Quantifying Supply Chain Resilience: A Markov Chain Approach ICTEA

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Abstract

In modern conditions, the effectiveness of supply chains depends largely on their fault tolerance. This is a complex characteristic that refers to the ability of chain participants to maintain operational efficiency or restore the performance of technological processes under the negative impact of external factors. It is crucial for supply chain participants to be adequately prepared to respond to these factors to avoid significant losses for businesses, markets, and national economies as a whole. The aim of our research is to establish a methodology for qualitatively assessing the resilience of supply chains. This methodology will allow us to obtain precise resilience values, supporting decision-making in response to deviations and failures within supply chains. The research examines contemporary methods for identifying the causes of supply chain failures, studies the dynamics of process states in individual links of supply chains, develops a methodology for assessing their fault tolerance based on the theory of Markov processes, and provides recommendations for improving the fault tolerance of supply chains. The methodology was used to evaluate the fault tolerance of consumer goods supplies from manufacturers to the retail network. The supply chain parameters were adjusted based on the obtained values of fault tolerance, resulting in increased sales for the trading company.

Keywords: Supply Chain Resilience, Fault Tolerance, Markov Chain Approach, Supply Chain Failures, Risk Management, Operational Efficiency, Decision-Making Support, Process State Dynamics, Resilience Assessment, External Factors Impact, Retail Supply Chains, Supply Chain Optimization, Business Continuity, Performance Recovery, Stochastic Processes.

1. Introduction

In the most general sense, the term "Supply Chains Resilience" (SCR) characterises the ability of supply chain participants to maintain operational efficiency or quickly restore normal operation in case of process failures [1,2,3,4]. Resilient execution of operations by supply chain participants is one of the most important conditions for the effective functioning of modern Global Value Chains (hereinafter - "GVC") and sustainable development of the economies of individual countries. The participation of national companies in GVCs positively affects social well-being and business efficiency by creating new jobs, attracting investment in infrastructure, and increasing foreign trade volumes [5,6,7,8].

Recently, SC failures have become more frequent, resulting in increased financial losses for GVC participants around the world, rising inflation rates, and deterioration of public welfare in many countries [9,10, 11]. For example, losses to world trade from the blockage of the Suez Canal by the grounded container ship "Ever Given" reached $10 billion per week. During the COVID-19 pandemic, many assembly plants around the world stopped operations due to the disruption of component supplies [12-20]. These examples highlight the practical significance of research in supply chain fault tolerance (Resilient functioning of SC). The results of these studies allow to increase the efficiency of response to failures and reduce the severity of their unfavourable consequences for SC participants [9,21,22,23]. The key research objective is to develop a methodology for the qualitative assessment of SCR (Quantification of Supply Chain Resilience, hereinafter - QSCR). The research will consider modern approaches to identifying the causes of SC failures, the influence of random factors on the change of SC states, will propose a method of quantitative assessment of fault tolerance, as well as the basic rules for making managerial decisions that ensure fast and efficient restoration of SC links operation.

2. Materials and methods

The SCR problem is an important part of modern scientific research in logistics [24, 25, 7, 26,27,28,29,30]. According to the authors [31], the basic definition of the term SCR was formulated in [32] - it is the ability of SC to return to the initial state or move to a new, more desirable state, after a disruption in one or more links of the chain. In the context of this study, this definition should be supplemented with three characteristics.

In the study [33,34] it is noted that SC operation is associated with many risks, as they are open complex-structured dynamic systems that actively interact with the external environment. This interaction is manifested in the following features of the impact of external factors on SCRs.

Let us introduce notations of SC links and their states. Under the state we will understand the result of the technological process execution ("successfully" or "unsuccessfully" executed).

The value of "transient" probabilities $P_{i,j}$ depends on two parameters: firstly, on the "strength" $q_{i,j}$ (z) of the impact of some unfavourable external factor on the operation of SC links, and secondly, on the "frequency" $v_{i,j}$ (z) of the manifestation of this factor [35].

"Frequency of occurrence of unfavourable impacts" $v_{i,j}$ (z) is determined by the nature of external factors. For example, in some regions natural disasters occur more often than in others. As a rule, statistical data are used to assess the value of the "frequency" of manifestation of external factors on individual processes, and expert opinions are additionally taken into account when assessing the "strength" of the influence of external factors. The parameters $q_{i,j}$ (z) and $v_{i,j}$ (z) can take values from 0 to 1. If at least one parameter is zero, the undesired event $E_{i,j}$ does not occur, respectively the system does not go from S_i to S_j .

