to Netherlands [%]
Amsterdam	Netherlands	41,870	100.00
Athens	Greece	18,150	43.35
Berlin	Germany	35,840	85.60
Bern	Switzerland	59,970	143.23
Bucharest	Romania	9,130	21.81
Dublin	Ireland	60,170	143.71
Helsinki	Finland	37,270	89.01
Madrid	Spain	25,170	60.11
Paris	France	33,270	79.46
Rome	Italy	26,860	64.15

The GDP per capita values in Table 12 were taken from Eurostat (https://ec.europa.eu/eurostat/web/products-datasets/-/sdg_08_10). (The data were downloaded in the second half of 2020. The current values slightly differ from the ones in the table.)

Table 13. Estimated daily facility costs of the potential LCs.

Potential LC location	Facility cost [USD/day]
Amsterdam	8,000
Athens	3,468
Berlin	6,848
Bern	11,458
Bucharest	1,744
Dublin	11,497
Helsinki	7,121
Madrid	4,809
Paris	6,357
Rome	5,132

The cost-oriented optimization showed that with the above data, one LC positioned in Berlin gave the minimum total cost. Compared with the baseline situation, the optimized distribution network resulted in 14.4%, 27.57% and 23.95% decreases in facility cost, transportation cost and total cost, respectively (Table 14). (Please note that the investigated 1-year period incorporated February 29 and therefore had 366 days.)

Table 14. Cost factors in the baseline situation and those given by the optimization.

LC location	Facility cost [USD]	Transportation cost [USD]	Total cost [USD]
Maarssen (baseline)	2,928,000	7,738,362	10,666,362
Berlin (optimization)	2,506,368	5,604,937	8,111,305

The structure of the optimized distribution network is shown in Figure 25.

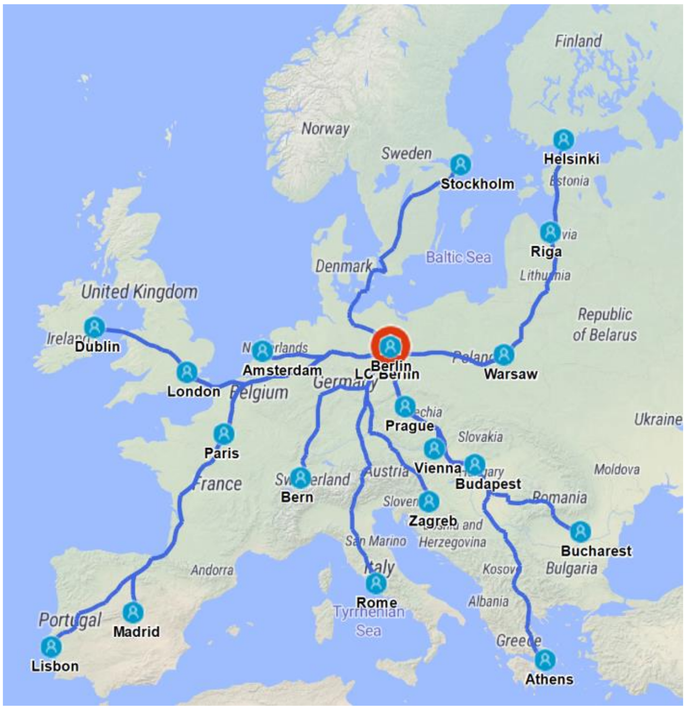

Figure 25. The optimal structure of the distribution network.

7.4. Generation of different network structures through cost minimization under various parameters, and their comparisons

The management was interested in how the parameters of the cost factors influence the optimal structure of the distribution network, the different kinds of costs, and the transportation-related CO_2 emission. Two series of experiments were run by modifying the kilometric transportation cost and the potential LCs' daily facility costs, respectively. (While changing the daily facility costs of the potential LCs', their ratios were kept according to Table 12.) For each pair of kilometric transportation and daily facility cost values, cost-oriented optimization was performed.

The results of the optimizations were always compared with the baseline, i.e. having the original structure with one LC in Maarssen but enforcing the given values of the cost parameters.

