# ANALYSIS OF THE IMPACT OF RISK AND UNCERTAINTY FACTORS IN DESIGN OF RESILIENT SUPPLY CHAINS

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**Abstract**

Modern engineered systems, both manufacturing and service-related include supply chains systems, are becoming increasingly complex. The complexity of these systems is multi-dimensional, namely: structural, spatial and temporal. The issue of assessing the risk of disruption in supply chains, in particular global ones, has been becoming more and more important in recent years. It results from the efforts to minimize costs by continuous processes of Lean Manufacturing, Lean Logistics, and Lean Management and the increasing number and intensity of external threats. The aim of this paper is to present the concept of the supply chain resilience assessment in the case of disruptive events occurrence. Firstly, the methods for modeling uncertainty in terms of their application to assess this type of risk will be discussed, and then the concept of agent base model enabling a quantitative assessment of supply chain resilience will be presented.

**Keywords:** Resilience, supply chain, uncertainty, fuzzy logic, modelling, simulation

## 1. INTRODUCTION

Modern engineered systems, both manufacturing and service-related include supply chains systems, are becoming increasingly complex. The complexity of these systems is multi-dimensional, namely: structural, spatial and temporal. The issue of assessing the risk of disruption in supply chains, in particular global ones, has been becoming more and more important in recent years. The aim of this paper is to present the concept of the supply chain resilience assessment in the case of disruptive events occurrence.

## 2. METHODS FOR UNCERTAINTY MODELLING

### 2.1. Theories of uncertainty

The starting point for considering uncertainty may be GIT - the Generalized Information Theory, proposed by Klir [4]. Compared to the classical information theory created by Shannon [9], based on concepts of probability and entropy, it has a much more universal character. GIT is the result of two significant mathematical generalizations:

- The classical theory of additive measures to the theory of monotone measures.
- The classical theory of crisp sets to a more general theory of fuzzy sets.

The first generalization, which started in the early 1950s, extends additive measures to less restrictive monotonic measures, characterized by more diverse features. The second one, introduced in the 1960s, expands the language of the classical set theory into a more universal language of fuzzy sets, allowing the use of vague linguistic terms. The theory of uncertainty of a given type is formed by choosing the appropriate language (e.g. based on the theory of fuzzy sets) and expressing uncertainty by means of specific monotone measures (e.g. based on the theory of probability).

The classical information theory is based on the theory of probability or alternatively, the theory of possibility, applied to classical sets. And applying the probability function or possibility function to standard fuzzy sets enables the creation of new, more general theories of information. Similarly, remaining at classical sets, we can apply various non-additive monotone measures (e.g. Sugeno's $\lambda$ measure, Dempster-Shafer measure, Choquet measure of *n*-th order or the general lower and upper probability function), creating new theories.

There are, therefore, a lot of formal theories of uncertainty. Each of them is more or less general, and any two theories at the same level of generality may not be mutually comparable. Each particular problem requires the use of such a theory, which would make it possible for a decision-maker to express his or ignorance and to protect against ignoring any information, relevant in a given situation. Currently, within the framework of the so-called imperfect knowledge trend, efforts are made to create GTU - the Generalized Theory of Uncertainty, which would go beyond the classical theory of probability and classical set theory, would characterize each type of uncertainty and work at four levels: formalization, computational tools, measurement and methodology [18].

In each of the above theories, uncertainty is represented by the so-called uncertainty function, assigning each possible realization from the set a number from the interval (0, 1), which determines the degree of certainty that a specific opportunity arises. Examples of uncertainty functions include: the probability function, the possibility function, the function of faith and credibility or function of the lower and upper probability. In each theory, the uncertainty function meets certain requirements that differentiate the various theories. The measure of uncertainty for a specific type of theory is the functional that assigns a non-negative real number to each function. Typical examples of uncertainty measures are the Shannon entropy [9] and Hartley measure. A functional representing the uncertainty measure must meet a number of requirements. Admittedly, mathematical formalization of each of the requirements depends on the theory used, however, these requirements can be represented in the general form as:

- Additivity - the uncertainty in the total data representations is equal to the sum of uncertainty of individual representations of data.
- Subadditivity - the uncertainty in the total representation of data cannot be greater than the total uncertainty of the sum of individual data representation.
- Range- the uncertainty is contained in the interval (0, *M*), where 0 is related to the function that describes the complete certainty and *M* depends on the size of the set used and the selected unit of measure.
- Continuity - the functional must be continuous.
- Expansibility - developing a set of alternatives by adding alternatives cannot change the level of uncertainty.
- Consistency - if uncertainty can be calculated in different ways (allowed in the method), the result must be the same.
- Monotonocity - if the data form an increasing series, their measure of uncertainty also increases and vice versa, if the data in a series are decreasing, uncertainty also decreases.
- Coordinate invariance - a measure of uncertainty cannot change with the isometric coordinate transformations.

