SIMULATION-BASED MEASUREMENT OF SUPPLY CHAIN RISKS

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ABSTRACT

For today's supply chains, risk management becomes an important instrument, which can protect a system from sudden collapses. Still, the meaning of the supply chain risk and techniques for its evaluation and mitigation still continue to be extensively researched. In this paper, simulation is used for risk management in supply chains. Within the discussed research, the supply chain risk is defined as possible disruptions that can affect the supply chain ability to function normally. Due to that, system reliability parameters are taken as a basis for risk evaluation. The difficulties of making the corresponding assessments mathematically are argued because of supply systems complexity. Then, simulation is applied as an effective tool for risk evaluation and management of the predefined supply chain. At the same time, the reliability theory mathematics is used for the created simulation model validation.

INTRODUCTION

The supply chains of today represent complex systems with wide profit increase opportunities and potentially high risks level. At the same time, the meaning and the concept of supply chain risk are not strongly defined. Most researches on this subject observe risks connected with separate disruptions within discrete supply chain members. Then, supply chain management influence on particular risks values is considered. For instance, such risks can be prescribed as deficiency in inventory, forecast failures, manufacturing quality failures, etc. Those risks are well known to managers in the sphere of logistics. A more detailed discussion of particular risks is presented in (Klimov and Merkuryev 2007). The obvious disadvantage of such supply chain risk management is difficulties in recognition, how particular risks affect other supply chain members. Thus, with such perception managers can at best evaluate failure rates for a single supply chain member, but not for the whole system. On the other hand, the conception of supply chain organization assumes management based on the whole system coordination. Thus, risk management should be directed to increase the reliability of the whole system. For example, within the management process, logistic specialists might be interested to know: what real reliability of supply system is and how many critical failures occur during a 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.

So, appropriate answers can provide supply chain managers with necessary decision support information for further supply system development, reorganization and supply chain risk monitoring. Within the current research the meaning of supply chain risk is accepted as failures, which lead supply systems to the so-called critical or emergency states that imply unavailability to fulfil main function of the supply chain system - satisfying end customer need and profit for supply chain members. Thus, within our research, it is advised to use reliability theory aspects with the aim to create a simulation model, which will be used for further supply chain risk management.

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RELIABILITY EVALUATION OF "NON-REPAIRABLE" SUPPLY CHAIN

Although pure mathematical approaches are hardly adoptable for supply chain reliability estimating, it is difficult to overstate the importance of the mathematical model development. Here, reliability theory basic aspects are considered with the aim to evaluate reliability parameters for a supply chain with various simplifications. An analogical simulation model is created and validated by mathematically estimated values. Then, a more complicated reliability simulation is performed on the basis of validation results.

Supply System

Within the current research, the supply chain is defined as a network of organizations involved in managing material, information and financial flows, that is necessary for realization of basic logistics operations (manufacturing, storing, transportation etc.), aimed to furnish the end customer with needed products or service produced by those organizations. In the paper the simplified supply chain is considered, whose network structure is shown in Figure 1a. 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 a 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 usage of substitution supplier and substitution transportation intermediary (Delivery 3) increases supply chain total costs.

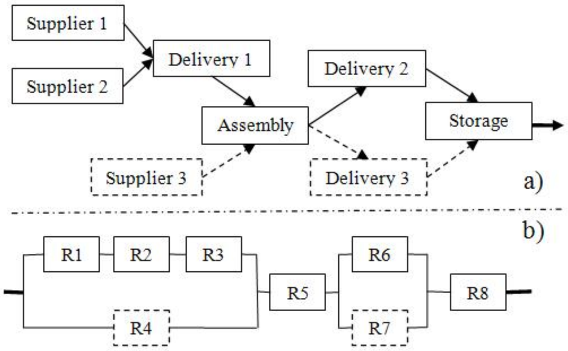

Figure 1: The Network of Simple Supply Chain

In this section, the supply chain risk is treated as particular (or several) supply chain member failures that leads the whole system to an unworkable state. Accordingly, system reliability parameters are studied as a basis for such risks evaluation.

System Reliability and Assumptions

Over time the system under study may have changed from one conditional state to another. Still, within this section, the supply chain is defined as a "non-repairable" system.

