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SIMULATION MODEL FOR SUPPLY CHAIN RELIABILITY EVALUATION

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Abstract. This paper investigates problems related to supply chain risk identification and simulation-based risk evaluation. Accordingly, the paper is divided into two logical parts. The first part represents earlier researches about risk recognition within the sphere of supply chains. The distinction between terms "uncertainty" and "risk" is discussed. Based on the predefined supply chain functions, additional risks connected with supply chain reliability are recognized. Then, a conception of simulation-based risk evaluation approach is discussed. Within the second part of the paper, a numerical example is provided, within which a simplified supply chain system is defined and corresponding risk evaluation is performed.

Keywords: risk, uncertainty, supply chain risk, simulation.

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1. Introduction

Nowadays information technologies help in managing large and complicated supply systems. Supply chain management provides wide profit increase opportunities for all potential members of its structure. But actually, as the range of available information becomes larger, the amount of uncertain factors increases too, and disruptions, which can be produced by those factors, become more destructive. Risk handling is becoming a very important part of the supply chain management process.

2. Supply chain risk recognition

There are many related works, which suggest various techniques of supply chain risks evaluation and mitigation. In many cases the advised approaches lead to various ideas of development about risk term perception within supply chains. The reason for such situations might

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be the lack of precise formulation of these terms: supply chain, risk and uncertainty. Thus, some discussions about mentioned terms are provided with the aim of defining risk meaning within supply systems.

2.1. Uncertainty and risk

Though risk and uncertainty has been an object of very extensive researches in various scientific directions for many years, the clear unique formulations of its meaning have not been stated yet. The attempts to define the terms uncertainty and risk have spawned a large variation of approaches, as evidenced by the broadly themed emanation from various academic disciplines (Brindley and Ritche 2004). There are at least two schools of thought on the issue, if risk and uncertainty have the same meaning; thus the clear definitions of the mentioned terms have to be provided. One way to distinguish between the two terms relies on the ability to make probability assessments. Then, risk corresponds to events that can be associated with given probabilities; and uncertainty corresponds to events for which probability assessments are not possible. This suggests that risky events are easier to evaluate, while uncertain events are more difficult to assess. According to another school of thought, there is no sharp distinction between risk and uncertainty because of the problem that there is no clear consensus about probability term (Chanvas 2004).

This paper discuses a modified idea about risk and uncertainty collaboration. First, it is suggested that, in general, the risk can be described by a few parameters like risk origin reasons, risk circumstances and risk origin probability (Pettere and Voronova 2003). Then, uncertainty can be declared as the risk causing factor, which forms a changing environment, in which risky events may occur. Any risky event is defined as an event that is not known for sure ahead of time, but the risk itself is defined as the potential harm that may arise in future due to some present processes or some future events (Chanvas 2004; Logistics Field Audit 2004). The time is defined as risk general characteristic, which declares things that have already occurred and are not the object of risk management any more. At the same time uncertainty may vary over time; accordingly, those changes may affect the ability to make probability assessments for risky events. This gives a reason to distinguish tactical and strategic risk managements, but not the risk and uncertainty management terms (see Fig. 1).

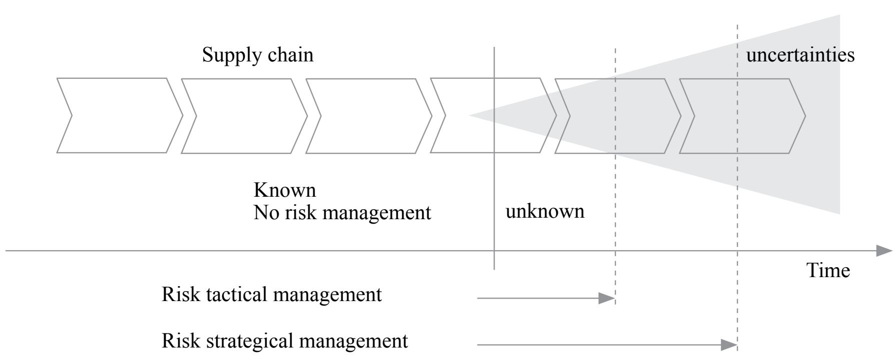

Fig. 1. Risk management horizon

It is suggested that in the studied system any risk appears due to a changing environment formed by different uncertainties. Each uncertainty can cause a risk event in the future. Yet, not all uncertainties produce risk for certain system functionality.