These requirements must be fulfilled by all types of uncertainty that exist in the theory. Uncertainty of information can be expressed through measures of probability, possibility and necessity, faith and credibility. Measures of possibility, necessity, faith (conceivability) and credibility are dual, i.e., if the event is necessary, the counter-event is impossible, if the event is credible, the counter- event is inconceivable.

There are three main principles of uncertainty management:

- The principle of minimum uncertainty - we accept only those solutions for which the loss of information (resulting from simplifications, transformations conflict solutions) is minimal, i.e. we choose solutions with a minimum of uncertainty.

- The principle of maximum uncertainty - we accept all solutions, after making sure that the information that raises doubt is reliable.
- The principle of uncertainty invariance - the level of uncertainty should be kept at each transition from one mathematical approach to another.

## 2.2. Formalized languages

Currently, three formalized languages are used to describe sets: CST - the Classical Sets Theory, SFST - the Standard Fuzzy Sets Theory and NFST - the Nonstandard Fuzzy Sets Theory. The first two theories are thoroughly described in the literature, are well-developed and widely used, while the last one is a relatively new theory and not yet fully developed.

### The classical set theory

In the classical set theory, it is assumed that each element of the considered space X belongs to either set *A* ($x \in A$) defined on the space *X* ($A \in P(X)$), or it complements the set *A* ($x \in \overline{A}$), that is, no element can belong simultaneously to both sets. The characteristic function (membership function) of the set *A* is

$$m_A : X \to \{0,1\} \text{ and } m_A = \begin{cases} 1 \text{ for } & x \in A \\ 0 \text{ for } & x \notin A \end{cases} \quad \text{for each } x \in X \tag{1}$$

Two sets are equal only when every element of one of them is the element of the other and vice versa. Two sets of the same number of elements are called equinumerous. The interference based on binary logic and classic sets is simple and unambiguous, but in many cases insufficient to describe the complex reality.

### The standard fuzzy sets theory

The concept of fuzzy sets was introduced by Zadeh [16] as a generalization of the classical set theory. In the case of fuzzy sets, each element of space *X* can belong partially to a set *A*, and partly to its complement $\overline{A}$. Fuzzy sets are defined by the membership function corresponding to the function characteristics of classical sets. Each element of the set *X* has the assigned value that defines the degree of membership to the fuzzy set. Membership of standard fuzzy sets is in the range (0, 1) and if the maximum value equals 1, we deal with normal fuzzy sets. Thus, the membership function of the set *X* is:

$$\mu_A : X \to (0,1) \tag{2}$$

We can distinguish three cases here:

a) $\mu_A(x) = 1$ - means full membership in the fuzzy set *A*

b) $\mu_A(x) = 0$ - means the lack of membership in the fuzzy set *A*

c) $0 < \mu_A(x) < 1$ - means a partial membership in the fuzzy set *A*

A fuzzy set *A* is contained in the fuzzy set *B* only when $\mu_A(x) < \mu_B(x)$ for each $x \in X$, and the fuzzy set *A* equals the fuzzy set *B* only when. $\mu_A(x) = \mu_B(x)$. The complement of the set *A* is a fuzzy set $\overline{A}$ with a membership function. $\mu_{\overline{A}} = 1 - \mu_A$.

Although the inference based on the fuzzy set theory and multi-valued logic is more complex and less intuitive, however thanks to widely available computer tools supporting the process of the fuzzy inference it is becoming more common [5].

### 2.3. Theories of risk

When we making decisions under risk, next state resulting from the adoption of the option is unknown, but we know probability of possible values (what is missing in conditions of uncertainty). If:

$w_1, w_2, ..., w_n$ - results (payment)

$p_1, p_2, ..., p_n$ - the probability of results,

we can define the expected value of resulting:

$$E(W) = \sum_{j=1}^{n} w_j \, p_j$$ - expected value of resulting (payment)

Decision-making under risk is related to the concept of a lottery:

LOTTERY: $$L = \left[ \{ (p_i, w_i) \}, \sum p_i = 1 \right]$$

which involves the payment $w_i$ and probability $p_i$ of acquisition. As in the case of the decision-making under uncertainty, there are several different criteria taking chosen strategies. If we have attributed the probability of various uncertain events, it appears the problem of choosing the criterion of decision-making.