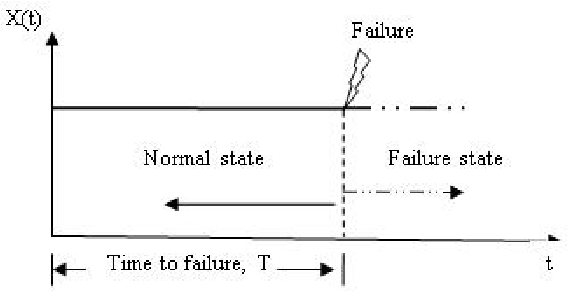

Figure 2: Reliability of "Non-Repairable" System

Thus, there are only two conditional states: failure and functioning (or normal) states.

$$X(t) = \begin{cases} 1, & system\ is\ functioning\ at\ time\ t \\ 0, & system\ is\ not\ functioning\ at\ time\ t \end{cases} \quad (1)$$

Two global assumptions are defined for this paper. Thirst, it is argued that studying a supply chain and its reliability, a "burn-in" and a "wear-out" period can be not taken into account. It is also suggested that supply chain managers can predict failure and recovery rates (in cases of failures) for a particular supply chain member and at the same time those values are fully independent. The last assumption is that time failure (and recovery) functions can be described by exponential distribution, as it is the most commonly used life distribution for technical systems reliability analysis (Andrews and Moss 2002; Rausand and Hoyland 2004).

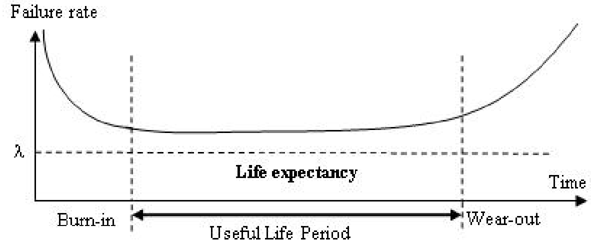

Figure 3: The "Bathtub" Curve

In general, the reliability of a supply chain can be defined as a probability that system will not fail before the predicted time moment *T*:

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

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

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

The above mathematics is usually used for describing a single component's (in most cases, a mechanical or electronic equipment) reliability (Jastrebeneckij and Ivanova 1989). However, supply chain system consists of several separate organizations; hence, a structural analysis should be used for further mathematical evaluations of the whole system reliability parameters.

Structural Analysis of a Supply Chain

As stated, it is assumed that the data about failure rates in particular supply chain organizations are known. Then, reliability or functionality for whole supply chain system can be evaluated using structural analysis methods. There are several techniques for reliability estimation within complex systems. Here "Combinations of simple series and parallel structures" and "Minimal path sets" methods are used for reorganizing the supply network into one complex node, whose reliability parameters can be calculated with similar equations (2, 3).

Combination of Simple Series and Parallel Structures

The redrawn network of the defined supply system is presented above (see Figure 1b). 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" (see Figure 4).

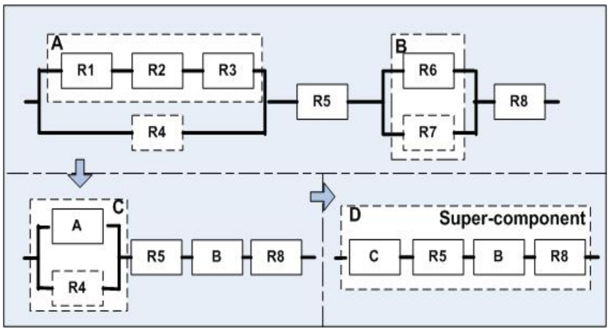

Figure 4: System Reliability Network

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

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

$$R_{parallel} = 1 - \prod_{i=1}^{n}(1 - R_i) \tag{5}$$

The accumulative formula for the whole supply system reliability calculation is shown below.

$$R_{sys} = \big(1 - (1 - R_1R_2R_3)(1 - R_4)\big)R_5\big(1 - (1 - R_6)(1 - R_7)\big)R_8 \tag{6}$$

$$R_{Sys}(t) = \Big(1 - \big(1 - e^{-\lambda_1 t}e^{-\lambda_2 t}e^{-\lambda_3 t}\big)\big(1 - e^{-\lambda_4 t}\big)\Big) * e^{-\lambda_5 t} * \Big(1 - \big(1 - e^{-\lambda_6 t}\big)\big(1 - e^{-\lambda_7 t}\big)\Big) * e^{-\lambda_8 t} \tag{7}$$

The corresponding evaluated parameters are provided in Table 3.

Minimal Path Sets
Unfortunately, the above method is hardly adoptable for real systems. Thus, in practice, more universal methods are used. The "minimal path" method has a wider range of applications and it is adoptable for systems, which do not consist only of combinations of series and parallel structures. Still, it has a disadvantage; it only provides an approximation of reliability values and this method becomes useless in cases when systems components have low reliability rates (Andrews and Moss 2002). The "minimal path" set (which is part of total component set), ensures that the system is functioning. In Table 1 the "minimal path" set for the predefined supply chain is provided.

