SIMULATION OF SUPPLY CHAIN RELIABILITY

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This paper investigates problems related to supply chain risk identification and simulation-based risk assessment. 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, risk is recognized as possible disruptions that can affect supply chain’s ability to function normally. Thus, it is advised to use a system reliability analysis as an approach to supply chain risk assessment. Within the second part of the paper, the use of simulation is advised as an effective approach for supply chains reliability evaluation. A simplified supply chain system is defined and corresponding supply chain reliability simulation model is created. Simulation results are validated using a mathematical description that proves the adequacy and effectiveness of simulation application. Then, it is stated that the mathematical reliability models application is limited due to potential complicity and risk quantification features.

Keywords: *uncertainty, risk, reliability, supply chains and simulation*

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. Currently, risk handling is becoming a very important part of the supply chain management. Still, the term supply chain risk is not strongly defined yet; it is a topic for the latest researches. Here, it is suggested that the definitions and goals for supply chain managements under uncertainty and risk can be prescribed only from the predefined terms about supply chain, supply chain risk and uncertainty factors. These terms are not established too. So, at the beginning of this paper, a description for these terms is provided with the goal to estimate the term – supply chain risk.

1.1. 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, evidence the broad themed emanation from various academic disciplines [2]. 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.

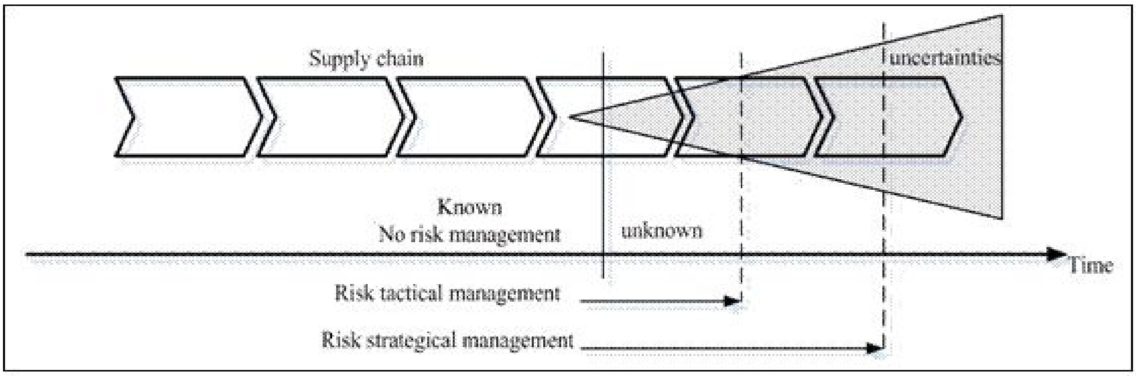

Fig. 1. *Risk management horizon*

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 [3]. The current paper investigates a modified idea about risk and uncertainty collaboration. 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 [7]. 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[3, 5]. The time is defined as risk general characteristic, which declares things that have already occurred and are not the object of risk management anymore. 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 Figure 1). 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.

1.2. Supply chain

Similar uncertainties and risk are considered in supply chain systems. Business environment can be characterized as turbulent that means an environment with high uncertainty, rapid change, novel markets, high margins and very demanding customers. Thus, it consists of many uncertain causing risks factors (see Figure 3). The possible destructiveness might be supply chain profit decline or unsatisfied end customer demand.