### 2.4. Criteria for decision-making under risk (with known probability of each state of nature)

There are the following rules for decision-making under risk:

- Rule of maximum likelihood - considering only the payment of the state of nature, which has the greatest likelihood and selects the strategy of having the highest paid in the state of nature.
- The rule expected (mean) value - calculated the expected payoff for each strategy, and selects the one that has the highest expected payout. Expected payment of the sum of the products of payouts for specific decisions for each state of nature, and the probabilities of occurrence of these states.
- Criterion advantage (dominance criterion) - can be used if the worst payment of one strategy is at least as good as the best payout different strategy (advantage withdrawals), or if one strategy is payment equal to or better than any other strategy in each state of nature ( advantage of events).
- The criterion of expected utility - the best decision corresponds to the strategy, for which the weighted average payments (weights being the probabilities of occurrence of these payments) reaches the highest value.

As with the rules of the decision-making under uncertainty, even at the risk can be guided by a variety of criteria. The choice of decision rule depends on the personal circumstances of the decision maker. There are three attitudes towards risk:

- Neutrality towards risk - occurs when the utility paid in is equal to the expected utility lottery, in which the expected payout is equal to (the utility function is then a straight line)
- Willingness to risk - occurs when the utility corresponding payment in less than expected utility lottery with the same expected payment in (convex utility function).
- Aversion to risk - is where the usefulness of the corresponding payment in greater than expected utility lottery with the same expected payment in (concave utility function).

## 3. LOGISTICS SYSTEM OF SUPPLYING THE METALLURGICAL PLANT

The subject of research is a steel mill located in Central Europe. The plant is supplied with large amount of raw material required for a production, of which the strategic one is an iron ore. The materials essential for a production process are being delivered to the stockpile buffer, which is characterized by a limited warehouse space. The capacity of the stockpile determines the maximum possible level of the reserve volume. Due to the significant collection and storage costs of resources in an investigated steel mill, the limit of the volume of the stock, has been set, which after assuming the regular supply of iron ore, should ensure the continuity of the production process. Iron ore is imported from abroad - from East Europe (railway transport) and Brazil (combined transport). In the investigated company iron ore is mainly delivered from Ukraine. It can also be delivered from Serbia, however the supply from this country is carried out only from time to time. The delivery can be realized in different ways depending on the current conditions. Typically, supplier A (Ukraine) covers 80% of the demand for raw materials, while the remaining 20% provides supplier B (Brazil). In case of supply disruptions from two of the above mentioned suppliers, the demand for raw materials may be covered by the delivery from a supplier C (Serbia), but this involves higher transport costs. Timely delivery depends on many often unpredictable factors. Such cases cause the discontinuity of supplies, the effects of which may be different, even including the production stoppage. In order to investigate the effect of such disturbances on the continuity of production process, the simplified simulation model of the logistics system of raw materials supply using the demo version of the software AnyLogic [19] was constructed (see Figure 1). The model takes into account the relevant logistic delays. [1] The risks arising from the disruption within a supply chain and the ways of preventing their adverse effects were modelled using agent systems [7, 13], while the moments, when threats occur were modelled as random discrete events with the use of the corresponding distributions [3]. The task of the agents is an appropriate (not too early or too late) response to the presence of distortions within the supply cycle in order to sustain continuity of a production by providing the required amount of raw materials to the plant. The different scenarios for disruptive events have been analysed using computer simulation. In addition, the following options were analysed for each scenario [2]:

- No resources in the stockpile („lean” strategy - Just In Time supplying).
- Resources in the stockpile covering the five-days production (sustainable safe strategy).
- Resources in the stockpile covering the ten-days production ("crisis" strategy).

The simulation model of delivery system allows the analysis of various scenarios of the consequences of random events, which can disrupt the smooth supply or affect to the volume of production. With simulation model we can study of the impact of interruptions in the supply of raw materials and disturbances on the demand side on the level of production. Disturbing factors on demand side are generated as follows:

- Single (unforeseeable) increase in demand by approx. 25% before the crisis associated with a break of supply.
- One-time increase in demand by approx. 25% during the ongoing disruption in supplies.
- Weekly changes in demand of about 10% relative to the assumed value of the average of the data.