2.2. Supply chains

Similar uncertainties and risk are considered in supply chain systems. Business environment can be characterized as turbulent, meaning an environment with high uncertainty, rapid change, novel markets, high margins and very demanding customers. So, it consists of many uncertainties causing risks (see Fig. 2). For instance, the uncertainty within currency exchange rates may cause a risk of additional costs connected with bills revaluations. The list of possible uncertainty factors in different supply chain planning levels is provided in Table 1 (Landeghem and Vanmaele 2002). Still, as well as for supply chain risks, a classification of possible uncertainty sources depends on a supply chain formulization.

As for many complex systems, there is no single definition established for a supply chain, different researchers provide various definitions, which more or less reflect the goals of supply chain management. When different perceptions of supply chain nature are possible, the mean of supply chain risk cannot be established. Accordingly, there are many various opinions about supply chain risk in different references.

In this work, the supply chain is defined as a network of organizations involved into managing material, information and financial flows, that is necessary for effective realization of basic logistics operations (manufacturing, storing, transportation etc.), aimed to furnish the end customer with needed products or services produced by those organizations.

In related researches, any organization, which is included in a supply chain management process, is called a supply chain resource. The effective realization of basic logistics operations means to minimize total logistics costs while maintaining necessary quality parameters.

It is important to distinguish between supply chain management and detailed logistics (micrologistics) inside separate organizations. The use of supply chain conception is wider than logistics operation management approaches within particular organizations; here it is accepted that supply chain management is part of total logistics system. At the same time, the micrologistics management should also be included in the supply chain management process (Fig. 3).

2.3. Supply chain risks

In general, supply chain risk management can be defined as the management of supply chain risks through coordination or collaboration among the supply chain partners, so as to ensure profitability and continuity. Then, the aim is to control, monitor and evaluate supply chain risk, which will serve to safeguard continuity and maximize profitability (Tang 2005; Deloitte: Enterprise Risk Services 2004). Still, the clear unique formulations of supply chain risk have not been stated yet.

In this paper, risks referred to disruption such as earthquakes, floods, terrorist attacks, etc., or economic crises or strikes, are assigned to supply chain external group (Fig. 3). Other risks

