Identification of Key Supply Chain Elements from the Supply Chain Resilience Viewpoint Using the Computer Simulation and Design of Experiments

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Abstract. Today's supply chains must face a wide spectrum of factors causing their disruption. The concept of supply chain resilience is response to this situation. Utilization of suitable decision support techniques is necessary to manage the supply chain resilience effectively. One of the key question in supply chain resilience management is to find such combination of investments to increasing the resilience of single supply chain elements to obtain maximal financial benefit for the whole supply chain. The aim of this article is to find an approach for identification of such supply chain elements, which are the most important for resilience of researched supply chain. The paper analyze possibilities of using computer simulation and design of experiments techniques for reaching the aim. Suitability of these techniques is confirmed on the supply chain model, which was created for that purpose.

Keywords: Supply chain resilience · Computer simulation · Design of experiments

1 Introduction

Today's supply chains must face a wide spectrum of factors causing their disruption. According to the World Economic Forum (WEF) [1], the major ones include: natural disasters, extreme weather changes, conflicts and political troubles, terrorism and sudden radical changes of demand. The concept of supply chain resilience is response to this situation.

The supply chain resilience is defined as follows - it is: (1) the ability of a system (supply chain) to return to its original state or move to a new, more desirable state after being disturbed [2], (2) the ability to bounce back from large-scale disruptions [3], (3) being better positioned than competitors to deal with – and even gain advantage from - disruptions [4], (4) the ability to maintain output close to potential in the

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aftermath of shocks [5]. The main idea of these definitions is to create such a supply chain that is not vulnerable to serious disruptions.

According to kinds of disruptions identified by WEF and mentioned resilience definitions, authors of the article define the supply chain resilience as the ability of a supply chain to return to its original state in case of its serious disruptions.

Utilization of suitable decision support techniques is necessary to manage the supply chain resilience effectively. One of the key question in supply chain resilience management is to find such combination of investments to increasing the resilience of single supply chain elements (subjects or groups of subjects) to obtain maximal financial benefit for the whole supply chain. Trade-off between investments and benefits resulting from increasing the supply chain resilience is investigated.

The aim of this article is to find an approach (using suitable quantitative techniques) for identification of such supply chain elements, which are the most important for resilience of researched supply chain. Even relatively small investments to these elements ensure relatively high benefits for the whole supply chain.

2 Methodological Basis

Computer simulation and Design of experiments were used as a methodological basis for reaching the research aim.

2.1 Computer Simulation and Its Utilization in Supply Chain Management

The computer simulation is defined as a numerical technique used to simulate a real system by means of an experimental model, with dynamical processes ongoing within the system factored in, in order to identify the behavior and effect thereof on the system operation [6].

The selection of computer simulation as a useful tool for an analysis of the supply chain resilience is motivated by its successful application in the sphere of simulation of supply chain management [7, 8, 9]. There is only a limited number of research works dealing directly with the computer simulation of resilient supply chains. On the basis of a critical evaluation of these studies, authors can say that the utilization of computer simulation in modelling of supply chain resilience is still in the initial research state [10] and developed own computer simulation-based model to eliminate the identified shortcomings [11]. The model will be described in the experimental part of the article.

2.2 Design of Experiments and Its Utilization in Computer Simulation

Design of experiments (DOE) refers to the process of planning, designing and analyzing the experiments so that valid and objective conclusions can be drawn effectively and efficiently. In order to draw statistically sound conclusions from the experiment, it is necessary to integrate simple and powerful statistical methods into the experimental design methodology. This indicates that there are two aspects to any experimental problem: the design of the experiment and the statistical analysis of the data. These two subjects are closely related because the method of analysis depends directly on the design employed. DOE methods have three basic principles, namely randomization, replication and blocking, which can be utilized in the experiments to improve the efficiency of experimentation and reduce or even remove experimental bias. [12, 13].

Basically, there are three main types of problems to which DOE is applicable. The first type is screening. Screening is used to identify the most influential factors, and to determine the ranges in which these should be investigated. The second type is optimization, which aims to find out the combination of important factor resulting in optimal operating conditions. The third type is robustness testing, which examining sensitivity. All of these types are used in the industrial practice to improve products and processes. [14].

One of the important areas where the DOE is used is a computer simulation. Systematized DOE can be used for improvement of understanding and utilization of computer simulation experiments. It is increasing the transparency of simulation model behavior and the effectiveness of reporting simulation results. Lorscheid et al. propose a systematic procedure for applying DOE principles for a more standardized computer simulation research process [15].