Table 1: "Minimal Path" Set

Path name	Path structure
Total path set	{R1;R2;R3;R4;R5;R6;R7;R8}, {R1;R2;R3;R4;R5;R6;R8}, {R1;R2;R3;R5;R6;R7;R8}, {R1;R2;R3;R5;R6;R8}, ..., {R4;R5;R7;R8}.
"Minimal path" set	{R1;R2;R3;R5;R6;R8}, {R1,R2,R3,R5,R7,R8}, {R4;R5;R6;R8}, {R4;R5;R7;R8}

According to the "minimal path" method, the following equations should be used for the network structure function evaluation:

$$R_{sys}(X) = \coprod_{j=1}^{p} p_j(X) = 1 - \prod_{j=1}^{p}\Big(1 - p_j(X)\Big) \tag{8}$$

$$p_j(X) = \prod_{i \in P_j} R_i \; for \; i = 1,2,\dots,s \tag{9}$$

p_i: is the minimal path set

Using the above equations, it is possible to define structural function (11), whose approximated value can be used for considering system reliability:

$$Q_{sys} \le \phi(X) = 1 - (1 - X_1X_2X_3X_5X_6X_8) * (1 - X_1X_2X_3X_5X_7X_8) * (1 - X_4X_5X_6X_8) * (1 - X_4X_5X_7X_8) \tag{10}$$

$$Q_{Sys}(t) \le 1 - \big(1 - e^{-\lambda_1 t}e^{-\lambda_2 t}e^{-\lambda_3 t}e^{-\lambda_5 t}e^{-\lambda_6 t}e^{-\lambda_8 t}\big) * \big(1 - e^{-\lambda_1 t}e^{-\lambda_2 t}e^{-\lambda_3 t}e^{-\lambda_5 t}e^{-\lambda_7 t}e^{-\lambda_8 t}\big) * \big(1 - e^{-\lambda_4 t}e^{-\lambda_5 t}e^{-\lambda_6 t}e^{-\lambda_8 t}\big) * \big(1 - e^{-\lambda_4 t}e^{-\lambda_5 t}e^{-\lambda_7 t}e^{-\lambda_8 t}\big) \tag{11}$$

Q_{sys}: approximated reliability value

The evaluated reliability characteristics are given in Table 2.

Reliability Simulation

The complexity of mathematical methods application is obvious. Thus, it is suggested that any network, which consists of basic supply chain members (no detailed information within separate nodes is taken into account), can be easily represented by a simulation model. Moreover, it is easy to develop a program for such simulation model automated generation. It gives to potential supply chain managers the opportunity to make simulation-based experiments using different input data: supply chain network structures and particular supply chain nodes failure rates (see Figure 5). Then, executed experiments will provide specialist with statistical data, which can be used for further reliability analysis.

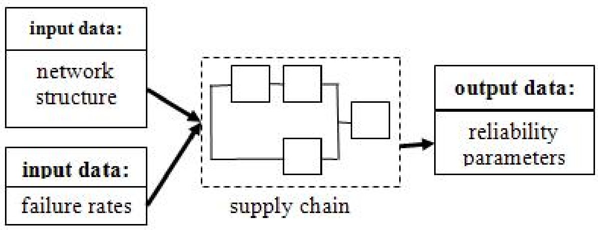

Figure 5: System Reliability Simulation

For our goals ARENA 8.0 simulation language is used. The simulation process of the "non-repairable" system includes three experiments; each of them consists of five hundred replications. The basic simulation time period is one day. The necessary reliability parameters values are evaluated using statistics gained from those five hundred replications.

The aim of the first experiment is to find the probability that the system will survive in 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 11th formula more suitable (t=730 days) for system reliability evaluation. The calculated experimental data are shown in Table 3. For all three experiments mean time to failure is calculated, where *MTTF* is gained from simulation results, but $MTTF_R$ and $MTTF_Q$ are calculated due to R_{sys} and Q_{sys} accordingly.