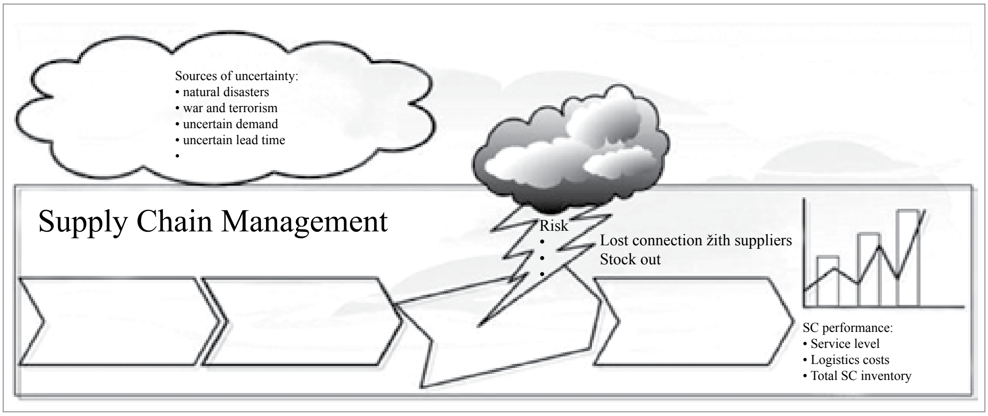

Fig. 2. Supply chain structural risk

Table 1. Sources of uncertainty in supply chains

Sources of uncertainties	Supply chain planning level		
	Operational	**Tactical**	**Strategic**
Exchange rates	high	medium	-
Supplier lead-time	low	high	low
Supplier quality	medium	low	-
Manufacturing yield	medium	medium	-
Transportation times	medium	medium	low
Stochastic costs	low	high	medium
Political environment	-	-	medium
Customs regulations	low	medium	high
Available capacity	medium	medium	low
Subcontract availability	high	medium	-
Information delays	high	medium	-
Stochastic demand	low	high	medium
Price fluctuations	low	high	low

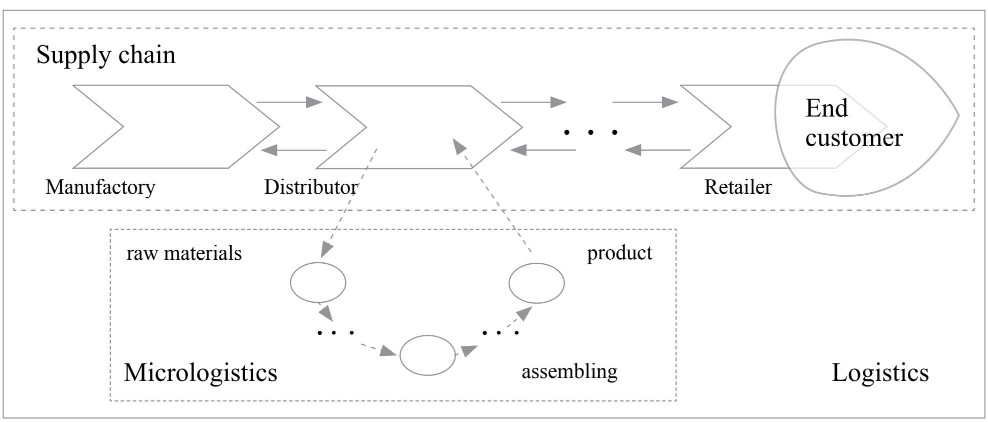

Fig. 3. Supply chain as part of logistics system

are defined as supply chain internal risks. Most researches on this subject observe risks that are related to some operation risks. These risks are usually connected with separate failure events within discrete supply chain resources. For instance, such supply chain risks might be related to the logistics activities in companies' flows of material and information (Norrman and Lindroth 2004; Hallikas and Virolainen 2004). A more detailed review of researches connected with such risks is presented in Tang's work (Tang 2005).

The obvious disadvantage of such supply chain risk management is difficulties in recognition, how particular operational risks affect other supply chain resources. Another drawback is that risks connected with supply chain structure characteristics are ignored. On the other hand, the conception of supply chain organization assumes management based on the whole system coordination. Thus, it is necessary to define an additional group within supply chain internal risks – supply chain management risks (Fig. 4). That means that additionally risk management should be directed to increase the reliability of the whole system. Similar works about these risks identifying, evaluation and mitigation can be found in a recent publication (Handfield and McCormack 2008). For example, within the management process, logistic specialists might be interested to know: what a real reliability for the whole supply system is and how many critical failures occur during the chosen period of time; which suppliers are vital and should be provided by particular detailed management; how the chosen supply chain can be reconstructed in order to reduce critical failure risks, etc.