In the first series of experiments, the kilometric transportation cost was increased stepwise starting from its original value (5 USD/km) by 2 USD/km, while keeping the daily facility cost constant at the level of 8,000 USD/day in the Netherlands as the basis.

The value pairs of the kilometric transportation cost and the daily facility cost in the Netherlands are enumerated in Table 15, together with the LC locations generated by the cost-oriented optimizations. (The first row refers to the case with the original values of the cost parameters, described in Section 7.3).

Table 15. The optimal LC locations under different kilometric transportation costs and fixed daily facility cost in the Netherlands.

Transportation cost [USD/km]	Facility cost, Netherlands [USD/day]	LCs, optimization
5	8,000	Berlin
7	8,000	Berlin
9	8,000	Berlin, Paris
11	8,000	Berlin, Helsinki, Paris
13	8,000	Berlin, Bucharest, Helsinki, Paris

The influence of the stepwise increase of the kilometric transportation cost on the optimized network structures can be clearly followed in Table 15, namely more and more LCs were involved in the distribution network, decreasing this way the average transportation distance.

Having only one LC in Maarssen (baseline situation), the yearly facility cost – naturally – remained the same, while the yearly transportation and total costs increased linearly with the growing kilometric transportation cost (Figure 26).

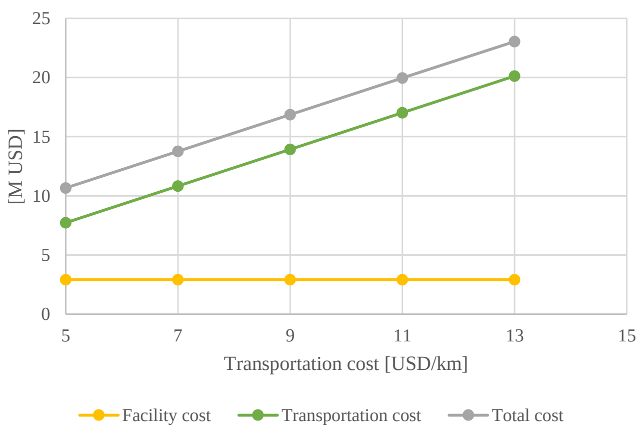

Figure 26. Yearly facility cost, transportation cost and total cost as functions of the kilometric transportation cost, under fixed daily facility costs – baseline cases.

As to the optimized cases (Figure 27), the yearly facility cost increased by the inclusion of additional LCs in the network. In the first two cases, the network had only one LC (in Berlin), consequently, the distances to be traveled remained the same, but because the kilometric transportation cost increased, the yearly transportation cost became higher. However, with the involvement of more and more LCs, the average transportation distance decreased. The effect of this decrease usually could surpass the influence of the increased kilometric transportation cost, and so the yearly transportation cost had a decreasing tendency. The yearly total cost increased monotonically.

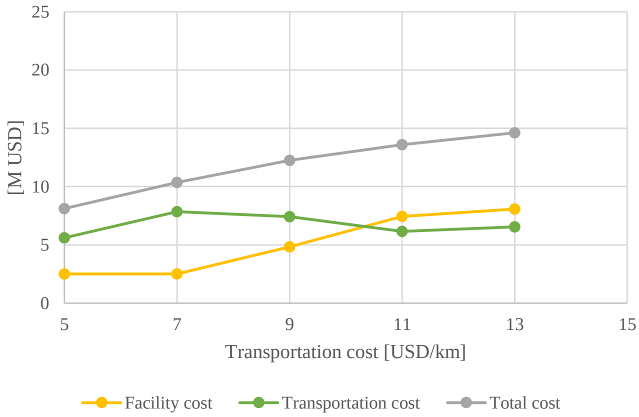

Figure 27. Yearly facility cost, transportation cost and total cost as functions of the kilometric transportation cost, under fixed daily facility costs – optimized cases.