3 Experimental Work

Experimental work was divided into five steps: (1) Mental model preparation, (2) Computer simulation model construction, (3) Determination of supply chain performance, (4) Design of experiments, and (5) Key supply chain elements identification.

3.1 Mental Model Preparation

The model was created on the basis of a supply chain from automotive industry because [11]: (1) the automotive industry is central to Europe's prosperity, (2) the automotive industry is a representative of global supply chains (worldwide), which contains all kind of elements from supplier of steel materials and other components trough manufacturing plants to distribution network, (3) these supply chains are affected by all major disruptions defined by the WEF, (4) the automotive industry is the leader in supply chain management.

To verify the computer simulation and the design of experiments are suitable techniques for identification of the most important supply chain elements from the resilience viewpoint, the model was designed in such way, the key elements to be obvious prior to the techniques utilization. If the results from application of the computer simulation and the design of experiments meet presumed outputs, the selected approach can be considered as right.

Structure and relations among single elements of the modelled supply chain are given in Appendix 1.A. Each element represents group of companies in the entire region, because a crucial disruption affects not only one company, but the whole region.

Regions 1 and 2 contain suppliers and logistics service providers (LSP) from larger distances. Therefore, their deliveries are consolidated in a cross-docking center in the region 4 and sent to production plants in the region 5 through a LSP. Suppliers from the region 3 deliver to a relatively short distance, again through LSPs. Suppliers from the region 4 are situated close to production plants. Producers are active on two markets. Market 1 is a part of the more distant region 6, which is supplied by an importer. Market 2 represents customers situated relatively close to the production plants.

The model is balanced as far as its capacity. Sum of the suppliers' capacity is equal to the producers' capacity and the total market demand. This capacity is lowered by occurrence of significant disruptions, i.e. there is lowering the supply chain performance and incomes.

The model uses JIT supply chain strategy. The individual links in the supply chain can be arranged in a series or in a parallel form. A disruption of a link in the series part of the supply chain will reduce the performance of this whole part.

To have presumed outputs for verification of the selected approach, the model assumes:

- Disrupted are all supply chain elements.
- Impact of any disruption on each element is identical (disruption parameters are set at each element in the same way).
- There is such solution for each element, which is able to eliminate any impact of disruptions completely.
- Investments for elimination or lowering the disruptions' impacts are for each element identical too.
- Suppliers' capacities in various regions are the same, similarly the capacities of PLSs in the region 5 and of both markets.
- Shutdown of suppliers from one region doesn't mean a total stopping of the production plants, but only reducing their production to the capacity of the suppliers from remaining regions.

With respect to these assumptions, the key elements are predetermined by the supply chain structure. The most crucial element from the resilience viewpoint are production plants, which process all material flows. As next key elements can be seen elements from region 4 and elements, which are situated after the producers.

3.2 Computer Simulation Model Construction

Simulation model in software DOSIMIS-3® (dynamic, stochastic, and discrete event simulation tool) was created on the basis of the mental model (see Appendix 1.B).

The whole capacity of the supply chain is 500 000 tons per year. The simulation step is one week and the simulated period is 20 years. The capacity of the elements and the performance of the whole chain are measured in tons per week.

Disruption parameters of each supply chain element (parameters were selected on the basis of [16]) are as follows: (1) disruption periodicity (time interval between disruptions) varies from 1 to 3 years according to uniform distribution, (2) disruption time period (time interval between disruption beginning and capacity recovery) varies from 30 to 90 days according to uniform distribution, (3) disruption capacity loss (the number of tons lost at the outset of the disruption) is assumed in the amount of 100 % (total capacity loss), (4) disruption profile (the shape of the disruption capacity loss from beginning to end) is represented in Fig. 1.

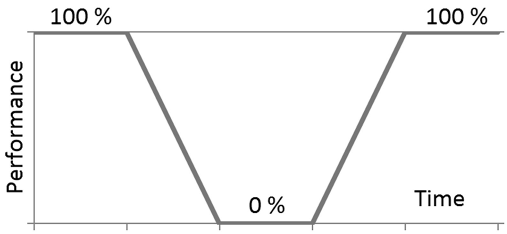

Fig. 1. Used disruption profile.

The model uses the loss of unrealized production caused by a disruption as a supply chain performance measure. This loss is represented by unsold tons per 20 years. A disruption in any element evokes stopping or strong limiting the other supply chain elements. To demonstrate it, an example of the whole supply chain performance fluctuation in simulated period is given in Fig. 2.