Let us advise three conditional states, which characterize supply chain system's ability to work properly. Normal condition defines supply chain normal work, which means material, financial and information stream run within the defined rules. At the same time some supplier failures are possible. For such cases, reserve suppliers or substitution materials should be used (Fig. 6a). Then, an emergency condition will be established, within which a final

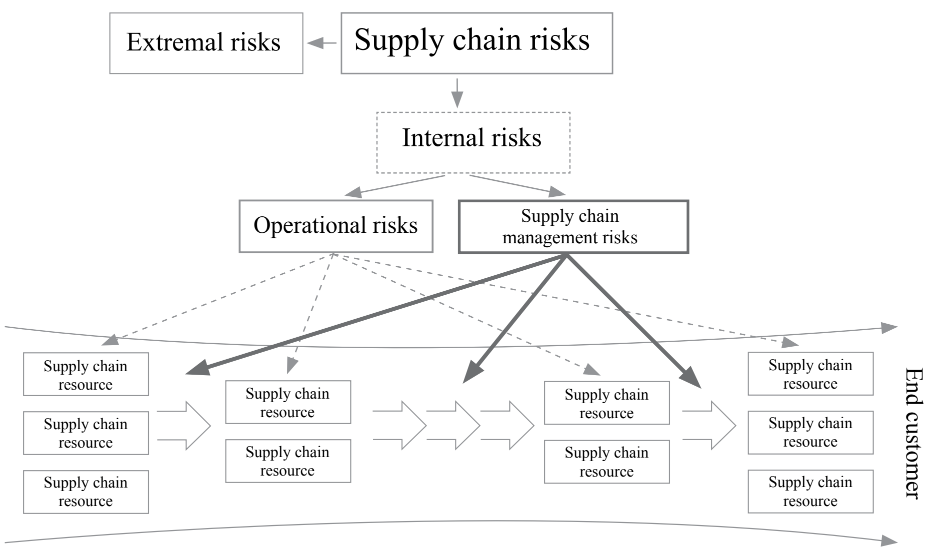

Fig. 4. Supply chain risks

profit decreases, but the supply chain still continues to function. Cases, in which reserve or substitution are not possible, are called crises, in the sense that they affect the ability to satisfy final customer.

It is accepted that supply chain management risks are associated with the ability of supply system to change its conditional state for the worse. So, supply chain management risk is possible disruptions that can affect supply chain ability to function normally (Fig. 5).

3. Supply chain risk evaluation

Risk evaluation is the next sophisticated step after risk recognition and identification. Commonly, risk assessment and evaluation are based on calculating a risky event occurrence probability with corresponding possible disruption values. There are 3 possible modes of probability evaluation: empirical, theoretical and subjective evaluation (Condamin *et al.* 2006). For previously defined concept of supply chains, risk evaluation might be based on varied mathematical methods. For instance, to evaluate characteristics of system transition between different conditional states, Markov process mathematics can be adopted; system stability for certain conditional states can be described by reliability theory. However, necessary mathematics becomes too labour intensive in large and volatile systems, such as supply chains. At the same time, some researchers state that risk quantification builds on knowledge elicitation rather than on data collection. Data must only be considered as part of the available knowledge, the main source being human expertise (Condamin *et al.* 2006). Thus, the use of simulation is advised as an effective tool for developing a supply chain model, which not only simplifies risk evaluation task within complicated systems, but also complies with expert opinion for input data realization.

Simulation is widely used in supply chain management. However, most supply chain risk evaluation models study operational risks within particular supply chain resources. Here, it is advised to perform a reliability analysis of supply systems. Initially, such analysis should be based on expert-based opinions. It is assumed that an expert can provide general information about organizations involved in a supply chain (see Table 2).