Comparing the yearly total cost values gained by optimization with the baseline ones (Figure 28), it can be seen that the optimized structures clearly outperformed the baseline situation, moreover, the level of the cost reduction increased with the growth of the kilometric transportation cost.

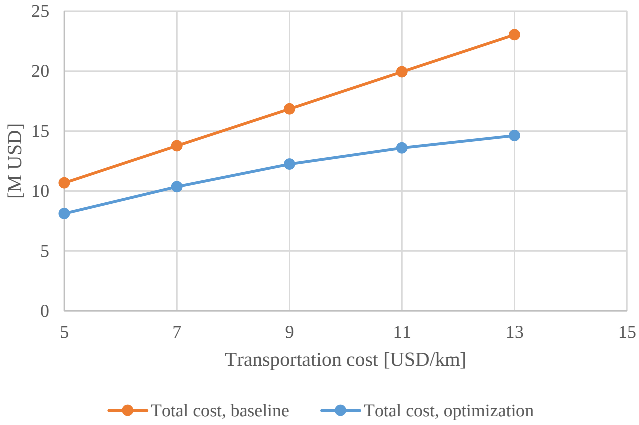

Figure 28. Comparison of the yearly total costs as functions of the kilometric transportation cost, under fixed daily facility costs – baseline cases and optimized cases.

In parallel with this, the cost-oriented optimization brought drastic reductions in the transportation-related CO_2 emission values (Figure 29).

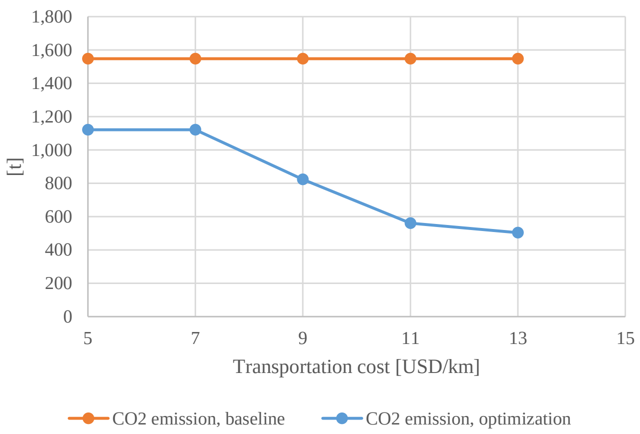

Figure 29. Comparison of the yearly transportation-related CO_2 emissions as functions of the kilometric transportation cost, under fixed daily facility costs – baseline cases and optimized cases.

In the second series of experiments, the daily facility cost in the Netherlands was decreased stepwise by 1,000 USD/day starting from its original value (8,000 USD/day), and the kilometric transportation cost was kept constant at the level of 5 USD/km (Table 16). The table also illustrates that the lowering of the daily facility cost in the Netherlands (and in the same ratio the daily facility costs of the potential LCs in other countries) can make the involvement of additional LCs remunerative.

Table 16. The optimal LC locations under different daily facility costs in the Netherlands and fixed kilometric transportation cost.

Transportation cost [USD/km]	Facility cost, Netherlands [USD/day]	LCs, optimization
5	8,000	Berlin
5	7,000	Berlin
5	6,000	Berlin
5	5,000	Berlin, Paris
5	4,000	Berlin, Helsinki, Paris

In the baseline situation with only one LC (in Maarssen), the yearly transportation cost remained the same (the distances to be covered were constant with unchanged kilometric transportation cost). The yearly facility and total costs decreased linearly with the reduction of the daily facility cost (Figure 30, moving from right to left).

