PERSPECTIVES AND LIMITATIONS OF ANALYTICAL MODELLING OF RESILIENCE IN METALLURGICAL SUPPLY CHAIN USING MODIFIED MANUFACTURING LINE MODELS

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Abstract

The concept of resilience has gained increasing attention in recent years for its importance and practical implications for a wide range of professionals across different disciplines. To date, much attention has been paid to defining resilience, the possibilities of its measurement, the methodological frameworks for its construction, and simulation models. So far, however, analytical models have not been introduced to assess the resilience according to individual scenarios of its increasing in particular supply chains with regard to costs incurred. The aim of the article is to introduce, analyse and evaluate the possibilities of using modified analytical production line models to optimize investments directed to individual supply chain links to increase its overall resilience. For the purposes of the article, a model example of the structure of the real metallurgical supply chain is used. The possibilities and limitations of individual models and possibilities of their practical implementation in the management of metallurgical supply chains are discussed.

Keywords: Resilience, supply chain, metallurgy, manufacturing line models, modelling

1. INTRODUCTION

As the supply chain management is gaining increasing level of attention in last years, there have been much effort made in the field of modelling its properties and behaviour. Especially the concept of supply chain resilience, its modelling, assessing and controlling is a common topic for logistics community. So far the most models presented have been simulation-based, which takes its limitations as well as advantages. The aim of this paper is to explore possibilities of analytical approach to modelling supply chain behaviour under resilience with the use of models developed originally for modelling production lines. The idea is to transfer and adjust the modelling methodology from the detailed scale of the production line to the more global scale of supply chain. Behind the idea is the assumption, that both structures can be considered similar in some basic characteristics, such as they are composed of interconnected links of certain structure, with certain up-times and down-times probabilities, production rate and kind of intermediate storage.

1.1. Supply Chain Resilience

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, for purposes of the paper the resilience of a system - supply chain - will be considered the ability to return to its original state or to move to a new, more desirable state after being disturbed [2]. According to the World Economic Forum (WEF) [3], the most important ones include: natural disasters, extreme weather changes, conflicts and political troubles, terrorism and sudden radical changes of demand.

1.2. Manufacturing line models

The purpose of this article is to explore possibilities and limitations of use of manufacturing lines models when modelling supply chain resilience. Manufacturing flow line systems consists of material, work areas and storage areas, where material flows from work area to storage area and to work area. Every work and storage area is visited exactly once and in fixed sequence and there is a first and the last work area where material enters and leaves the system. Randomness of models may due to stochastic processing times, failure rates and repair times [4]. 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 historical we recommend historical reviews on the topic, including Buzacott [5], Schick and Gershwin [6], Liu [7] or very valuable review by Dallery [4] providing comprehensive explanation of the models characteristics, demands and properties. Comprehensive comparison of two-machine line models according to line type and reliability distribution was presented by Li and Alden [8]. All models presented so far work with the basic structure (see **Figure 1**) and set of general assumptions presented below as well as some specific assumptions according to each particular type of the model [8]:

1) The system consists of two machines arranged serially and a buffer separating the machines (see **Figure 1**, where circles represent the machines and the rectangle is the buffer).
2) Each machine (m_1 and m_2) has two states: up and down. When up, the machine is capable of producing parts; when down, no production takes place. Machine uptimes and downtimes are independent random variables.
3) Each machine requires a fixed unit of time to process a part. This unit is referred to as the cycle time.
4) The buffer is characterized by its capacity N.
5) Machine m_1 is never starved; machine m_2 is never blocked.
6) If a machine fails while processing a part, the part remains at the machine, and repair will include any necessary operations needed to complete processing of the part. No scrap is assumed.
7) The buffer does not delay job movement, i.e. the buffer transition time is zero.

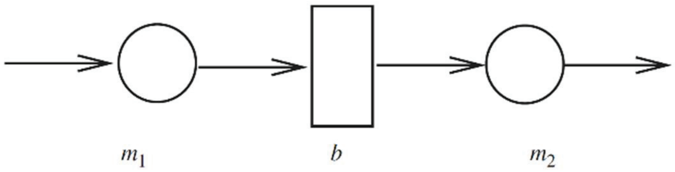

Figure 1 Two-machine line with two machines m_1 and m_2 separated by a buffer b [8].