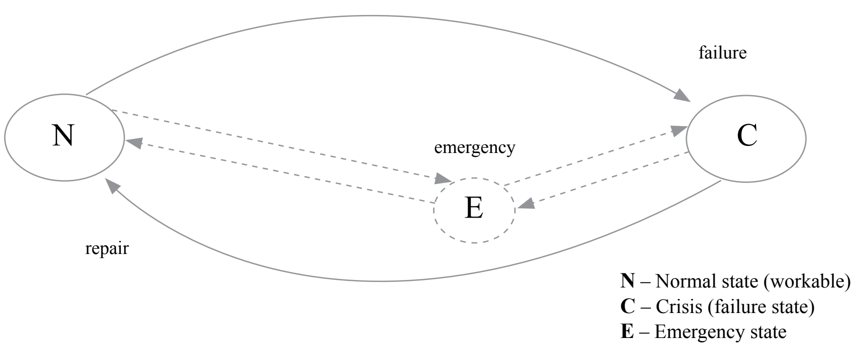

Fig. 5. Supply system processes

Table 2. Supply system general information

Name	Description
Supply chain main resources	Organizations (or supply chain members), which are regularly involved in supply system
Supply chain alternative resources	Organizations involved in supply system in cases, when some main resources cannot function normally
Failure rates	Conditional criteria for assessing risk of particular resource functioning failure
Repair rates	Conditional criteria for assessing probability that particular resources return to operation

Similar to a reliability analysis in a mechanical environment, the functioning failure of the whole system (crisis) can be easy evaluated mathematically or simulated. In case of supply chains, the additional conditional state – emergency can be formulated as the necessity to involve alternative resource into the supply system. Then, conditional state changing parameters will represent supply chain management risks. A mathematical and simulation-based risks evaluation numerical example for a more simplified supply system is presented below.

3.1. Simplified supply chain

For further discussion, a simplified supply system will be described (Fig. 6a). It consists of six main and two substitution supply chain members. The first two suppliers provide the system with raw materials of two different types. Then, the remaining relevant supply chain members assemble final product and deliver it to customers. The substitution supplier (Supplier 3) can deliver both types of material directly to the assembly, if necessary. The usages of substitution supplier and substitution transportation intermediary (Delivery 3) increase supply chain total costs.

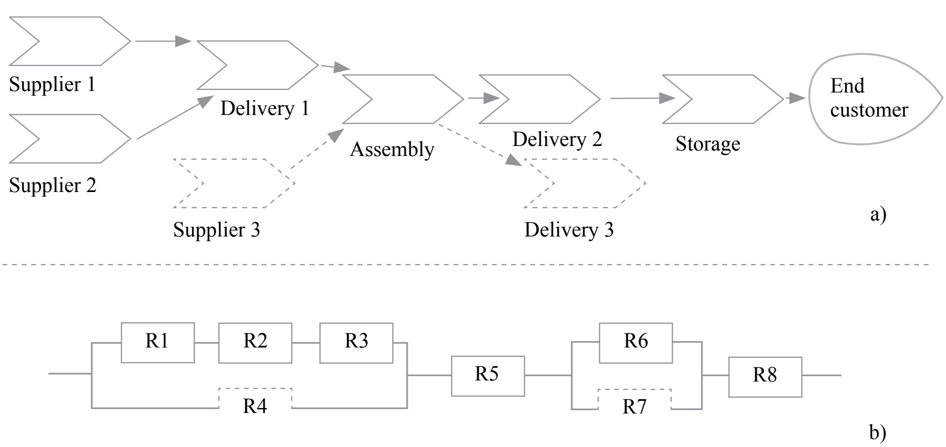

Fig. 6. Simplified supply chain

Table 3 provides individual characteristics of organizations involved in this network. In current simple case, there are only two conditional states (failure and functioning); thus, characteristic parameters of the defined system reliability are an object of interest.