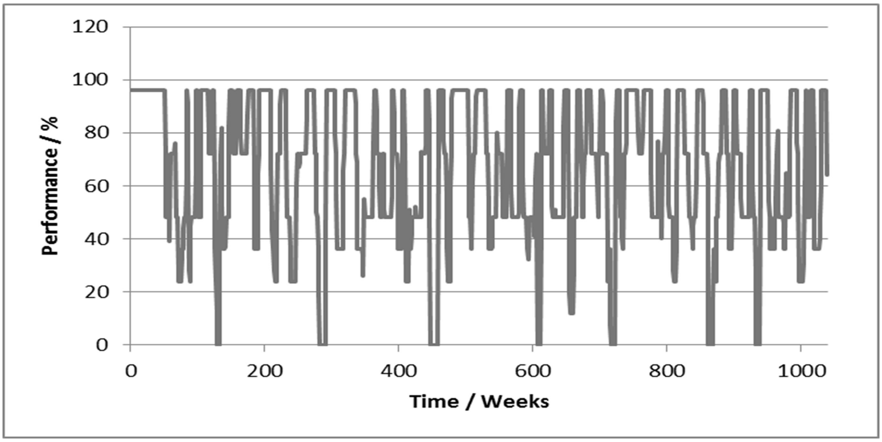

Fig. 2. Supply chain performance fluctuation in one simulation run [17].

3.3 Determination of Supply Chain Performance

Average supply chain performance for defined above assumptions is the main input value for identification of the key supply chain elements. The value was determined as average from 30 simulation runs and it is app. 6.7 million tons per 20 years. It means only app. 67 % performance of the supply chain in comparison with its theoretical capacity (without occurrence of any disruptions) of 10 million tons per 20 years.

3.4 Design of Experiments

To determine simulation experiments, which make identification of the key supply chain elements possible, fractional factorial design 2^7 were used with coding as follows:

1. Code −1: the given supply chain element is exposed to disruption with periodicity from 1 to 3 years according to uniform distribution and time period from 30 to 90 days according to uniform distribution. Investment to elimination of the disruption impact in this element is zero.
2. Code 1: the given supply chain element isn't disrupted at all, i.e. the disruption periodicity is set on a value higher than 20 years. Investment of 20 billion MU is expected to eliminate any disruption.

Software Minitab was used to generate 128 experiments. All experiments were conducted using simulation model created in DOSIMIS-3®. Overall benefit from investments to supply chain element resilience was calculated for each experiment according the following formula:

$$B_i = m(Q_i - Q_a) - \sum\nolimits_{j=1}^{k} I_{ij} \quad \text{for } i = 1, 2, \ldots, n \tag{1}$$

B_i – overall benefit from investments to supply chain element resilience in case of i-th experiment (MU per 20 years)
M – unit margin of the supply chain products (sum of margins from single supply chain elements) = 90 000 MU per ton
Q_i – quantity of the sold supply chain final products in case of i-th experiment (tons per 20 years)
Q_a – average supply chain performance (quantity of sold products) in the initial state = 6.7 million tons per 20 years
I_{ij} – investments to increasing the resilience of j-th supply chain element in case of i-th experiment = 0 MU for coded value −1 or 20 billion MU for coded value 1
n – number of experiments = 128
k – number of the supply chain elements = 15

List of profitable experiments (sum of investments is lower than profit from increased sales) is given in Appendix 2. It is obvious from the results the Plant element (Production plants in the region 5 is the most important supply chain element, because at all experiments is coded value 1. It means if the supply chain should reach profitable resilience, it should invest to eliminating the disruption impacts in production plants primarily. On the contrary, investments to increasing the resilience of suppliers and their LSPs aren't effective. These preliminary conclusions were verified statistically in the next step.

3.5 Key Supply Chain Elements Identification

Analysis of variance (ANOVA) in statistical software Minitab was used to determine statistical significance of the single supply chain elements for the overall benefit from investments to supply chain element resilience B_i. Significance level α for P-value was set to 0.05. Statistical significance was confirmed at all supply chain elements. For final selection of key elements was used Pareto chart of standardized effects (see Fig. 3).

