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

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Abstract

Environmental sustainability is considered as one of the most important 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 (SCs) as well. The paper introduces an approach to achieve trade-offs between the economic (e.g. profit) and the environmental (e.g. CO_2 emission) aspects of SCs' sustainability. Its applicability is demonstrated on a hypothetical multi-level SC, showing how relatively minor relaxations of the expected profit can lead to SC structures not only with reduced transportation-related CO_2 emission, but also with increased structural robustness and complexity.

Keywords: Supply chains; Sustainability; CO_2 emission; Profitability; Robustness; Complexity

1. Introduction

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 [1] 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. The aim of the paper is to underline the importance of getting rid of the solely profit-centric thinking in the process of (re)designing SCs. A novel approach to offer SC variants for trade-offs between the economic and the environmental aspects for the management is introduced. Uniquely, the structural robustness and complexity of the variants are also analyzed.

Concentrating on SCs' sustainability, related concepts are summarized in Section 2, emphasizing the significance of striving for trade-offs between the different sustainability dimensions of the field. Section 3 outlines some previous attempts, in short, to incorporate CO_2 emission reduction into the (re)design of SCs, and describes the main steps of the proposed approach. Its applicability is illustrated in Sections 4 and 5 on a hypothetical multi-level SC, 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 SC structures possess increased structural robustness and complexity.

2. Sustainability of SCs

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" [2]. While investigating sustainable development or sustainability of any corporate processes, *economic*,

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environmental and *social pillars (dimensions)* are all to be taken into account [3]. 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 [3,4].

Sustainable SC management refers to the management of the material, information and capital flows, and the cooperation between the companies incorporated in the SC, with consideration of the above three pillars of sustainability [4].

2.1. Environmental impacts of SCs

In SCs, 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 [5,6]. Emphasizing the environmental aspects, *green manufacturing*, *green SC management* and *green logistics* are usually distinguished, depending on the focus of the investigation [7,8,9].

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 SCs) 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 [10,11].

2.2. Decarbonization of SC logistics and its measures

The most visible causer of environmental pollution in SCs 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 [9]. 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 [12].

A conceptual framework for measuring and studying environmental impact in SCs is given in [13]. 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 [12].

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 [14,15,9]. As an example, the values for heavy trucks are estimated as 0.18 kWh/t/km, and 50 g/t/km, respectively [9].

2.3. Trade-offs between the dimensions of SCs' 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 [16].

As an example, – remaining at the main topic of the paper – 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 [6].

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

3. Incorporation of CO_2 emission reduction into the design and redesign of SCs

Modeling approaches for sustainable SC management are reviewed in [4]. 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) applications of the analytical hierarchy process. It is underlined that the environmental aspects dominate the social ones, and the cost minimization is the most frequently considered element of the economic dimension.

A mixed-integer programming mathematical model for determining the locations of distribution centers (DCs) in green SCs is given in [17]. The impacts of the crude oil price on the transportation mode options and on the DC locations are also investigated.

In [18], cooperative game theory is used for allocation of transportation cost and CO_2 emission in pooled SCs given by the horizontal cooperation among several independent SCs 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 the target of CO_2 emission reduction [19].

The approach presented in the paper consists of the following steps:

1. Estimation of the demand and its geographical distribution for the product(s) within the area to be served by the SC.
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 SC structure by mixed-integer linear programming (MILP).
4. Generation of alternative SC 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.

4. Achieving trade-offs between the economic and the environmental aspects of SCs' sustainability – A multi-level supply chain case study

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 SC. The management's task is to design the SC (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 key performance indicators (KPIs), such as demand fulfillment, are to be considered, too.

4.1. Parameters of the case study 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 1, for details).

Table 1. 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 Fig. 1.

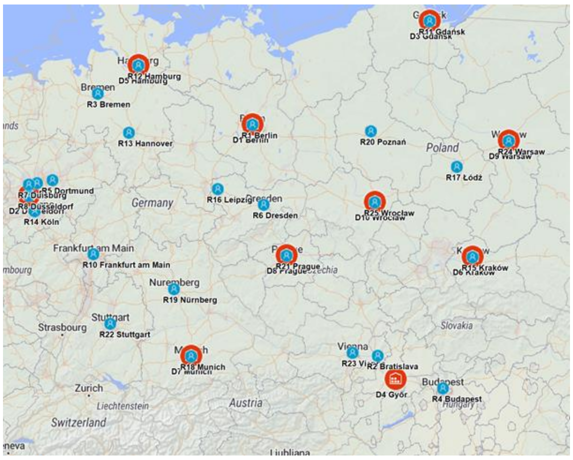

Fig. 1. Locations of the 25 regions and the 10 DCs.

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 2 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 2. 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 3).

Table 3. 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

Tables 4 and 5 incorporate the cost parameters of the factories and the first-tier suppliers, respectively.

Table 4. 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 5. 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

4.2. Determination of the geographical locations of the potential DCs

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 SC software, the locations of 1, 2, …, 10 DCs were generated, with the requirement that each of them should have at least 100,000 inhabitants. Fig. 1 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 (Fig. 2).