Table 3. Functioning characteristics of supply chain resources

ID	Supply chain resource mark	Supply chain resource	Failure rates, λ days^{-1}	
			Experiments 1–2	Experiment 3
1	R1	Supplier 1	$3{,}87*10^{-4}$	$1{,}35*10^{-4}$
2	R2	Supplier 2	$3{,}80*10^{-4}$	$1{,}15*10^{-4}$
3	R3	Delivery 1	$3{,}75*10^{-4}$	$0{,}90*10^{-4}$
4	R4	Supplier 3	$2{,}55*10^{-4}$	$0{,}45*10^{-4}$
5	R5	Assembly	$2{,}75*10^{-4}$	$0{,}35*10^{-4}$
6	R6	Delivery 2	$2{,}90*10^{-4}$	$1{,}80*10^{-4}$
7	R7	Delivery 3	$2{,}70*10^{-4}$	$1{,}55*10^{-4}$
8	R8	Storage	$1{,}85*10^{-4}$	$0{,}25*10^{-4}$

The system is defined as not repairable. Then, survival rate for a certain period of time is taken as a basic system reliability parameter that will be used for simulation model validation. The conditional state is defined in the following way:

$$X(t) = f(x) = \begin{cases} 1, & \textit{tf a system is functioning at time t} \\ 0, & \textit{tf a system is in a failed state at time t} \end{cases} . \quad (1)$$

The other two assumptions are: a "burn-in" and a "wear-out" periods can not be taken into account, time failure functions can be described by exponential distribution (as it is the most commonly used life distribution for technical system reliability analysis) (Andrew and Moss 2002; Rausand and Hoyland 2004).

3.2. Reliability mathematical evaluation

As stated above, mathematics provides a wide range of methods for evaluating systems reliability characteristics. In this paper, reliability theory is applied to study the simple system. At the same time, basic mathematical methods (which are provided in this paper) are necessary for further validation of the created simulation model.

So, within the studied supply chain, the reliability is defined as a probability that a system will not fail before predicted time moment T:

$$R(t) = \Pr(T \geq t) = \int_t^{20} f(u)\,du = e^{-\lambda t} . \quad (2)$$

In the same way, from a known probability distribution (exponential) it is possible to define a mean time to failure:

$$MTTF = \int_0^{20} R(t)\,dt = \int_0^{20} e^{-\lambda t} dt = \frac{1}{\lambda} . \quad (3)$$

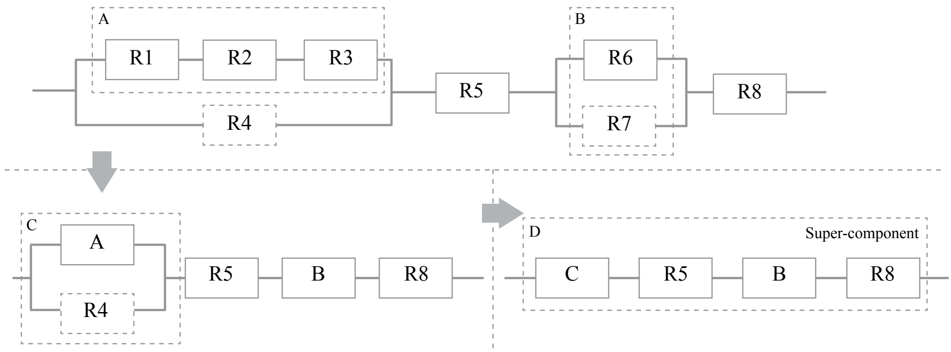

Fig. 7. System reliability network

The above mathematics is usually used for describing a single component's (in most cases, a mechanical or electronic equipment) reliability. Still, supply chains consist of several separate nodes. The redrawn network of defined supply system is represented above (Fig. 6b). Then, a structural analysis is needed.

When a network consists of only combinations of series and parallel structures, its analysis can be carried out in stages. Each stage simplifies the network by combining series and parallel sections. By using equations for series and parallel combinations, network sections can be obtained at each stage. The reduction process continues until one "super-component" remains, which links the start and end component (Rausand and Hoyland 2004). The performance of the studied system is identical to the developed "super-component" (Fig. 7).

