MODELLING INVESTMENTS ALLOCATION IN SUPPLY CHAIN RESILIENCE IMPROVEMENT

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Abstract

The concept of resilience is well developed as it has been studied extensively in last decade. The effort has been made to find ways to increase the supply chain resilience and thus to reduce an impact on supply chain long term performance. Supply chains and its management is a subject to globalization, which causes that suppliers, together with manufacturers and other shareholders of supply chains are getting more aware of the need to cooperate and find solutions to improve properties of all links to ensure proper long term functioning of supply chain and thus the prosperity of all links involved. There are still issues comprising how to build the overall supply chain resilience and how to support decisions regarding investments in the supply chain links to improve its properties and thus to increase its resilience. This article presents an initial experimental modelling of the impacts of investment on time to recovery after disruptions. The modelling approach assume that a mean time to recovery of specific links of supply chain can be reduced using investments to improve links properties and skills and availability of the supply chain is used as an indicator of resilience improvement. Modified transfer system model was used to model a studied system and Python 2.7.1 software with modules NUMPY and SCIPY was used to optimize the model using the SLSQP algorithm.

Keywords: Resilience, supply chain, modelling, investment, transfer line models, time dependent failures

1. INTRODUCTION

The concept of resilience is considered a successive concept as the past leading concepts of leanness and others are fading with the volatile environment and various factors causing disruptions [1]. As many definitions of resilience occurred in past years the best fit for the presented article is the one considering resilience the ability of supply chain to return to its original state or to move to a new, more desirable state after being disturbed. According to the World Economic Forum (WEF) [2] the most important ones include: natural disasters, extreme weather changes, conflicts and political troubles, terrorism and sudden radical changes of demand. Extensive effort has been made so far in defining the whole resilience concept [3] as well as its measurement using various approaches such as [4] or [5] and [6]. As the supply chain exhibits similar characteristics as the transfer or production line with the difference of a scale considered, it is possible to approach to the modelling of supply chain the similar way as to of such lines. Modelling of manufacturing lines has been intensively studied since early 1950's. As the nature of the problem, analytical models has been presented only for lines with two, and later with three machines in the sequence. Significant effort has been made in the field and large number of publications describing various approaches is available. For further reading and references we recommend historical reviews on the topic, including Buzacott [7], Schick and Gershwin [8], Liu [9] or very valuable review by Dallery [10] providing comprehensive explanation of the models characteristics, demands and properties. For the purposes of this article study by Tan [11] and his model was used to create the objective function subjected to optimization.

2. PROBLEM FORMULATION

As introduced above, global companies and supply chain managers' faces disruptions to supply chains and its links respectively. With certain probability specific supply chain links will be hit by the force majeure with significant impact on functioning of the link and the whole supply chain. Such disruption and links' temporary decommissioning will stop all successive stages of supply chain and block precedent stages as it results in reducing the links capacity of production or transfer respectively. Such disruptions are exponential random variables occurring with certain probability which can be derived from historical statistical data on specific regions and various disruption causes. Disruptions are, unlike failures of manufacturing machines, time-dependent which means they are independent of state of a links and of each other. After a disruption, the supply chain link can be and will be repaired and operational again after a certain period of time. Duration of this period of time is assumed to be a random variable and link specific, or region specific respectively. The main assumption made is that we can't prevent occurrence of large scale disruptions but we can work on reducing its impacts on supply chain in the context of its ability to be operational again as soon as possible after a disruption. That is the paraphrase of the definition of supply chain resilience. We assume that the period of non-operational state of a supply chain link, and thus the whole supply chain, can be reduced under certain conditions and improvement of supply chain link resilience respectively. That will require an investment which will be used to finance and support the improvement of supply chain properties and thus resilience, which means, next time the disruption occur, supply chain link will recover faster. Then the question is how to decide where the investment should be allocated, which supply chain link is the bottle neck in the context of resilience improvement and what is the relationship between the money invested and supply chain resilience improvement. To answer these questions is the aim of this article.

3. MODELLING APPROACH

Four stages supply chain is considered in the study, see **Figure 1** below. Subsequent stages of the modeled systems represent supplier, manufacturer, servis centre and distributor. Supply chain links are considered to be located in regions independent of each other in the context of disruptions occurring in specific regions. As links of the modeled supply chain are subjects to failures due to random disruptions, we assume, with respect to the context of resilience concept, that disruptions and thus failures caused are relatively long compared to processing rate of supply chain and so is the time of recovery. Mean time to disruption and failure and mean time to recovery are considered to be exponential, processing times are considered to be deterministic. For each supply chain link following parameters has been used in the model. Let mean time to failure of the link I ($MTTF_i$), or failure rate respectively be represented by λ_n and let μ_n be the repair rate, defined by mean time to recovery after failure due to a disruption ($MTTR_i$) and its functional relationship with the investment allocated I_i, which is discussed below. Let *t* stand for the period of time at which we assess the availability of supply chain and I_{max} the maximal sum of resources allocated in the improvement of supply chain resilience.