An undesirable event $E_{i,j}$ can occur with probability $P_{i,j}$, only when both parameters are greater than zero: $q_{i,j}$ (z) > 0; $v_{i,j}$ (z) > 0. Therefore, the final value of the probability $P_{i,j}$ of the system transition from the state S_i to the state S_j under the influence of unfavourable external factors is defined as the product of:

$$P_{i,j} = q_{i,j}(z) \cdot v_{i,j}(z). \tag{1}$$

The sum of transition probabilities $P_{i,j}$ for each *i-th* event must be equal to one, since, whatever state the system is in before the next transition, all subsequent j-th events are incompatible and form a complete group:

$$\sum_{j=1}^{n} P_{i,j} = 1. \tag{2}$$

The probability values p_i^* (k) and p_i (k) are calculated using the same methodology based on the provisions of the theory of Markov processes.

3. RESULTS AND DISCUSSION

Markov Process is used as a means of creating a dynamic model of stochastic processes that are realised in different systems [36-42]. In this study, the SC model is designed as a homogeneous Markov Chain (homogeneous Markov Chain) with discrete time, in which transitions of the system from state to state are possible only at strictly defined, pre-fixed moments of time: t_1 , t_2 ... . In the time intervals between these moments, the system S preserves its state [43-48].

Based on the modelling results, QSCR will be produced in the form of probability values p_i^* (k) of finding the system in successful intermediate (S_2^* , S_5^* , S_{10}^*) and final (S_{12}^*) states. In turn, the obtained values of probabilities p_i (k) of being in "unsuccessful" states will be used in the selection of corrective solutions that ensure the increase of p_i^* (k).

After corrective solutions, the transition probabilities $P_{i,j}$ may be revised. However, this fact does not indicate that the SC model will become an inhomogeneous Markov chain. After corrective solutions, a new SC model is created, which will also be a "homogeneous Markov chain".

SC functioning in random conditions is characterised by the change of link states after each step. Transient probabilities of SC states after the *k-th* step can be written as conditional probabilities of preceding and following events:

$$P_{ij} = P(S_j^{(k)} / S_i^{(k-1)}). \tag{4}$$

To calculate p_i (k), we write the transition probabilities $P_{i,j}$ as a rectangular matrix:

$$\| P_{i,j} \| = \begin{Vmatrix} 0 & 0.7 & 0.1 & 0.2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.7 & 0.2 & 0.1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.95 & 0.05 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.8 & 0.2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1.0 & 0 & 0 & 0 & 0 \\ 0.3 & 0 & 0.6 & 0.1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.8 & 0.2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1.0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1.0 \\ 1.0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{Vmatrix} \tag{3}$$

$$\begin{Vmatrix} 1.0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{Vmatrix}$$

The state probabilities p_i (k) after each k-th step will be determined by the dynamics of the possible states and the values of the transition probabilities for the corresponding pairwise states. According to the methodology from [43], the probabilities of states p_i (k) are determined by the recurrence formula:

$$p_i(k) = \sum_{j=1}^{n} \left(p_j(k-1) \cdot P_{ji} \right). \tag{5}$$

We will record the obtained values of state probabilities p_i (k) for the next step in Table 1.

Table 1. Probabilities pi (k) of SC link states at the k-th step (developed by the authors only.

S_i	1	2	3	4	5	6	7	8	9	10	11	12	$p(k)$	R_i^* (k)
Step 0	1	0	0	0	0	0	0	0	0	0	0	0	1	1
Step 1	0	**0.7***	0.1	0.2	0	0	0	0	0	0	0	0	1	0.7
Step 2	0.1	0.19	0.01	0	**0.49***	0.14	0.07	0	0	0	0	0	1	0.49
Step 3	0.031	0.07	0.052	0.027	0.133	0.038	0.019	0.14	0	**0.392***	0.098	0	1	0.392
Step 4	0.1557	0.04735	0.01585	0.0081	0.049	0.014	0.007	0.038	0.112	0.1344	0.0266	**0.392***	1	0.392

* fault tolerance value for a "successful" state

Step 0 (k = 0, SC start). At the initial moment (k = 0) the system is in the state S_1. The probability of the system being in this state is p_1 (0) = 1. The probabilities of all other states are zero.