Equations for calculating reliabilities of simple series and parallel networks of n components with reliabilities R_i are the following:

$$R_{series} = \Pi_{i=1}^{n} R_i \,, \tag{4}$$

$$R_{parallel} = 1 - \Pi_{i=1}^{n} \left(1 - R_i\right). \tag{5}$$

The accumulative formula for the whole supply system reliability calculation is shown below; the corresponding evaluated parameters are provided in Table 3.

$$\begin{gathered} R_{sys} = \left(1-\left(1-R_1R_2R_3\right)\left(1-R_4\right)\right)R_5\left(1-\left(1-R_6\right)\left(1-R_7\right)\right)R_8\,, \\ R_{sys}\left(t\right) = \left(1-\left(1-e^{-\lambda_1 t}e^{-\lambda_2 t}e^{-\lambda_3 t}\right)\left(1-e^{-\lambda_4 t}\right)\right) * e^{-\lambda_5 t} * \\ \left(1-\left(1-e^{-\lambda_6 t}\right)\left(1-e^{-\lambda_7 t}\right)\right) * e^{-\lambda_8 t}\,. \end{gathered} \tag{6}$$

3.3. Simulation example

For the problem under consideration, discrete-event simulation model was created using the ProModel software (Harrell *et al.* 2004). The simulation process includes 3 experiments; each of them consists of 500 replications. The basic simulation time period is one day; each replication

Table 4. Reliability evaluation results

Exp. No.	Mathematical evaluations		Experimental data	
	$R_{sys,}$	$MTTF_R$	R_{Sim}	$MTTF_{Sim}$
1	62,4 %	1304 days	61,2 %	1277 days
2	72,5 %	1304 days	73,4 %	1277 days
3	93,3 %	5263 days	94,0 %	5525 days

continues until simulated system gets into a failed conditional state. The necessary reliability parameter values are evaluated using statistics gained from those 500 replications.

The aim of the first experiment is to find a probability that the system will survive for the time period of 730 days. In the second experiment, the necessary survival time period is decreased by 200 days. Then, failure rates for separate network components are increased in the third experiment with the goal to make 9^{th} formula (9) more suitable (T=730 days) for system reliability evaluation. The calculated experimental data are shown in the table below:

By observing simulation and mathematical evaluation results, some conclusions can be made. First of all, it is possible to draw conclusions about the created simulation model adequacy following from the comparing simulation and "combinations of simple series and parallel structures" methods results. Then, in cases of more complicated supply chain systems, this mathematical method would be too labour intensive. Moreover, the method of simple structures combinations is limited and cannot be used for every network structure analysis. On the other hand, the created simulation model can be restructured with the aim to analyse different supply chains with no limit on network complicity. In addition, simulation can be used for "repairable" or "multi-conditional states" systems.

4. Target simulation model for supply chain reliability evaluation

It can be seen that the above example has many limitations. For instance, the data about failure rates in particular supply chain nodes, which can be gained from organizations managers (expert-based), make simulation output results very subjective. Consequently, it is advised that in further simulation model development, within a global network, each resource can be represented as an additional organizational chain at micrologistics level (Fig. 3). Using a more detailed simulation of particular supply chain resources (for which this information is available) it is possible to consider interconnections between processes at various supply chain organizations. At the same time, in a real business supply chains should be considered as "repairable" systems.

Finally, it is possible to conceive about irrationality to perform more complex mathematical evaluations for the advised model. Still, simulation environment allows easy performing of necessary improvements.

5. Conclusions

This current paper investigates problems related to risk recognition and simulation-based risk evaluation in the sphere of supply chains. Though a lot of methods for the supply chain risk management have been developed, there is no a universal solution for this problem yet. Thus, the definitions of risk, uncertainties and supply chains terms are discussed. Using these definitions, the supply chain risk is defined as possible disruptions that can affect supply chain ability to function normally. Risk evaluation can be considered as separate sophisticated process within risk management. In the current research, the use of simulation techniques is advised as an effective instrument for supply chain risk evaluation. It is very important that the simulation model can fully consider expert opinion through the input data about risks in separate supply chain members. By observing these data, the model provides risk values for the whole supply network.