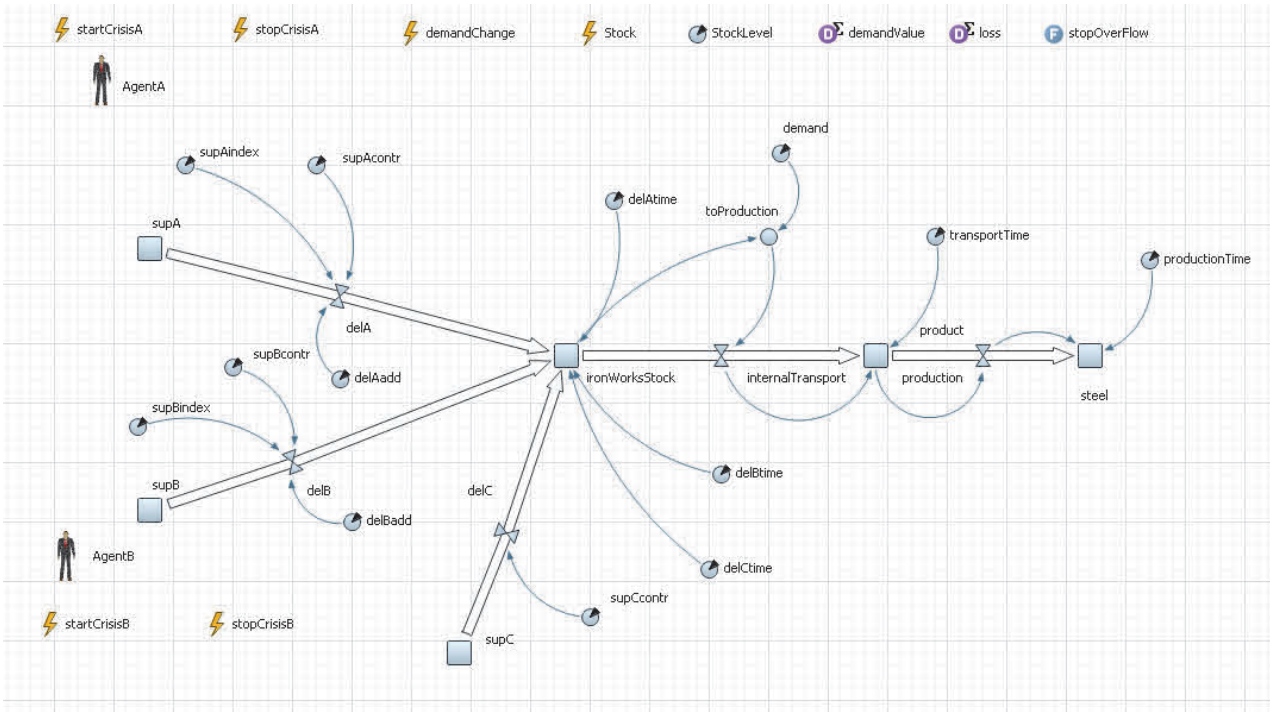


**Fig. 1** The simulation model of the steel mill transport system

These factors should be considered as the risk of changes in demand, in simulation model they are generated at random way by above-mentioned scenarios. The causes of disruption on the supply side can be different. In the example it was assumed that the moment an interruption in the supply and the duration of the break is a random variable. Figure 2 shows an example of simulation results. On their basis we can estimate the loss of production due to interruptions in the supply of raw materials and the effects of a demand change.

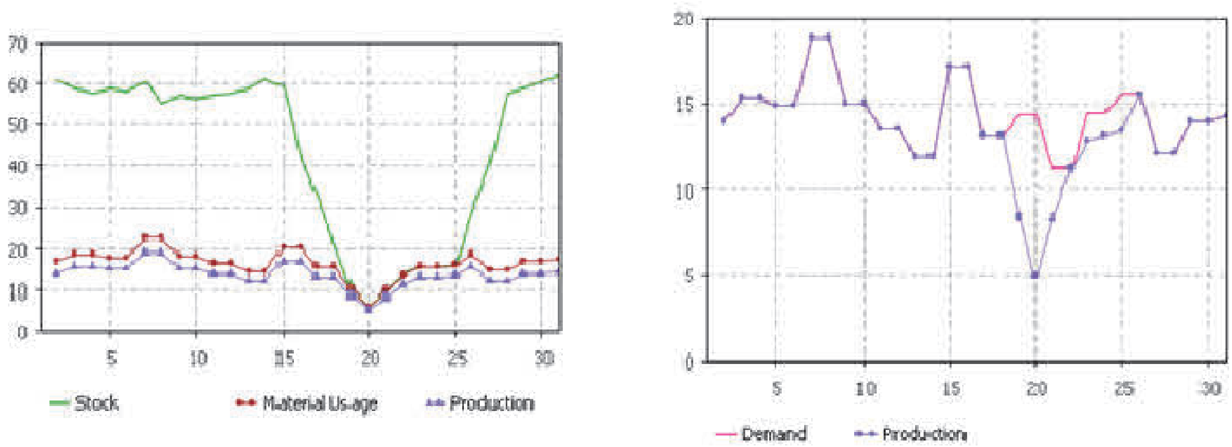


**Fig. 2** Simulation results

## 4. CONCLUSION

Presented model allows to analyse the various scenarios of the impact of the disruption in the raw material delivery and changing demand to the level of the production. The purpose of the research was to assess the vulnerability of the logistical system in a response to various disturbances that may occur within the supply of raw materials on the way to steel mills The analysis of the results can give an answer to the question of what level of the reserve should be maintained in order to prevent the negative effects brought by the lack of the raw materials depending on the source, time and duration of the of disruption, also allow for the analysis of the effects of a demand change on a continuity of the operation of the system.

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