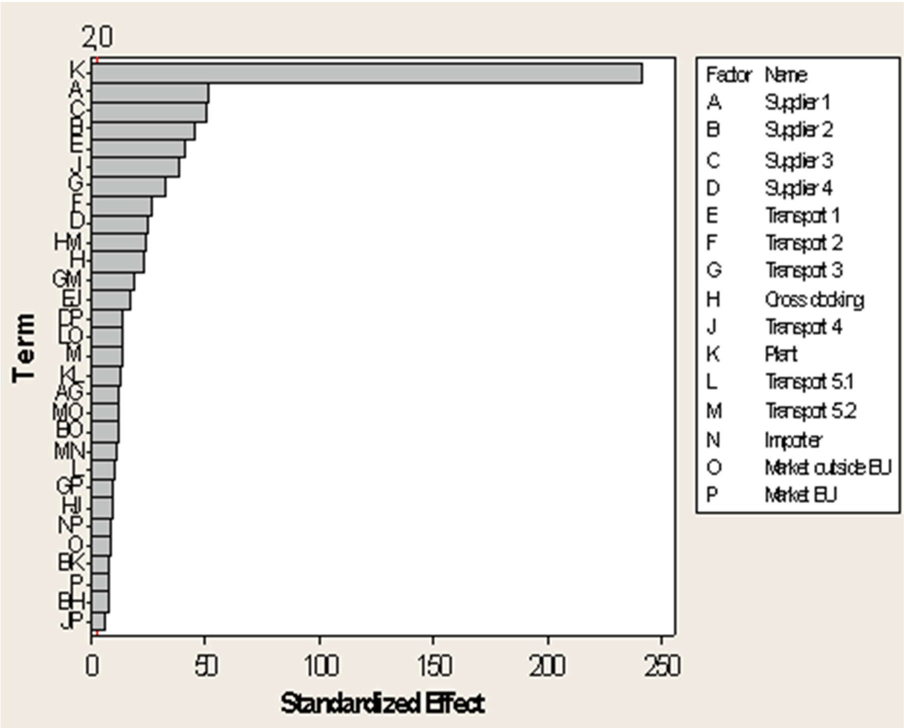

Fig. 3. Pareto chart of the standardized effects.

The most statistically significant is the element Plant, which is followed by Supplier 1, Supplier 3, Supplier 2, Transport 1, Transport 4, Transport 3, Transport 2, Supplier 4, and Cross docking. However, sign plus and minus at the single effects must be taken into consideration (see Table 1).

Table 1. Results from ANOVA.

Element	Effect	P-value
Plant	46.68	0.000
Supplier 1	−9.89	0.000
Supplier 3	−9.84	0.000
Supplier 2	−8.73	0.000
Transport 1	−7.93	0.000
Transport 4	7.45	0.000
Transport 3	−6.37	0.000
Transport 2	−5.11	0.000
Supplier 4	−4.64	0.000
Cross docking	4.36	0.000

If the effect is plus, increase of the supply chain element resilience has positive impact on overall benefit B_i. While the effect is minus, the impact is opposite (decrease of the B_i). From that reason, Plant, Transport 4, and Cross docking were identified as the key supply chain elements from the resilience viewpoint.

4 Conclusion

Experimental part of the research confirmed the suitability of computer simulation and design of experiments techniques for identification of the most important supply chain elements from resilience viewpoint. Future research work is focused on optimization of the investment problem. In other words, the aim is to find such amount of investments to the identified key supply chain elements to obtain maximal overall benefit from increasing the resilience of these elements for the whole supply chain. The first possibility how to reach the aim is to use design of experiments once again, but only for the key elements. The limitation of this approach is number of elements in researched supply chain. To eliminate the problem, authors apply genetic algorithms as the alternative approach.