Table 2: Failure Rates

Node	**Failure rates, λ days^{-1}**	
	Experiments 1-2	Experiment 3
R1	$3{,}87*10^{-4}$	$1{,}35*10^{-4}$
R2	$3{,}80*10^{-4}$	$1{,}15*10^{-4}$
R3	$3{,}75*10^{-4}$	$0{,}90*10^{-4}$
R4	$2{,}55*10^{-4}$	$0{,}45*10^{-4}$
R5	$2{,}75*10^{-4}$	$0{,}35*10^{-4}$
R6	$2{,}90*10^{-4}$	$1{,}80*10^{-4}$
R7	$2{,}70*10^{-4}$	$1{,}55*10^{-4}$
R8	$1{,}85*10^{-4}$	$0{,}25*10^{-4}$

Table 3: Reliabilities of "Non-Repairable" System

Exp. No.	**Mathematical evaluation**			
	$R_{sys,}$	Q_{sys}	$MTTF_R$	$MTTF_Q$
	percentages		days	
1	62,4	≤85,	1304	1693
2	72,	≤93,	1304	1693
3	93,	≤99,	5263	5841
Exp. No.	**Simulation**			
	$R_{sys,}$, %		*MTTF, days*	
1	63,2%		1303	
2	71,0%		1303	
3	94,4%		5458	

By observing the results of simulation-based and mathematics-based evaluations some obvious conclusions can be made. First of all, the method of "minimal path" set, which is more usable for the network structural analysis, can't be used for components with large failure rates; thus, it is useless in most supply chains reliability analysis tasks. On the other hand, the method of simple structures combinations is limited by analysed system network complexity. Besides, mathematical methods are labour intensive enough even for simplified tasks. On the other hand, the simulation results are very close to mathematical evaluation; this gives the opportunity to conclude about further simulation model application to the reliability estimation of more complicated systems.

SUPPLY CHAIN RELIABILITY SIMULATION

In the previous section the simplified system was considered, which gives the opportunity to realize a validation for the created simulation model. Still, the results gained are hardly adoptable in a real life supply chain management. Then, the next step is to extend the system characteristics in order to get a more adequate reliability management tool. Thus, the created simulation model can be restructured with the aim to analyse various supply systems with no limit on a excessive complicity. In addition, simulation can be used for "repairable" or "multiconditional states" systems.

Repairable Supply Chains

Supply chain functioning doesn't end at the moment when the first failure has occurred. In practice, a supply chain can go through multiple disruptions, which stop system functioning only for a certain period of time, within which a necessary repair process is initialized (see Figure 6). Thus, repairable systems more precisely characterize supply chain functioning.

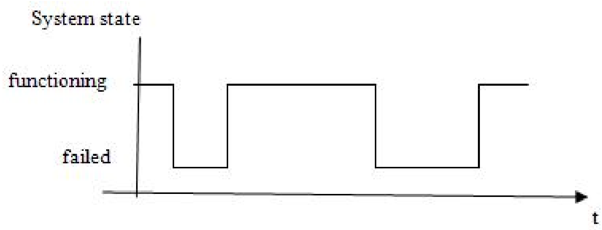

Figure 6: Repairable System Life History

As it is mentioned above, within the current paper repair distributions are described by exponential functions. The repair rates are assumed to be the same for all supply chain members. The corresponding repair rates are shown in Table 4.

Table 4: Repair Rates

Experiment No.	**Repair rates, υ days^{-1}**
4 and 7	$2{,}5*10^{-2}$
5 and 6	$10{,}5*10^{-1}$

The common parameters, which characterize a repairable system performance and which should be studied within a reliability analysis, are: system availability, system unavailability, failure intensity, expected number of failures, repair intensity, expected number of repairs, etc. Since our research is entirely theoretical and non-realistic input data are used, only a few parameters are presented in the output data Table 5.

Table 5: Results of Experiments 4 and 5

Experiment No.	**4**	**5**
Number of failures	520	481
Average time for repairs	40,1 days	8,44 days
Approximate system failure rate	$5{,}2 \cdot 10^{-4}$	$4{,}8 \cdot 10^{-4}$
Staying in repair state	2,11%	0,42%

So, to perform two additional experiments, the simulation of the repairable supply system is considered. Each experiment consists of one replication. Since the goal of those simulation experiments is to find the frequency of system failures, but not the moment until the first failure had occurred, the time length of replications is extended to a million.
The output data of our simple experiments show self-evident correlation between components repair rates and system functioning characteristics. In practice, simulation can help to determine, which supply chain member repair rate is most important for the whole system normal functioning.