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

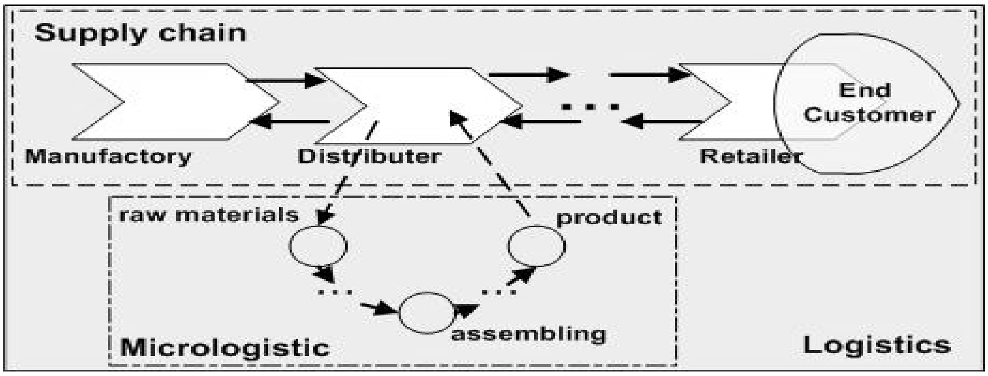

Fig. 2. *Supply chain as a part of total logistics system*

Within the current research, the supply chain is defined as a network of organizations involved into 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. It is very important to distinguish between supply chain management and detailed logistics (micro-logistic) inside separate organizations. Here, it is accepted that the function of supply chain management is to make optimisations aiming to minimize total logistics costs raised by finished production (finished within certain supply chain member) storing, transportation, etc. At the same time, supply chain management is part of total logistic management and ditto it is very similar to logistics systems inside separate organizations (see Figure 2).

1.3. Supply chain risk recognition

A precise understanding of risk essence is the most important point in risk management. Speaking about supply chain risks, most researchers 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 deficiencies 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 our previous work [6]. The obvious disadvantage of such supply chain risk management is difficulties in recognition, how particular risks affect other supply chain members. So, these cases don't make difference between logistic individual risks within separate organization and a risk of disruption for a whole supply system. Accordingly, in best cases such perception allows evaluation of failure rates for single supply chain nodes, but not for the whole system.

On the other hand, risk management should be directed to increase reliability of the whole system (see Figure 3). 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.

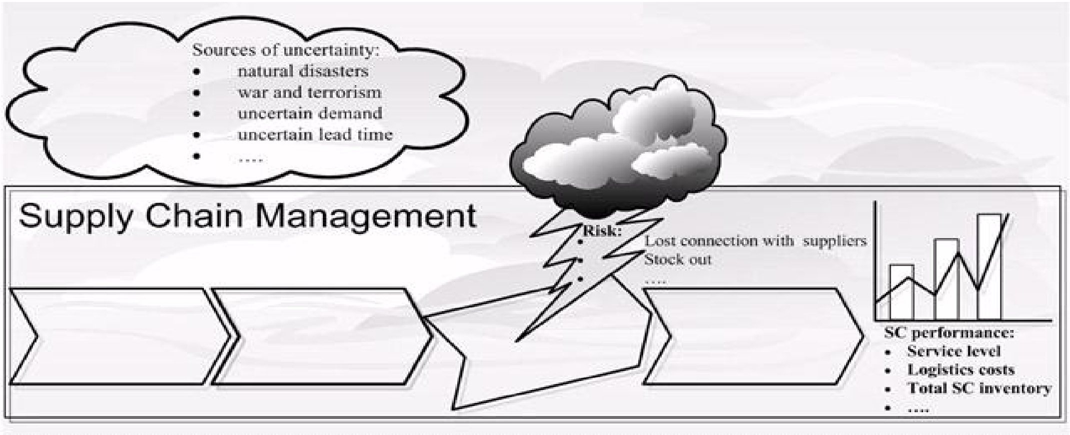

Fig. 3. *Supply chain under uncertainty and risk*

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 (see Figure 4a). Then, an emergency condition will be established, within which a final 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 it affects the ability to satisfy final customer. Here, it is accepted that risks are associated with the ability of supply system to change its conditional state in worse direction. So, supply chain risk is possible disruptions that can affect supply chain ability to function normally.

2. Simulation-Based 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 three possible modes of probability evaluation: empirical, theoretical and subjective evaluation [4]. 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 [4]. Thus, the use of simulation is advised as an effective tool for development of a supply chain model, which not only simplify risk evaluation task within complicated systems, but also comply with expert opinion for input data realization.

The goal of the second part of the paper is supply chain reliability model development with different simplifications, which allows for necessary model validation with the help of mathematical evaluations. Further, the validated model can be used as a basis for more complicated and realistic system simulation.

2.1. System formulation

For further discussion, a simplified supply system should be described (see Figure 4a). 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 rest 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.