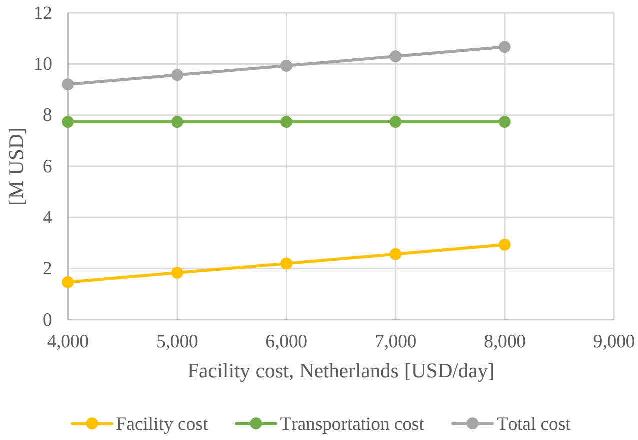

Figure 30. Yearly facility cost, transportation cost and total cost as functions of the daily facility cost in the Netherlands, under fixed kilometric transportation cost – baseline cases.

Regarding the optimized cases (Figure 31), moving in the figure from right to left again, as long as the LC in Berlin was selected alone, the yearly transportation cost kept its starting value. The further reduction of the daily facility costs in the countries led to the involvement of additional LCs. Consequently, the average distance to be traveled decreased significantly and the yearly transportation cost alike. In the beginning, the yearly facility cost decreased, but with the inclusion of new LCs, this trend was broken. A monotonous decrease of the yearly total cost was experienced.

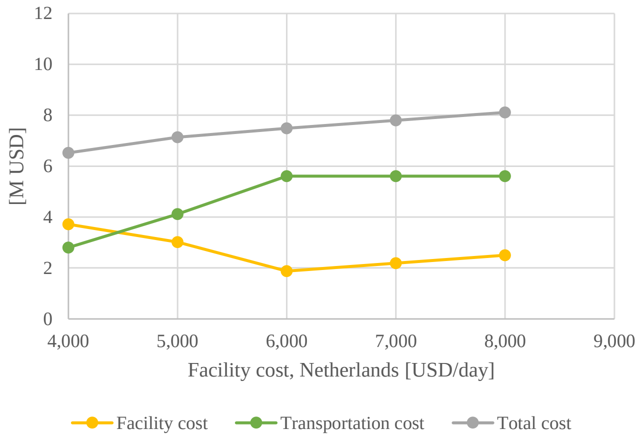

Figure 31. Yearly facility cost, transportation cost and total cost as functions of the daily facility cost in the Netherlands, under fixed kilometric transportation cost – optimized cases.

The comparison of the yearly total cost values given by optimization with the baseline ones can be seen in Figure 32. Moving from right to left again, the total cost in the baseline setting decreased linearly and did nearly linearly in the optimized solutions, with the clear superiority of the latter ones.

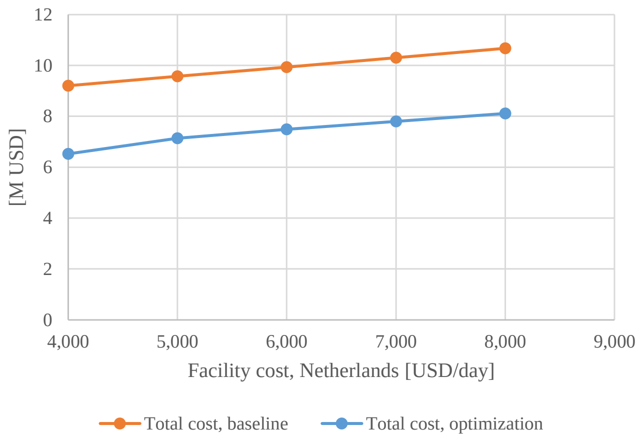

Figure 32. Comparison of the yearly total costs as functions of the daily facility cost in the Netherlands, under fixed kilometric transportation cost – baseline cases and optimized cases.

The optimization brought clear benefits also regarding the transportation-related CO_2 emission (Figure 33). In the optimized solutions, the increase in the number of LCs went hand in hand with the significant reduction of the CO_2 emission.