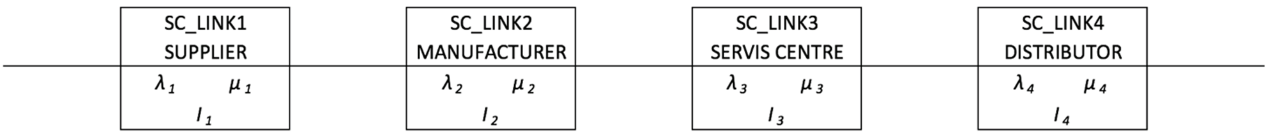

Figure 1 Structure of the modeled supply chain

We assume a real supply chain usually operates as a discrete items flow or batches flow respectively. Batches varies in the size as a specific links of the supply chain perform different operations. According to a literature, discrete flows can be approximated with continuous materials flow models especially if the processing rates are much smaller that the failure and repair rates. No intermediate storages are considered in the system as in the real world they are usually located within the region of specific link and thus are also subjects to occurring disruptions. We assume high dependence of subsequent links of the supply chain, which means once a specific link is not working due to a failure after a disruption, the whole supply chain is not working. Thus the performance and availability of the supply chain is a random variable dependent on the failure rates and recovery rates of specific links. We assume that it is not possible to influence the failure rates as the disturbances are usually of the nature of natural disaster, political conflict or unpredictable decrease of demand. What can be influenced, and thus optimized, is the time to recovery, recovery rate respectively. As we assumed that investments allocated in efforts made to increase the supply chain links resilience will lead to decrease of time to recovery and thus the availability of supply chain will be increased so more items will be produced in the certain period of time.

As we assume the decrease of mean time of recovery with an increase of investment allocated, the linear functional relationship is considered. In future research, linear dependency will be replaced with function more corresponding with the real world. Specific links of the supply chain are considered to be located in regions with different conditions and thus the meant time to recovery and its functional relationship with the improvement after certain investment is also region specific. Thus four different profiles were defined for the purposes of the study, which are presented on the **Figure 2** below.

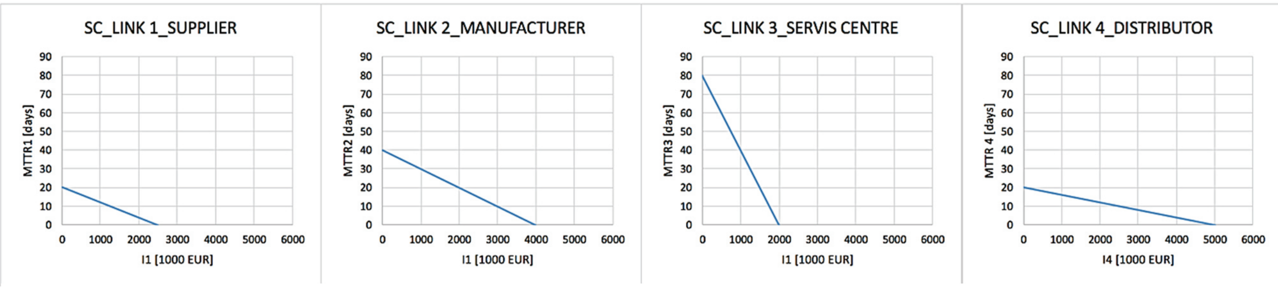

Figure 2 Functional relationship of mean time to recovery and investment allocated

For the purposes of this article as an initial study in the field of optimizing investments allocation in resilience improvements modified model of transfer system developed by Tan [1] was used and the availability of the supply chain was used as an indicator of supply chain resilience increase. The original model was design to calculate instantaneous availability ($A_{(t)}$) of a production system in the certain moment in time which is the probability that the system will be operational at given moment in time. The instantaneous availability of systems is asymptotically normal, which was used to simplify the optimization procedure and *t* of 20 years was used in the calculation. Later it was subject of the control calculation experiment, which is discussed in results below. Modeled system is assumed to produce discrete items in the rate of one item per one minute, random disruptions may occur with mean time of 3 years and specific links can be operational again after a random period of time with mean time of 20 to 80 days. With respect to the assumption, modeled supply chain is considered to process, or transfer respectively, one item per one unit of time, which is one minute in this case and modeled system is synchronized. Failure rate and repair rates are then recalculated with regard to the assumed production rate.