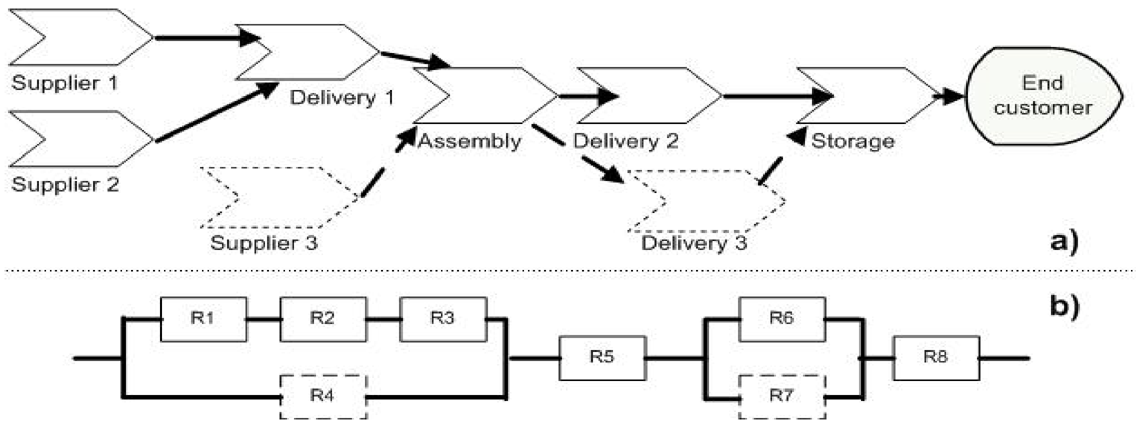

Fig. 4. *Simple supply chain network*

Table 1 provides individual characteristics about organizations involved in this network. It is assumed that the data about failure rates in particular supply chain nodes can be gained from organization managers (expert opinion). In a 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 1. Functioning characteristics of supply chain members

ID	Component mark	Supply chain member name	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:

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

The other two assumptions are: a "burn-in" and a "wear-out" periods can be not taken into account, time failure functions can be describable by exponential distribution (as it is the most commonly used life distribution for technical system reliability analysis) [1, 8].

2.2. Reliability theory

As it was 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. In practice, supply chain systems consist of more complicated networks. Moreover, in a real business, the assumption that a supply chain is a "non-repairable" system is not acceptable. Nevertheless, there are labour calculations even for a system with these assumptions, so it is possible to conceive about irrationality to perform more complex evaluations. At the same time, basic mathematical methods (which are provided in this paper) are necessary for further validation of the created simulation models.

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

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

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

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

The above mathematics is usually used for describing a single component's (in most cases, a mechanical or electronic equipment) reliability. Still, supply chains consist of several separate nodes. The redrawn network of defined supply system is presented above (see Figure 4b). Then, a structural analysis is needed.

2.2.1. Combinations of simple series and parallel structures

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 [8]. The performance of the studied system is identical to the developed "super-component" (see Figure 5).