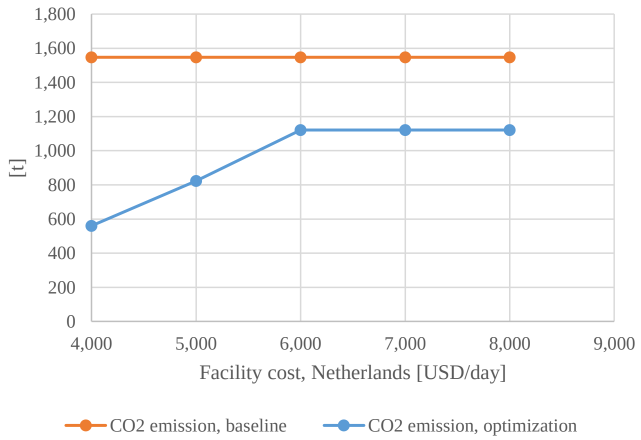

Figure 33. Comparison of the yearly transportation-related CO_2 emissions as functions of the daily facility cost in the Netherlands, under fixed kilometric transportation cost – baseline cases and optimized cases.

As results of the two series of optimization experiments, four different structures came out, with one (Figure 25), two (Figure 34), three (Figure 35) and four (Figure 36) LCs. The figures illustrate these structures including the capitals to be served and the routes of transportation.

The reduction of the average distance to be traveled can also be clearly seen, which has a similar consequence on the transportation-related CO_2 emission.

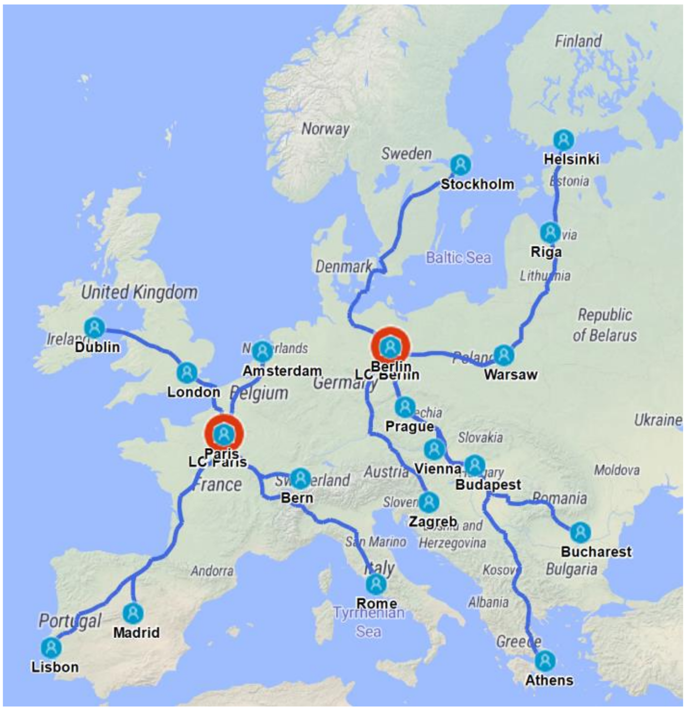

Figure 34. The optimal structure of the distribution network with two LCs (in Berlin and Paris).

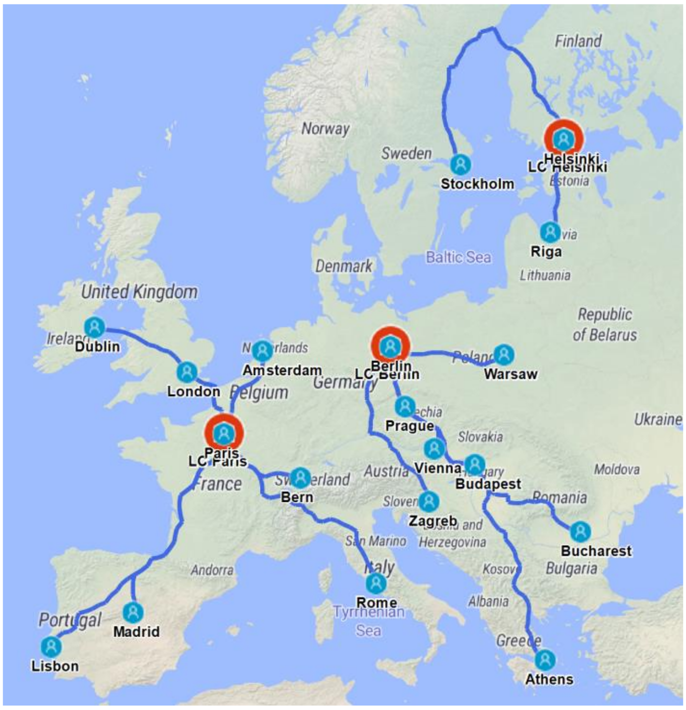

Figure 35. The optimal structure of the distribution network with three LCs
(in Berlin, Helsinki and Paris).