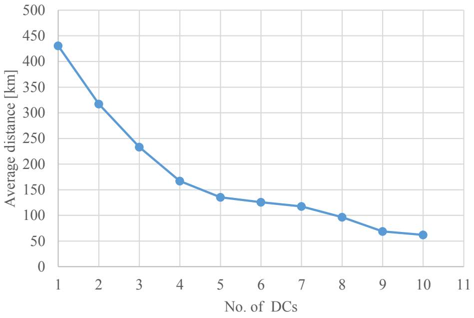

Fig. 2. The average distance the products travel between the DCs and the regions as a function of the number of DCs.

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 SC, into account, so further considerations are needed.

4.3. Profit-oriented optimization of the SC structure

The next step is to optimize the whole SC by MILP, considering the parameters described in Subsection 4.1. 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 SC levels are to be selected from the second- and first-tier suppliers, the factories, and the 10 DCs of Fig. 1.

The result of the optimization is a profit of 85.898 M€, with the following SC 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 SC structure (Figs. 3-4). The transportation-related CO_2 emission was 17,991 t.

In Figs. 3, 4, 9 and 10, the following additional coloring are used: brown for the factories, orange for the first-tier suppliers, and green for the second-tier ones.

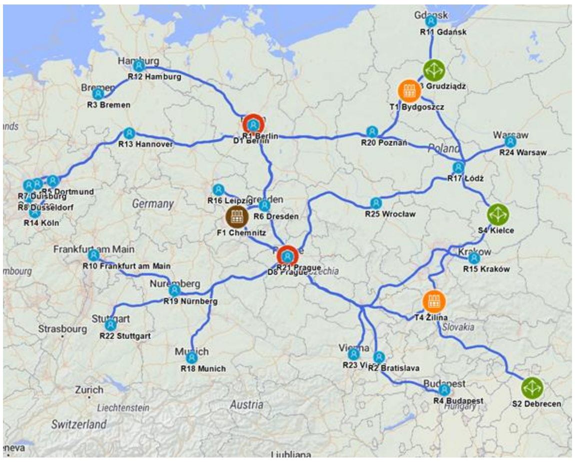

Fig. 3. The structure of the SC as a result of the profit optimization.

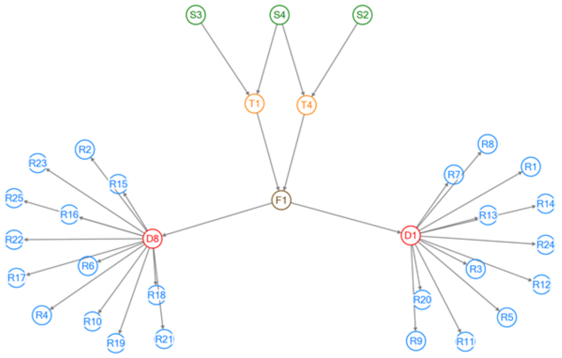

Fig. 4. The graph structure of the SC as a result of the profit optimization.

4.4. Generation of alternative SC 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. Figs. 5 and 6 show the main financial indicators.

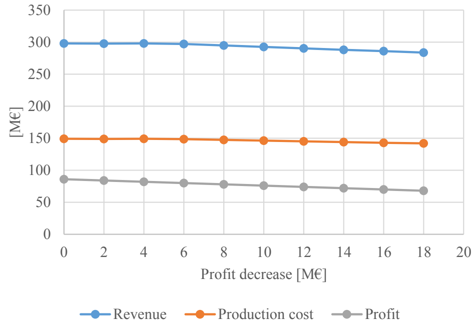

Fig. 5. Revenue, production cost and profit as functions of the profit decrease.

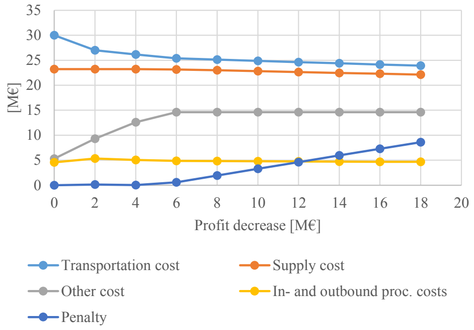

Fig. 6. Different cost factors as functions of the profit decrease.

Using the quintuple notation introduced in Subsection 4.3, the following SC 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 Fig. 6 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 Fig. 7 and in Fig. 8, through the amounts of the transportation-related CO_2 emission decrease, and the values of the demand fulfillment, respectively.

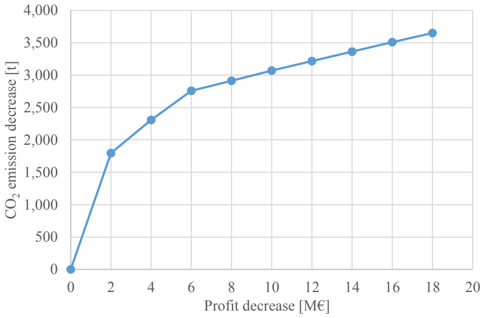

Fig. 7. The transportation-related CO_2 emission decrease as a function of the profit decrease.