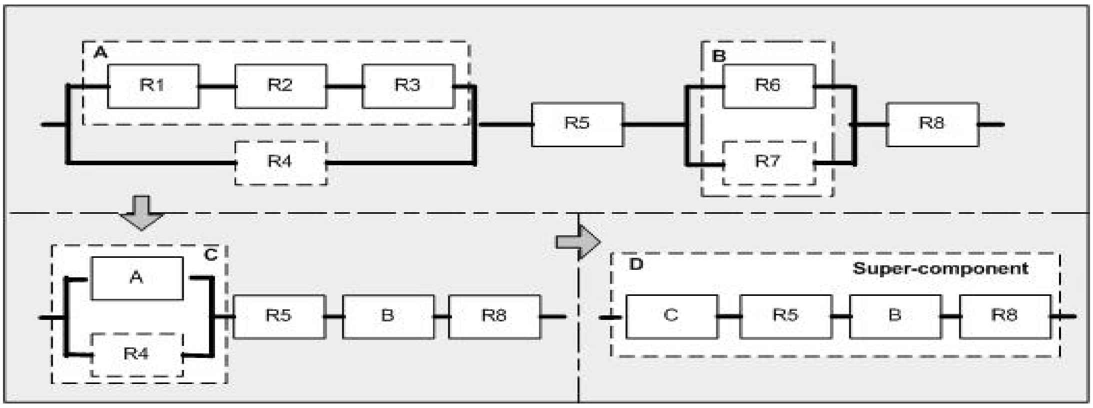

Fig. 5. *System reliability network*

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

$$R_{series} = \prod_{i=1}^{n} R_i, \quad (4)$$

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

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

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

$$R_{sys}(t) = (1-(1-e^{-\lambda_1 t}e^{-\lambda_2 t}e^{-\lambda_3 t})(1-e^{-\lambda_4 t})) * e^{-\lambda_5 t} * (1-(1-e^{-\lambda_6 t})(1-e^{-\lambda_7 t})) * e^{-\lambda_8 t}.$$

2.2.2. Minimal path sets

Unfortunately, the presented above method is hardly adoptable for complex 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 only consist of combinations of series and parallel structures. The disadvantage is that it only provides an approximation of reliability values; this method becomes useless in cases, when systems components have low reliability rates [1]. The "minimal path" set (a part of total component set) ensures that the system is functioning. In Table 2 the "minimal path" set for the predefined supply chain is provided.

Table 2. "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},..{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:

$$\phi(X) = \coprod_{j=1}^{p} p_j(X) = 1 - \prod_{j=1}^{p} (1 - p_j(X)), \quad (7)$$

$$p_j(X) = \prod_{i \in Pj} R_i \; for\, i = 1,2,...,s, \qquad (8)$$

where p_i is minimal path set and R_i is reliability (failure function) for a particular component.

Using the above equations, it is possible to define structural function (9), whose approximated value can be used for considering system reliability:

$$Q_{sys} \leq \phi(X) = 1 - (1 - X_1X_2X_3X_5X_6X_8) * (1 - X_1X_2X_3X_5X_7X_8) * (1 - X_4X_5X_6X_8) * (1 - X_4X_5X_7X_8),$$

$$Q_{sys}(t) \leq 1 - (1 - e^{-\lambda_1 t}e^{-\lambda_2 t}e^{-\lambda_3 t}e^{-\lambda_5 t}e^{-\lambda_6 t}e^{-\lambda_8 t}) * (1 - e^{-\lambda_1 t}e^{-\lambda_2 t}e^{-\lambda_3 t}e^{-\lambda_5 t}e^{-\lambda_7 t}e^{-\lambda_8 t}) * (1 - e^{-\lambda_4 t}e^{-\lambda_5 t}e^{-\lambda_6 t}e^{-\lambda_8 t}) * (1 - e^{-\lambda_4 t}e^{-\lambda_5 t}e^{-\lambda_7 t}e^{-\lambda_8 t}).$$

Evaluated reliability characteristics are given in Table 3.

2.3. Supply chain reliability simulation

For the problem under consideration, discrete-event simulation model was created using Promodel software (see Figure 6). The simulation process includes three experiments; each of them consists of five hundred replications. The basic simulation time period is one day; each replication continues until simulated system gets into a failed conditional state. The necessary reliability parameter values are evaluated using statistics gained from those five hundred 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 9th formula (9) more suitable (T=730 days) for system reliability evaluation. The calculated experimental data are shown in the table below:

Table 3. Simulation results

Exp. No.	Mathematical evaluations				Experimental data	
	$R_{sys,}$	Q_{sys}	$MTTF_R$	$MTTF_Q$	R_{Sim}	$MTTF_{Sim}$
1	62,4 %	≤85,4%	1304 days	1693 days	61,2 %	1277 days
2	72,5 %	≤93,5%	1304 days	1693 days	73,4 %	1277 days
3	93,3 %	≤99,6%	5263 days	5841 days	94,0 %	5525 days

By observing simulation and mathematical evaluation results, some conclusions can be made. First of all, it is possible to conclude 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 method of "minimal path" set, which is more usable for network structural analysis, cannot be used for components with large failure rates; therefore it is useless in most supply chains reliability analysis tasks.

Then, the advantages of reliability simulation are obvious. 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.

3. Conclusions

The 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 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 evaluation 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.

In the current paper advised models have many simplification and assumptions, what make them hardly adoptable in practise. Thus, the future research is directed on extending of 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.

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