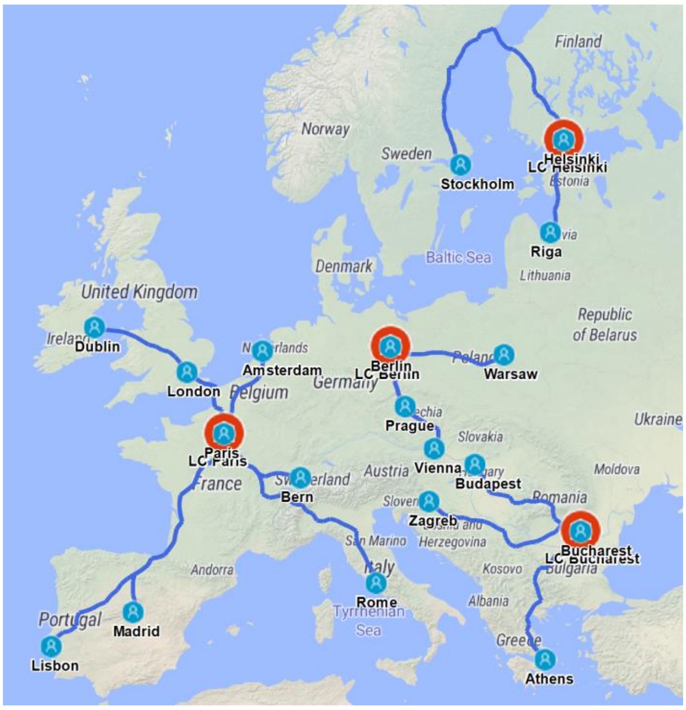

Figure 36. The optimal structure of the distribution network with four LCs
(in Berlin, Bucharest, Helsinki and Paris).

7.5. Conclusions

The project with the global manufacturing company offered a valuable opportunity to test – at least partly – the approach described in Subsection 5.2 in an *industrial setting*. The application of GFA followed by optimization – this case by cost minimization – resulted in a network structure that, according to the available data, proved to be *more efficient than the network run by the company*.

Moreover, the deeper analysis highlighted the dependence of the optimal network structure on the parameters of the cost factors considered. Those results for example, which indicated the benefits of opening more LCs, and this way shortening the average distance the products have to travel in case of higher transportation costs, e.g. fuel prices, gained *special relevance in the energy crisis of our time*.

The results of the investigations, presented to the representatives of the company, gave also important insights into the environmental load caused by the transportation in the different network structures, and can be considered when the management aims at a *more environment-friendly operation* of the distribution network.

The project described in this section satisfied the company and paved the way for *further projects* outside the concrete scope of the dissertation.

8. Summary and outlook

8.1. New scientific results

Thesis 1: Structural robustness and complexity of supply chains

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.

Thesis 2: Structural and operational robustness and complexity, as well as efficiency of supply chains

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.

Thesis 3: Ripple effects in supply chains

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.

Thesis 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. 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.

8.2. 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 (Section 7). It served as a door opener project which was followed by other challenging bilateral ones.

8.3. Outlook

The *COVID-19 pandemic* pointed out some weaknesses of present-day production including the related logistics, see e.g. Monostori and Váncza (2020); Illés and Wagner (2021); Monostori et al. (2021). The statements formulated in the above publications underline the significance of the R&D topics treated in the dissertation.