Behind the scientific effort made in the field, a need for performance estimation is found as it is essential to design and improve manufacturing systems. Various approaches and equations have been developed for throughput calculation. However, input parameters for each machine of a model are λ_i, the probability of failure of machine i, and μ_i, the probability of completing the repair of machine i, N which stands for buffer size and S, cycle time.

1.3. Modelling of Complex Structures

Real world manufacturing systems are rarely composed of only two stations. As the state space which's analysis is needed for analytical formula construction is growing exponentially, approximate methods are used to model more complex systems. The basic principles of such modelling methods were published in the 1960's [9]. The idea of decomposition methods comes from the assumption, that if we place an observer into a buffer in the line, he will see only incoming and leaving parts. So if we put the observer at the end of the line, he will see the total throughput of the line, even if he doesn't know what happened to upstream machines or how much downtimes occurred. Various systems have been studied so far, such as serial lines, assembly/disassembly systems [10], parallel lines, split/merge scraping, closed loop systems, rework loops and some other types [11]. The general idea of decomposition - or aggregation - of longer linear production systems is to replace a two-machine line by a single equivalent machine, which has the same throughput in the isolation as the original two-machine lines, respectively decompose the original line into the set of two-station lines, for which the analytical formulas are available (see **Figure 2**).

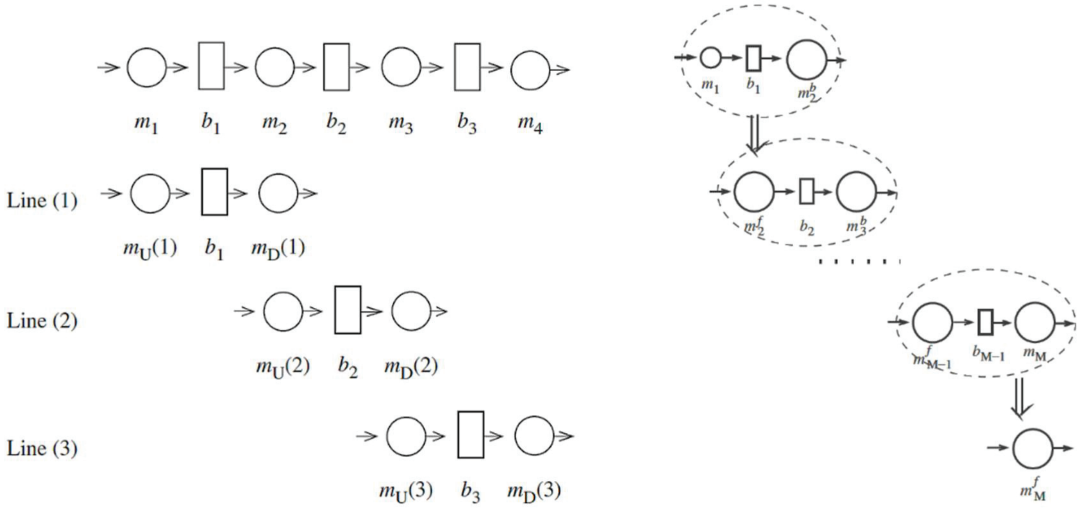

Figure 2 Decomposition (left) and aggregation of serial production systems [11]

Based on the above mentioned basic principles, methods and algorithms were proposed for modelling more complex production systems composed of various production operations. The basic idea of throughput estimation is called overlapping decomposition. Complex productions system is decomposed into serial lines, the first and last stations are modified to include the effects from the other lines. As the topic has been extensively studied especially in the scope of the automotive industry, more issues have been investigated, such as production systems with quality check devices, multiple part types and others.

2. MODELLING METALLURGICAL SUPPLY CHAIN IN THE CONTEXT OF RESILIENCE

The above-mentioned models of manufacturing systems have considerable potential for modelling the metallurgical supply chains. Modelling should take into account the characteristics of the metallurgical supply chain, its structure and its way of functioning. The resulting metallurgical supply chain model (see **Figure 3**) may, according to the modification, serve to examine the change in supply chain resilience or, for example, the influence of the link storage capacity on the value of the whole chain.

Based on the introductory chapter on supply chain resilience, we will work with a high degree of aggregation into geographic, economic and political regions, respectively. This is mainly due to the fact that the disturbance affects not only the enterprise but also the entire territory where the enterprises are located.