Step 1 (k = 1). After the first step, the system can move to states S_2, S_3 and S_4 with transition probabilities P_{12}, P_{13} and P_{14} , which are written in the first row of the matrix. Then the probabilities of the states that SC can be in after the first step are as follows: probability of SC staying in state $S_2^{(1)}$: p_2 (1) = 1 · 0.7 = 0.7 (**successful process**); probability of SC staying in state $S_3^{(1)}$: p_3 (1) = 1 · 0.1 = 0.1 (unwanted deviation); probability of SC staying in state $S_4^{(1)}$: p_4 (1) = 1 · 0.2 = 0.2 (unwanted deviation).

The sum of the probabilities of SC staying in states $S_2^{(1)}$, $S_2^{(1)}$ and $S_4^{(1)}$ after the first step is equal to one: p(1) = 1.0:

$$p(k) = \sum_{i=1}^{n} p_i(k). \tag{6}$$

Step 2 (k = 2). After the second step, the SC can move from each possible state S_2 , S_3 and S_4 to the following states: from state S_2 to states S_5 , S_6 and S_7 ; from state S_3 to state S_1 ; from state S_4 to states S_2 and S_3 . Let us determine the probabilities of SC staying in the listed states - S_1 , S , S , S_{235} , S_6 and S_7 after the second step: probability of SC staying in state $S_1^{(2)}$: p_1 (2) = p_3 (1) · $P_{3,1}$ = 0.1 · 1 = 0.1 (**resumption of supply after failures**); probability of SC staying in state $S_2^{(2)}$: p_2 (2) = p_4 (1) · $P_{4,2}$ = 0.2 · 0.95 = 0.19 (**retrying a successful process**); probability of SC staying in state $S_3^{(2)}$: p_3 (2) = p_4 (1) · $P_{4,3}$ = 0.2 · 0.05 = 0.01 (unwanted bias); probability of SC staying in state $S_5^{(2)}$: p_5 (2) = p_2 (1) · $P_{2,5}$ = 0.7 · 0.7 = 0.49 (**successful process**); probability of SC staying in state $S_6^{(2)}$: p_6 (2) = p_2 (1) · $P_{2,6}$ = 0.7 · 0.2 = 0.14 (unwanted bias); probability of SC staying in state $S_7^{(2)}$: p_7 (2) = p_2 (1) · $P_{2,7}$ = 0.7 · 0.1 = 0.07 (unwanted bias). The sum of the probabilities of SC staying in states S_1 , S_2 , S , S_{35} , S_6 and S_7 after the second step is equal to one: p(2) = 1.0.

Step 3 (k = 3). After the third step, the SC can move from each previous state S_1 , S , S , S_{235} , S_6 and S_7 to the following states: from state S_1 to states S_2 , S_3 and S_4 ; from state S_2 to states S_5 , S_6 and S_7 ; from state S_3 to state S_1 ; from state S_5 to states S_{10} and S_{11} ; from state S_6 to state S_8 ; from state S_7 to states S_1 , S_3 and S_4 .

The sum of the probabilities of SC staying after the third step in states S_1 , S_2 , S , S_{34} , S , S_{56} , S , S_{78} , S_{10} and S_{11} is equal to one: p(3) = 1.0.

Step 4 (k = 4)/ After the third step, the SC can move from each previous state S_1 , S , S_{23} , S_4 , S , S_{56} , S , S_{78} , S_{10} and S_{11} to all possible states: from state S_1 to states S_2 , S_3 and S_4 ; from state S_2 to states S_5 , S_6 and S_7 ; from state S_3 to state S_1 ; from state S_4 to states S_2 and S_3 ; from state S_5 to states S_{10} and S_{11} ; from state S_6 to state S_8 ; from state S_7 to states S_1 , S_3 and S_4 ; from state S_8 to states S_9 and S_{10} ; from state S_{10} to state S_{12} ; from state S_{11} to state S_1 .

Let us determine the probabilities of SC staying in states S_1 , S_2 , S_3 , S_4 , S_5 , S_6 , S , S , S_{789} , S_{10} , S_{11} and S_{12} after the fourth step: probability of SC being in state $S_1^{(4)}$: p_1 (4) = p_3 (3) · $P_{3,1}$ + p_7 (3) · $P_{7,1}$ + p_{11} (3) · $P_{11,1}$ = 0.052 · 1 + 0.019 · 0.3 + 0.098 · 1.0 = 0.1557 (**resumption of supply after failures**); probability of SC being in state $S_2^{(4)}$: p_2 (4) = p_1 (3) · $P_{1,2}$ + p_4 (3) · $P_{4,2}$ = 0.031 · 0.7 + 0.027 · 0.95 = 0.04735 (**retry success of the process**); probability of SC being in state $S_3^{(4)}$: p_3 (4) = p_1 (3) · $P_{1,3}$ + p_4 (3) · $P_{4,3}$ + p_7 (3) · $P_{7,3}$ = 0.031 · 0.1 + 0.027 · 0.05 + 0.019 · 0.6 = 0.01585 (undesirable variance); probability of SC being in state $S_4^{(4)}$: p_4 (4) = p_1 (3) · $P_{1,4}$ + p_7 (3) · $P_{7,4}$