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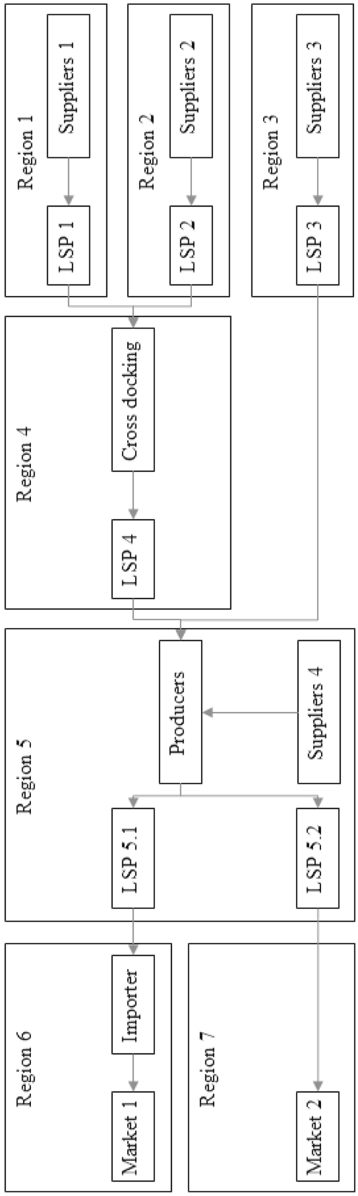
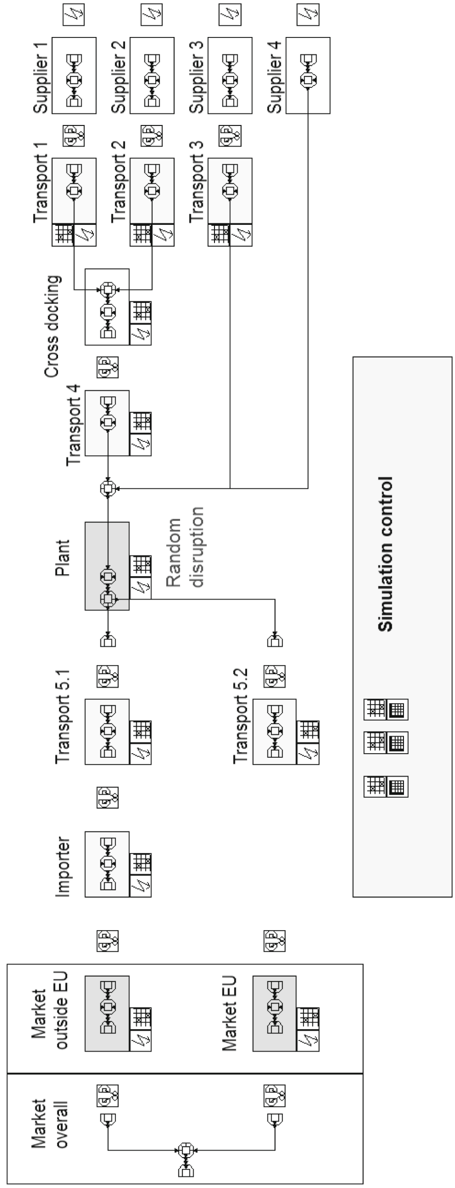
Appendix 1: Supply Chain Model



A. Mental supply chain model



B. Simulation supply chain model

Appendix 2: List of Profitable Experiments [17]

	Supply chain elements															
i	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Transport 1	Transport 2	Transport 3	Cross docking	Transport 4	Plant	Transport 5.1	Transport 5.2	Importer	Market outside EU	Market EU	B_i (MU per 20 years)
3	-1	1	-1	-1	-1	-1	-1	-1	-1	1	1	1	-1	-1	-1	1.83
4	1	1	-1	-1	-1	-1	-1	1	1	1	-1	1	1	-1	1	3.48
7	-1	1	1	-1	-1	-1	-1	-1	1	1	-1	-1	1	-1	-1	1.42
11	-1	1	-1	1	-1	-1	-1	-1	1	1	1	-1	1	-1	1	5.43
17	-1	-1	-1	-1	1	-1	-1	1	1	1	1	1	1	1	-1	23.91
29	-1	-1	1	1	1	-1	-1	1	1	1	-1	1	1	1	1	5.86
33	-1	-1	-1	-1	-1	1	-1	-1	1	1	-1	-1	-1	1	-1	17.96
37	-1	-1	1	-1	-1	1	-1	-1	-1	1	1	1	1	1	-1	4.63
41	-1	-1	-1	1	-1	1	-1	-1	-1	1	-1	1	1	1	1	0.88
42	1	-1	-1	1	-1	1	-1	1	1	1	1	1	-1	1	-1	4.90
45	-1	-1	1	1	-1	1	-1	-1	1	1	1	-1	-1	1	1	2.19
59	-1	1	-1	1	1	1	-1	1	1	1	-1	1	-1	-1	1	0.67
71	-1	1	1	-1	-1	-1	1	1	1	1	1	1	-1	1	1	4.83
75	-1	1	-1	1	-1	-1	1	1	1	1	-1	1	-1	1	-1	7.26
81	-1	-1	-1	-1	1	-1	1	-1	1	1	-1	-1	-1	-1	1	5.70
90	1	-1	-1	1	1	-1	1	1	1	1	1	1	-1	-1	1	0.53
97	-1	-1	-1	-1	-1	1	1	1	1	1	1	1	1	-1	1	12.51

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