In addition to the pandemic, the sharpening international tension and economic competition inclined the Subcommittee on Advanced Manufacturing Committee on Technology of the National Science and Technology Council of the United States to update the former Strategy for American Leadership in Advanced Manufacturing (N.N. 2018).

The document entitled *National Strategy for Advanced Manufacturing* was issued in October 2022 (N.N. 2022), with the aim to present "a vision for United States leadership in advanced manufacturing that will grow the economy, create quality jobs, enhance environmental sustainability, address climate change, strengthen supply chains, ensure national security, and improve healthcare".

The following interrelated goals were set to achieve the stated vision:

Goal 1: develop and implement advanced manufacturing technologies,

Goal 2: grow the advanced manufacturing workforce, and

Goal 3: build resilience into manufacturing supply chains.

To achieve these goals, 11 strategic objectives and 37 technical and program recommendations were identified for the next four years. In Table 17 the 3 objectives of Goal 3 and the related 11 recommendations are enumerated:

Table 17. Objectives and recommendations under Goal 3: build resilience into manufacturing supply chains (N.N. 2022).

Objectives	Recommendations
3.1 Enhance supply chain interconnections	3.1.1 Foster coordination within supply chains in supply chain management
	3.1.2 Advance innovation for digital transformation of supply chains
3.2 Expand efforts to reduce manufacturing supply chain vulnerabilities	3.2.1 Trace information and products along supply chains
	3.2.2 Increase visibility into supply chains
	3.2.3 Improve supply chain risk management
	3.2.4 Stimulate supply chain agility
3.3 Strengthen and revitalize advanced manufacturing ecosystems	3.3.1 Promote new business formation and growth
	3.3.2 Support small and medium-sized manufacturers
	3.3.3 Assist technology transition
	3.3.4 Build and strengthen regional manufacturing networks
	3.3.5 Improve public private partnerships

The handling of the problems raised by the COVID-19 pandemic and the achievement of Goal 3 and its objectives can be supported by further digitalization and the use of cyber-physical solutions.

Cyber-physical systems (CPSs) are systems of collaborating computational entities which are in intensive connection with the surrounding physical world and its ongoing processes, providing and using, at the same time, data-accessing and data-processing services available on the internet (N.N. 2011a; N.N. 2012; N.N. 2013).

Today it is generally accepted that the *cyber-physical production systems (CPPSs)*, relying on the latest and foreseeable further developments of computer science (CS), information and communication technology (ICT), and manufacturing science and technology (MST) led to the *4th Industrial Revolution*, frequently noted as *Industry 4.0 (Industrie 4.0)* (Kagermann, Wahlster, and Helbig 2013). CPPSs consist of autonomous and cooperative elements and subsystems that are connected on the contextual basis within and across all levels of production, from processes through machines up to production and logistics networks (Monostori et al. 2016). Three main characteristics of CPPSs are as follows (Monostori et al. 2016):

- *Intelligence (smartness)*: the elements are able to acquire information from their surroundings and act autonomously.
- *Connectedness*: the ability to set up and use connections to the other elements of the system – including human beings – for cooperation and collaboration, and to the knowledge and services available on the internet.
- *Responsiveness* towards internal and external changes.

The concept of Industry 4.0 quickly influenced logistics and supply chain management, and new concepts have been established, i.e. *Logistics 4.0* (Akinlar 2014; Illés, Varga, and Czap 2018; Vida, Illés, and Bányainé-Tóth 2023), and *cyber-physical logistics systems (CPLSs)* (Akinlar 2014; Thoben et al. 2014). "A CPLS is to be understood as a summarization of primary CPSs which carry out logistics tasks. … Logistics tasks deal in particular with the flow of information and goods in the value chain. CPLSs aspire to economic, ecological and social aims" (Thoben et al. 2014).

In the following, some of the main features of CPLSs and the related challenges and opportunities with relevance to the subject of the dissertation are enumerated (Monostori 2018):

- *Internet of things (IoT) and sensor networks*: as a result, better *transparency* can be achieved regarding both the processes within the suppliers (e.g. the readiness level of the orders, the probability and level of the potential late deliveries), and the inter-organizational logistics processes (e.g. the actual geographical position of the transports and their estimated arrival times). The challenge is how to use the available information for decreasing or even eliminating the effects of the potential disruptions and disturbances.