The output results of the model are statistical data about structure reliability of the simulated supply chain. In the same way, reliability parameters were evaluated using the analytical mathematics. For all that, the corresponding mathematical formulas application becomes too labour intensive in large and volatile systems. Still, mathematical model application helps in validation of simulation models.

The models considered in the numerical example of this paper have many simplifications and assumptions, which make them hardly adaptable in practice. Thus, the future research is directed towards extending simulation-based supply chain reliability models. The final goal of the research is to provide supply chain managers with powerful simulation-based software for supply networks reliability analysis.

References

Andrew, J.; Moss, T. 2002. *Reliability and Risk Assessment*. Professional Engineering Publishing Limited.

Brindley, C.; Ritche, B. 2004. Supply Chain Risk, in Brindley, C. (ed.). *Supply Chain Risk*. Ashgate Publishing Ltd, 3–13.

Chanvas, J. 2004. *Risk Analysis in Theory and Practice*. Elsevier Inc.

Condamin, L.; Louisot, J.; Naim, P. 2006. *Risk Quantification: Management, Diagnosis and Hedging*. John Wiley & Sons Ltd.

Hallikas, J.; Virolainen, V. 2004. Risk Management in Supplier Relationships and Networks, in Brindley, C. (ed.). *Supply Chain Risk*. Ashgate Publishing Ltd, 43–65.

Handfield, R.; McCormack, K. 2008. *Supply Chain Risk Management: Minimizing Disruptions in Global Sourcing*. Auerbach Publications.

Harrell B; Chosh, B.; Bowden, R. 2004. *Simulation Using ProModel*. The McGraw-Holl Companies, Incorporated.

Landeghem, H.; Vanmaele, H. 2002. Robust planning: a new paradigm for demand chain planning, *Journal of Operational Management* 20(6): 769–783.

Norrman, A.; Lindroth, R. 2004. Categorization of Supply Chain Risk and Risk Management, in Brindley, C. (ed.). *Supply Chain Risk*. Ashgate Publishing Ltd, 14–27.

Pettere, G.; Voronova, I. 2003. *Business Risk Management*. Banking Institution of Higher Education (in Latvian).

Rausand, M.; Hoyland, A. 2004. *System Reliability Theory: Models, Statistical Methods and Applications*. John Wiley & Sons Ltd.

Tang, C. 2005. Perspectives in Supply Chain Risk Management, *International Journal of Production Economics* 103(2): 451–488.

Websites

Deloitte: Enterprise Risk Services. 2004. Supply Chain Risk Management: Better control of your business environment. Available from Internet: <*http://www.deloitte.com*>.

Logistics Field Audit, Inc. 2004. LFA Supply Chain Risk Management. Available from Internet: <*http://www.lfa.ru/files/download/14.html*> (in Russian).

TIEKIMO GRANDINĖS PATIKIMUMO ĮVERTINIMO IMITACINIS MODELIS

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Santrauka

Šiame straipsnyje nagrinėjamos problemos, susijusios su tiekimo grandinės rizikos identifikavimu ir modeliavimu pagrįstu rizikos įvertinimu. Straipsnis suskaidytas į dvi logines dalis. Pirmojoje dalyje aprašomi ankstesni tiekimo grandinėse slypinčių rizikų tyrimai. Aptariami terminų *neapibrėžtumas* ir *rizika* skirtumai. Remiantis pasirinktomis tiekimo grandinės funkcijomis, nustatytos naujos rizikos, kurios veikia tiekimo grandinės patikimumą. Toliau aptariama modeliavimu pagrįsta rizikos įvertinimo koncepcija. Antroje straipsnio dalyje pateiktas skaitmeninis pavyzdys, kuriame sudaroma supaprastinta tiekimo grandinės sistema ir įvertinama su ja susijusi rizika.

Reikšminiai žodžiai: rizika, neapibrėžtumas, tiekimo grandinės rizika, modeliavimas.

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