= 0.031 · 0.2 + 0.019 · 0.1 = 0.0081 (unwanted variance); probability of SC staying in state $S_5^{(4)}$: p_5 (4) = p_2 (3) · $P_{2,5}$ = 0.07 · 0.7 = 0.049 (**retrying a successful process**); probability of SC staying in state $S_6^{(4)}$: p_6 (4) = p_2 (3) · $P_{2,6}$ = 0.07 · 0.2 = 0.014 (unwanted bias); probability of SC staying in state $S_7^{(4)}$: p_7 (4) = p_2 (3) · $P_{2,7}$ = 0.07 · 0.1 = 0.007 (unwanted bias); probability of SC staying in state $S_8^{(4)}$: p_8 (4) = p_6 (3) · $P_{6,8}$ = 0.038 · 1.0 = 0.038 (unwanted bias); probability of SC staying in state $S_9^{(4)}$: p_9 (4) = p_8 (3) · $P_{8,9}$ = 0.14 · 0.8 = 0.112 (unwanted bias); probability of SC being in state $S_{10}^{(4)}$: p_{10} (4) = p_5 (3) · $P_{5,10}$ + p_8 (3) · $P_{8,10}$ = 0.133 · 0.8 + 0.14 · 0.2 = 0.1344 (**retry success of the process**); probability of SC staying in state $S_{11}^{(4)}$: p_{11} (4) = p_5 (3) · $P_{5,11}$ = 0.133 · 0.2 = 0.0266 (unwanted bias); probability of SC staying in state $S_{12}^{(4)}$: p_{12} (4) = p_{10} (3) · $P_{10,12}$ = 0.392 · 1.0 = 0.392 (**successful completion of the process**). The sum of the probabilities of SC staying in all twelve states after the fourth step is equal to one: $p(4)$ = 1.0. If we continue modelling the SC processes, in the fifth step new transitions between states will be added that will influence the final fault tolerance score in state S_{12} .

The value of the proposed QSCR methodology lies in the fact that it allows us to obtain generalised quantitative assessments of reliability of operational activities of all SC participants (links): fault tolerance indices Ri (k) and R and probability of staying in unsuccessful states pi (k). The calculated values of Ri (k) for "successful" states show that with each "step" this indicator decreases and eventually reaches the value R = 0.392. This information suggests that at the current level of failure preparedness of SC participants, only 39% of orders will be fulfilled as planned. The rest will be delayed or cancelled. It is possible to increase the SCR by reducing the transition probabilities Pi,j to unsuccessful states pi (k through response measures [37, 33, 48, 49, 50, 51,52, 53,54,55,56,57].

3. Conclusion

The methodology's implementation begins with creating a model of changes in the states of technological processes of SC participants [58]. To achieve this, we collect detailed information on failures that affect their technological processes, including how often and under what negative scenarios 'unsuccessful' events develop. We then analyse all unsuccessful states and identify the factors that determine the outcome of processes in all SC links. The parameters for replenishing products delivered with failure conditions are adjusted based on the obtained results. Additionally, the size of insurance stocks for these products in distribution centres and retail networks is modified. These measures increase fault tolerance and reduce losses from late deliveries. The effect is achieved by reducing the range of goods that are periodically unavailable in the retail network due to late deliveries. Additionally, the average duration of time during which the goods are unavailable is reduced, resulting in increased sales of such goods.

This example demonstrates the methodological commonality and connection between QSCR methodology and procurement planning methods. Therefore, it appears promising to conduct research on implementing SCR indicators into existing methods for planning and optimizing business processes in the supply chain. Additionally, given the large amount of data generated in modern supply chains, applying machine learning methods for quantitative assessment of SCR indicators is a promising area for further research.

This template is designed to assist you in the preparation of your manuscript for the thirteen international conference on thermal engineering theory and applications. We are looking forward to seeing you in Baku, Azerbaijan in June 2020.

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