4. RESULTS AND DISCUSSION

For the purposes of the experimental work the modified Tans' model in the form of availability calculation expression (equation 1) was used as the objective function for the optimization algorithm, as stated below together with expressions describing the linear functional dependence of mean time to recovery, or repair rate respectively, on investment allocated in the specific link improvement (equations 2-5). Bounds and constrains were defined for the model, as well as maximal amount of allocated resources (6) which were to be allocated into specific supply chain links to maximize the overall availability of the supply chain, for the purposes of the experiment 10 M EUR.

$$A_{(t)} = \prod_{n=1}^{N}\left[\frac{\mu_n}{\lambda_n+\mu_n} + \frac{\lambda_n}{\lambda_n+\mu_n}e^{-(\lambda_n+\mu_n)t}\right] \qquad (1)$$

$$\mu_1 = \frac{1}{-11.52 I_1 + 28800} \quad (2)$$

$$\mu_1 = \frac{1}{-14.4 I_2 + 57600} \quad (3)$$

$$\mu_1 = \frac{1}{-5.76 + 11520} \quad (4)$$

$$\mu_1 = \frac{1}{-5.76 I_4 + 28800} \quad (5)$$

$$I_{max} = 10 \times 10^6 \quad (6)$$

Above described mathematical model has been subjected to the Sequential Least Squares Programming (SLSQP) optimization algorithm in Python 2.7.1 using modules NUMPY and SCIPY. Progress and results of the optimization iterative process are depicted in the **Figure 3** below. The algorithm terminated after 42 iterations with resulting availability $A_{(t)}$= 0.926506 which can be ensured by allocation of the whole amount of maximal budget of 10 M EUR in the proportion of 2500:4000:1715:1785 into a links of order from I1 to I4. On the **Chyba! Nenalezen zdroj odkazů.** below, the course of the algorithm and provided solutions of respective iterations can be observed. On the **Figure 4** the propagation of the solutions' improvement is visualized.

ITERATION	I1	I2	I3	I4	A(t)	ITERATION	I1	I2	I3	I4	A(t)
1	1000,000006	1000,000008	1000,000003	1000,000003	0,88733	22	2499,9999	2858,231888	1712,598449	1753,961646	0,916835
2	1000,000038	1000,000047	1000,000018	1000,000019	0,88733	23	2499,9999	2906,498571	1731,03972	1773,446452	0,917358
3	1000,000199	1000,000245	1000,000094	1000,000099	0,88733	24	2499,9999	3147,73746	1823,209959	1870,832323	0,919977
4	1000,001	1000,001231	1000,000472	1000,000499	0,88733	25	2499,9999	3516,368646	1964,053022	2019,645264	0,924003
5	1000,00501	1000,006166	1000,002365	1000,002502	0,887331	26	2499,9999	3516,331227	1964,038721	2019,630154	0,924002
6	1000,025006	1000,030778	1000,011803	1000,012488	0,887331	27	2499,9999	3516,331226	1964,03872	2019,630153	0,924002
7	1000,125132	1000,154011	1000,059062	1000,062491	0,887333	28	2499,9999	3516,331231	1964,038718	2019,630151	0,924002
8	1000,626123	1000,770626	1000,295528	1000,312685	0,887342	29	2499,9999	3516,331257	1964,038705	2019,630139	0,924002
9	1003,130706	1003,85324	1001,477684	1001,563471	0,88739	30	2499,9999	3516,331384	1964,038639	2019,630077	0,924002
10	1015,668063	1019,284089	1007,395278	1007,824612	0,88763	31	2499,9999	3516,332022	1964,038311	2019,629768	0,924002
11	1078,211071	1096,261374	1036,915389	1039,058515	0,88883	32	2499,9999	3516,335203	1964,036673	2019,628225	0,924002
12	1391,735843	1482,144409	1184,898135	1195,63241	0,894875	33	2499,9999	3516,351136	1964,028466	2019,620498	0,924002
13	2499,9999	2846,184313	1707,995427	1749,098153	0,916705	34	2499,9999	3516,430746	1963,987469	2019,5819	0,924003
14	2499,9999	2846,184338	1707,995437	1749,098163	0,916705	35	2499,9999	3516,829076	1963,782298	2019,388725	0,924005
15	2499,9999	2846,184461	1707,995484	1749,098213	0,916705	36	2499,9999	3518,820462	1962,75653	2018,422932	0,924015
16	2499,9999	2846,185079	1707,99572	1749,098462	0,916705	37	2499,9999	3528,780597	1957,627009	2013,593373	0,924066
17	2499,9999	2846,18817	1707,996901	1749,09971	0,916705	38	2499,9999	3578,62784	1931,952326	1989,419933	0,924323
18	2499,9999	2846,203609	1708,002799	1749,105943	0,916705	39	2499,9999	3828,126876	1803,445754	1868,42747	0,925614
19	2499,9999	2846,280726	1708,032264	1749,137074	0,916706	40	2499,9999	3999,9999	1714,92111	1785,07909	0,926506
20	2499,9999	2846,666313	1708,179585	1749,292732	0,91671	41	2499,9999	3999,9999	1714,92111	1785,07909	0,926506
21	2499,9999	2848,596224	1708,916947	1750,071819	0,916731	42	2499,9999	3999,9999	1714,92111	1785,07909	0,926506