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 (Fig. 7).

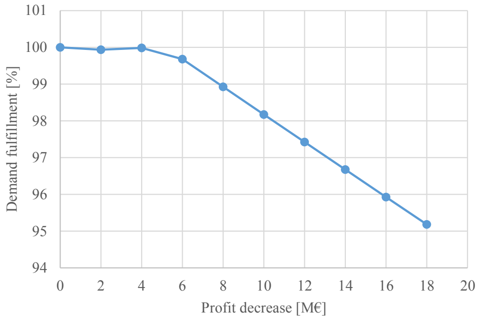

Fig. 8. The demand fulfillment as a function of the profit decrease.

Fig. 8 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 SC.

Figs. 5-8 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 Figs. 9-10, which involves all the considered second and first-tier suppliers, factories and 6 from the potential DCs.

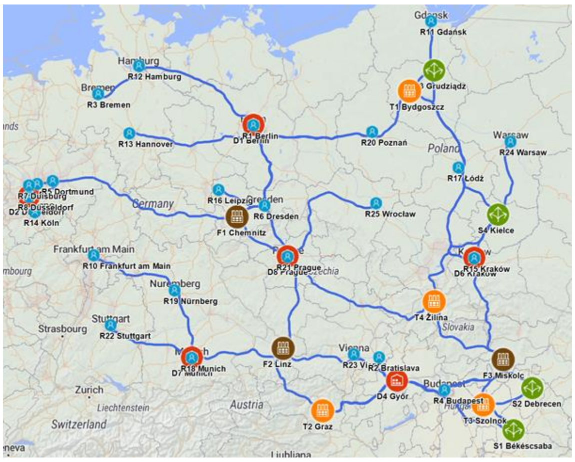

Fig. 9. The (4-4-3-6-25) structure of Case 4.

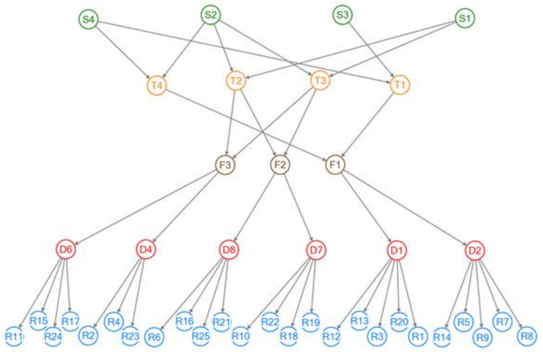

Fig. 10. The (4-4-3-6-25) graph structure of Case 4.

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

The robustness and the complexity of the different SC structures may be of interest to the management. Cases 1-10 of the previous section – 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 SC levels, in order to handle unexpected disruptions.

In an earlier publication of the author, quantitative graph measures were introduced, and their applicability for characterizing the structural robustness and complexity of supply chains and networks was illustrated [20]. Later, measures of operational robustness were also described, and a framework for evaluating SCs' robustness, complexity – both from structural and operational views – and efficiency was elaborated [21].

The following structural complexity measures of SCs were applied: the *order of the graph* (the number of the vertices / nodes), the *size of the graph* (the number of the edges), the *vertex degree* (the number of edges incident to the given vertex), and the *graph's entropy*. For characterizing SCs' structural robustness, the *factor R*, and the *vertex betweenness centrality* (the latter as a measure of the graph's vulnerability at the given vertex, which is opposite to the robustness) were determined. (For more details, see [20,21].)

The above measures were now computed for the structures derived in Section 4, with the extension of allowing alternative sourcing between the consecutive SC 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 SC structures with shorter distances the products and their components have to be transported, but also in more robust ones with increased structural complexity (Table 6).

Table 6. Values of the structural complexity and robustness measures.

Case	No. of nodes	No. of edges	Avg. degree	Entr.	Max. of norm. betw. c.	Fact. R
Case 1	33	60	1.818	4.203	0.454	2.212
Case 2	35	116	3.314	4.563	0.201	4.000
Case 3	40	161	4.025	4.874	0.149	5.200
Case 4	42	196	4.667	5.029	0.117	6.476

6. Conclusions

In the paper, an approach to achieve trade-offs between the economic and the environmental aspects of SCs' sustainability was introduced, and its applicability was illustrated through a case study on a hypothetical multi-level SC. As an economic parameter, the profit earned in the SC was considered, while as an environmental one of high importance, the transportation-related CO_2 emission was involved in the investigations.

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 SC 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 SC 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 SC managers, which can be advantageously used in their SC design and redesign activities.

The investigations showed 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 distances* the products and their components have to be transported (as a result, *relocation* of some suppliers nearer to the factories or even of some factories nearer to the customers may be justified, also as a consequence of CO_2 minimization), but also with the *increase of the structural robustness and complexity* of the resulted SC structures.

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

7. Acknowledgements

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