Emergency and Crisis

Previously, the simulation of the system, with only two possible conditional states, was considered. Thus, the supply chain risk has been defined as the likelihood that the system will have changed its state from functioning to unworkable. In practice, however, it is more effective to analyze system conversions within various conditional states, which gives additional management flexibility.
For instance, in the sphere of risk managements, some researchers pose conditional states for a studied system: normal state, emergency and crisis (Borodzicz 2005). Similar various conditional states can be considered in supply chains:

$$X(t) = \begin{cases} N, & \textit{normal state at time } t \\ E, & \textit{emergency at time } t \\ C, & \textit{crisis at time } t \end{cases} \quad (11)$$

Normal condition defines supply chain normal functioning that is material, financial and information streams flow through the system within the predefined rules. At the same time some failures of suppliers are possible; for such cases, reserve suppliers or substitution materials are used. Accordingly, the final profit for supply system decreases, thus such functioning is called emergency state. Cases, in which reserve or substitution are not possible, are called crises in the sense that they affect the ability to satisfy end customer. It is self-evident that any state is possible for real supply chain. At the same time, system will always try to reach the normal state (see Figure 7).

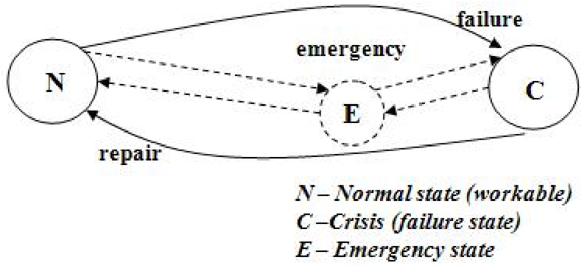

Figure 7: System Processes

Usually the parameters, which characterize changes of a system from one state to another, can be described by Markov processes (Andrews and Moss 2002). Accordingly, an assessment of transition probabilities between different conditional states (so called transition matrix) is needed for further system reliability analysis. Theoretically these probabilistic values can be obtained with the help of mathematical equations in cases when failure and repair rates of each network node are known; but in practice, a task of that kind is almost undoable. Still, simulation uses failure and repair rates as input data, and then the necessary statistical data about transitions can be modelled.
Another goal of the last two experiments is to estimate system functioning characteristics, which provide information about:

- how long a system stays in normal, emergency and crisis states?
- for how long a system stays in each of the states before next transition to another conditional state?

The final results of the last two experiments are presented in Table 6:

Table 6: Results of Experiments 6 and 7

Experiment 6				
		N	**E**	**C**
Time in each state		92,46%	2,11%	5,42%
Average time of staying in state		511 days	41 days	39 days
Rate of transition to state:	**N**	99,81%	0,05%	0,14%
	E	2,19%	97,64%	0,17%
	C	1,19%	0,03%	98,78%
Experiment 7				
		N	**E**	**C**
Time in each state		98,13%	0,43%	1,43%
Average time of staying in state		548 days	9 days	11 days
Rate of transition to state:	**N**	99,82%	0,05%	0,13%
	E	10,49%	89,31%	0,20%
	C	4,82%	0,04%	95,14%

The simulation conditions of the last two experiments are similar to the simulation conditions used in Experiments 4 and 5. The only difference exists in the changed output data assembling module, which provides the necessary statistical data about system transition events.

It should be noted that the length of the replication must be large enough to get reliable data. Moreover, the simulation length directly affects the output values of the transition matrix; with a sufficiently long simulation, the transition matrix becomes limiting matrix, which characterizes probabilities that the system will be in a certain conditional state at a certain moment of time. (Andronov et al. 2004). As an alternative, these values can be obtained directly from the simulation experiment output data or can be evaluated mathematically using the primary transition matrix.

CONCLUSIONS AND FUTURE WORK

The goal of this paper is to advise using system reliability parameters in order to analyse supply chain risks and possibilities of its future management. The supply chain risk is defined as possible disruptions that can affect the supply chain ability to function normally. Thus, the system reliability parameters are taken as an approach to risks assessment. As the discussed research has a theoretical nature, the simplified supply chain is considered. At the same time, the assumptions made provide the opportunity to make necessary mathematical evaluations. This mathematics is too time-consuming to be completed without the predefined limitations (for more realistic systems); although performed calculations are valuable, as they can be used for simulation model validation.

The simulation tool is assumed to be a very effective way to analyse system reliability; it can seriously abate the necessary mathematical instrument. At the same time, simulation models are very flexible and can be easily transformed synchronously to changes in a studied supply chain. Experiments demonstrate the efficiency of simulation application within system reliability analysis. Still, it only helps in cases, when necessary input data are available.

The target of further research is simulation-based decision support tool development, which can be used by supply chain managers as an additional aid for risk analysis. It also can be used for studying risk mitigation methods. At the same time, some complementary parallels with mathematical justifications should be made with the purpose to increase the objectiveness of simulation models output results.

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