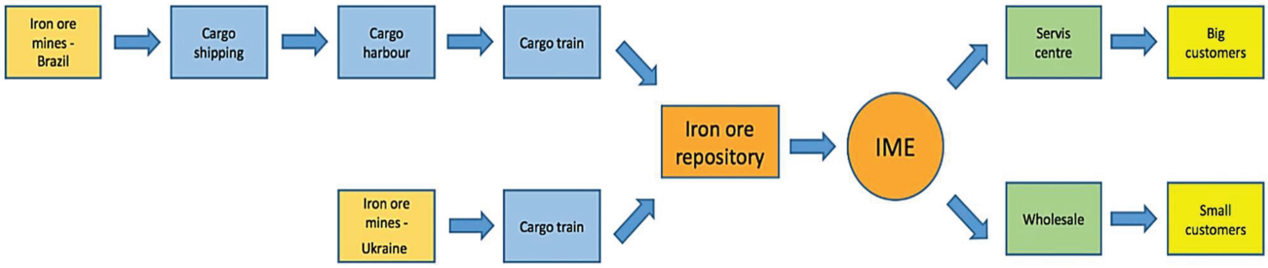

Figure 3 Metallurgical Supply Chain model

Using the above mentioned methodology of modelling of production systems, the approach to modelling metallurgical supply chain will remain similar. The adjustment of input parameters is necessary in the terms of terminology used. Instead of naming chains “machines” and “buffers”, as the metallurgical supply chain compose of links represented by suppliers of iron ore, integrated metallurgical enterprise and distribution centres for both wholesale and retail customers, the model will compose of SC link and intermediate storages characterized by specific parameters based on the principle of manufacturing line models. Thus, for each SC link of a model, parameters λ_i and μ_i, will be defined together with S_i, where λ_i will stand for probability of disruption to SC link *i*, and μ_i stands for the probability of completing the recovery of SC link *i*, *N* which stands for intermediate storage capacity and S_i for cycle time.

In the context of supply chain resilience, disruptions of individual links, such as natural disasters, extreme weather changes, conflicts and political problems, terrorism and sudden radical changes in demand, are considered. This is a violation that causes a reduction in capacity or a disruption of the activity of individual links until recovery, which affects the performance of the entire supply chain, as the following links can’t perform its operations without the supply from previous links. The main objective of the discussed model is to assess whether or not the investment should be allocated to the specific links of the supply chain and how much the overall impact of investment would be the highest in terms of the overall output of the supply chain. A prerequisite for modelling using modified models of production lines is knowledge, respectively the estimation of the dependence of the change of performance of individual links on the allocated investment. The model will therefore work with the assumption that if investment is allocated to the links of the supply chain to increase its resilience, this will result in a shortening of the time the link will need for recovery to the original performance in the event of a breakdown due to the disruption. It is assumed that the allocation of investments and improvement of specific link can’t directly affect the probability of occurrence of the disturbances described above, such as how often an earthquake or other natural disaster occur or a rapid decline in demand, a war or a political crisis happen. However, we may, in some circumstances, influence how much, respectively, for how long the supply chain link in this region will be affected by the event in such a way that its performance will be reduced, respectively the activity stopped.

Since the original production line models do not work with the resilience parameter, it must be included somehow in the modified model. Probability of completing recovery, or the MTTR - mean time to recovery, represented by μ_I must become the function of investments allocated to the specific supply chain link, for the purpose represented by I_i. Thus $\mu_I = f(I_I)$ which enriching the model of the investment variable. One of the main limitations of the modelling approach is how the functional relation between investment and the mean time to recovery. As it is quite clear that the relation will not be linear nor of any basic type, the relation must be carefully determined for each supply chain link taking into regard all possible disruptions which can occur in the specific area. As the model as described above can take into account only the overall resilience of the specific link, the proper analysis must precede. We propose to work with the list of basic disruptions defined in the concept of resilience and assess the specific threats for each link. The analysis will work with the available data on the historical occurrence of various disruptions in the region, the analysis of business environment, and also outcomes of internal SWOT analysis. Based on the analysis the main threats will be defined and then evaluated so the functional relationship could be estimated. It can be assumed that the function describing the relationship of the investment and the shortening of the mean time to recovery will be quite complex with reduction possible. The example of expected profile of the function is presented on **Figure 4** below.