Figure 3 SLSQP Algorithm optimization process results

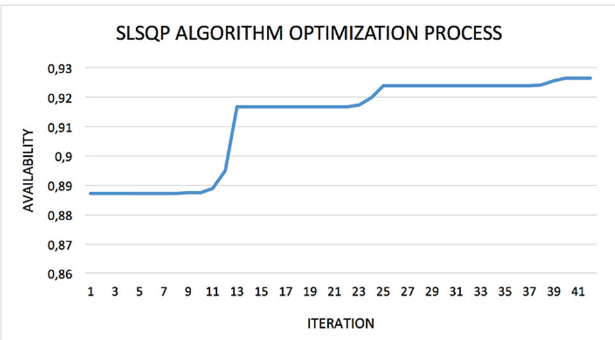

Figure 4 Propagation of optimization process

To verify the usability of acquired results in the context of using the instantaneous availability as a simplified indicator of improvement of supply chain resilience we run an experimental control calculation. The model was recalculated using the set-up with results of the last iteration while the *t* was changed with step of 60 minutes, running from *t* = 60 minutes to 41 years. Results of the control experiment (see the **Figure 5**) showed that the parameter *t* is negligible when enough long period of time is used to optimize the model, which is in line with literature and which corresponds with the reality as in the long term the availability and thus performance of systems tends to stabilize.

As the modeled system of four supply chain links in linear configuration is quite simple and does not meet modeling demands of complex production systems, this study is considered to be an initial effort made to outline the possible approach when building the supply chain resilience. Simulation experiments answering the same questions on resources allocation has been made so far, so using analytical approach could be used as complementary or substitute method. In the follow up research we will develop the approach and present a methodology of calculating an expected availability and throughput of the supply chain of more complex structure, which will more precisely follow the real world structures.

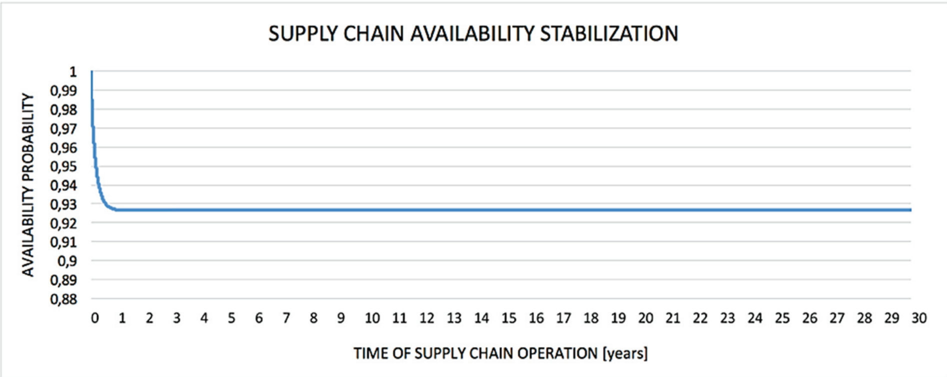

Figure 5 Instantaneous availability stabilization with prolonging the parameter t

5. CONSLUSIONS

An analytical model to optimize the future investments allocation in the supply chain to increase its overall resilience was presented and the SLSQP algorithm was used to optimize it. Instantaneous availability of supply chain was used as an indirect indicator of supply chain resilience. Presented approach is usable for linear supply chains no matter how many links involved. The main limitation of the approach is the need to define, and thus average a functional relationship of recovery rate and investment allocated. Further research will be focused on developing the methodology which will allow to allocate investments destined to increase resilience of complex global supply chains which will provide us a tool for support the decision making process in the context of strategic management.

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