- *Big data and data mining*: the potential is given by the huge amount of data, but the valuable information is usually hidden, consequently, novel *data analytic methods* are to be used (Fajszi, Cser, and Fehér 2010). An important question is how to harmonize the *data-driven approaches* with the use of application-dependent, *domain knowledge*.
- *Smart elements with own intelligence*: the resulted *autonomous logistics systems* can show up emergent behavior, consequently, the present control structures have to be replaced with new solutions which are able to handle the distributed settings. Here novel *standards* for information exchange are of fundamental importance.
- *Coupling of the physical and virtual worlds*: the processes can be mapped in the virtual sphere, where the opportunity for *optimization* arises, on the one hand, by *looking into the future*, i.e. by investigating the consequences of the actual decisions, and, on the other hand, by *learning from the past* based on the stored information. The concept of *digital twins*, or *digital shadows* can play a significant role in the operation of supply chains and the related logistics processes. However, the importance of the *tight coupling*, i.e. the frequent synchronization of the two worlds is a prerequisite for the successful functioning.

Among the other challenges and opportunities, the realization of more comprehensive supplier management and evaluation, the changing role of the human beings in the complex process of supply chain operation (Wang et al. 2019; Koltai et al. 2021; Korkulu, Bóna, and Péter 2021), the potential of a greener logistics, and of novel transportation systems with partially or totally autonomous vehicles can be mentioned first.

As a summary, it can be expected that the cyber-physical solutions – through the quicker and more reliable recognition of the potential external and internal disruptions and disturbances, and through the minimization or avoidance of their negative consequences – will significantly contribute to the better transparency and to the more robust functioning of supply chains. In the cyber-physical era, the complexity of production and logistics systems will increase in parallel with the opportunity for realizing more robust systems (Monostori 2018).

Consequently, *the investigation of the interrelationships of robustness, complexity and efficiency in the field of supply chains will prospectively gain even higher importance in the future*.

9. Acknowledgements

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11. Appendices

11.1. List of figures

11.2. List of tables

11.3. List of symbols

$BC(v)$: Betweenness centrality of vertex v

$BC'(v)$: Normalized betweenness centrality of vertex v

$BCE(e)$: Edge betweenness centrality of edge e

$deg(v)$: Degree of vertex v

H_{graph}: Entropy of the graph

m: Size of the graph

n: Order of the graph

R: Factor R

V: Set of all vertices in the graph

σ_{uw}: Number of the shortest paths between vertices u and w

$\sigma_{uw}(e)$: Number of the shortest paths between vertices u and w, which incorporate edge e

$\sigma_{uw}(v)$: Number of the shortest paths between vertices u and w, which incorporate vertex v

11.4. List of abbreviations

BMS: Biological Manufacturing System

BOM: Bill of Materials

CAS: Complex Adaptive System

CoG: Center of Gravity

CPLS: Cyber-Physical Logistics System

CPPS: Cyber-Physical Production System

CPS: Cyber-Physical System

CS: Computer Science

DC: Distribution Center

ELT: Expected Lead Time

EMEA: Europe, the Middle East and Africa

FTL: Full Truckload

GDP: Gross Domestic Product

GFA: Greenfield Analysis

GHG: Greenhouse Gas

HMS: Holonic Manufacturing System

HSP90: Heat Shock Protein 90

ICT: Information and Communication Technology

ILP: Integer Linear Programming

IoT: Internet of Things

KPI: Key Performance Indicator

LC: Logistics Center

LTL: Less than Truckload

MILP: Mixed Integer Linear Programming

MST: Manufacturing Science and Technology

OEM: Original Equipment Manufacturer

RLR: Randomized Local Rewiring

SCVI: Supply Chain Vulnerability Index

UNFCCC: United Nations Framework Convention on Climate Change

WCED: World Commission on Environment and Development