The initial resilience which is for the purposes of the model reduced to the parameter of mean time to recovery is for example 10 weeks from the occurrence of a disruption. As the investment is increasing, the mean time to recovery remains the same until the first turning point, where the investment is high enough to make a difference. For example, in real life it means that until certain point, level of investment, it is not possible to proceed any important precautions, such as contracting the substitute supplier, building a secondary warehouse or move or secure current premises against extreme weather conditions. As the investment is growing from that point, the meant time to recovery is decreasing - more robust solutions are implemented, the link is more protected - just to the second turning point, where the decrease is suppressed. In real life that moment means that it is not able to influence the resilience positively any further, so the higher investments doesn't pay off. Once such profiles are defined for each supply chain link and then implemented to the modified production line model, it is possible to proceed to the overall evaluation of investment scenarios, for example with genetic algorithms to obtain a solution which will pair the certain level of investment with certain links of the supply chain to minimize the overall investment and maximize the overall throughput of the supply chain.

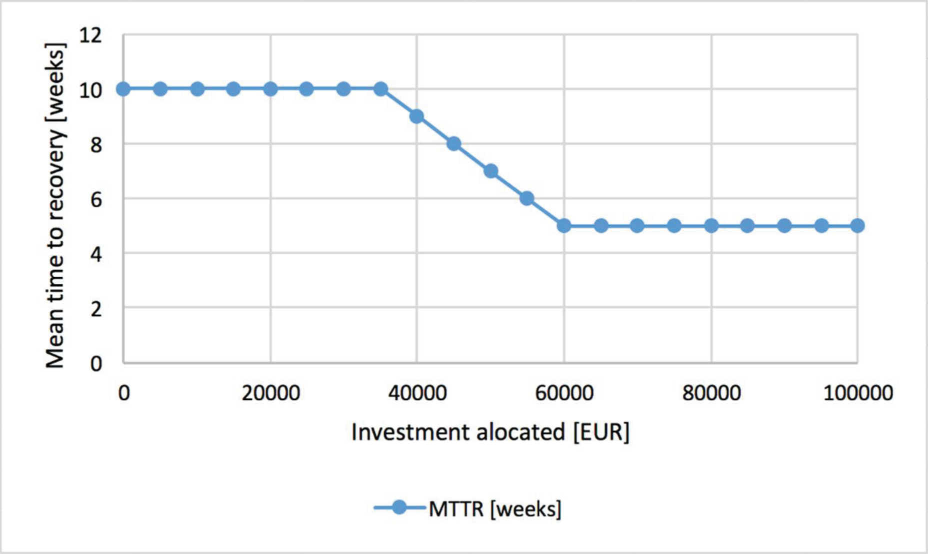

Figure 4 Profile of the functional relationship between the investment allocated and mean time to recovery after big scale disruption

3. DISCUSSION

As the supply chain can be considered to be a specific type of a transfer production line, the modelling approach is very promising when it comes to analytical analysis of supply chain performance under resilience. Many various basic kinds of models have been presented so far, which differ in characteristics such as continuity, synchronicity and type of production, time or operation dependency of failures and others, so the right technique must be used to fit the supply chain operation characteristics. Modelling of complex system is quite demanding as the number of links is increasing, but the provided outcomes will be very helpful and valuable especially as it is the new approach which will extend the concept and methodology of supply chain resilience improvements. Main simplifying assumptions must be considered, especially the fact that it will be very difficult and potentially misleading to define the profile of functional relationship between investment allocated and supply chain link resilience, as it will be the cornerstone of decision making.

4. CONCLUSION

Modified production line models potentially represent a new tool for modelling supply chain performance and decision support in the context of planning investments. As some initial simplifying assumptions must be made, the limitation of the approach must be considered. Our future work will be focused on creating a model using above mentioned approach for analytical analysis of supply chain performance. Initial experiments with basic linear structure of supply chain will be performed to verify the modelling approach and subsequently genetic algorithm will be run to solve the model. Based on the experiments and results, methodology will be created which will extensively describe the procedures of model creating, analysis and assessment of business environment and potential threats to supply chain links as well as the procedures of solving of the model. The main outcome of the effort and research in the area is to provide strategical logistics community the tool for decision support as the importance of supply chain resilience is increasing and high investments will be allocated to the field in the future.

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