Structural and functional analysis of supply chain reliability in the presence of demand fluctuations

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Abstract
The following article presents an approach to modelling, evaluating and analysing the structural and functional reliability and survivability of supply chains in conditions of fluctuating demand. The article proposes the concept of a parametric genome of the structure of complex multi-mode objects for calculating integral indicators of the structural and functional reliability of the supply chain with dynamic consumer orders.
Keywords
Structural and functional reliability, supply chain, parametric genome.

1 Introduction

In the process of implementing supply chain management (SCM) in practice, managers have faced with the problem of adapting to customers' unplanned orders and individual technological and economic requirements. How and with what methods and technologies is it possible to assess the reliability and stability of the supply chain in the event of more or less serious deviations and violations, fluctuations? So, finance losses derived due to not received orders, fines and penalties in certain supply chains reach 15% of the annual turnover [1]. In modern SCM, the final consumer of products has become the most important link. Therefore, one of the key reasons for improving the reliability and survivability of supply chains is caused by the necessity to meet their requirements taking into account changing demand. This issue is reflected in the following works by [2-11]. It should be noted that the current trend in understanding the efficiency of the supply chain is the design of such supply chains that would be characterized by a high level of economic efficiency and the required level of survivability [12, 13]. It seems that in the coming years it will be possible to talk about a paradigm shift in supply chain optimization: a transition from minimizing costs to ensuring a balance of efficiency and survivability. In this regard, a promising direction for future research is the development of models and formulas for calculating structural and functional indicators of reliability and survivability of supply chains, taking into account fluctuations in demand.

2 The concept of a parametric genome of the structure. Integral indicators of the structural and functional reliability of the supply chain

These indicators should be used as an additional factors of economic efficiency to characterize the target (functional) conflict "efficiency or reliability" from an objective point of view [1]. To analyse the properties of structural and functional reliability and survivability of the supply chain, as well as for the structural and functional synthesis of a system corresponding to a given level of structural reliability and survivability, it is necessary to introduce a quantitative measurement. As a rule, structural and functional analysis of complex objects to which the supply chain belongs begins with the construction of their functional integrity diagram [14, 15]. The diagram of the functional integrity of any complex object allows to represent graphically logical conditions for the implementation of their

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own functions by elements and subsystems, as well as the goals of modelling the logical conditions for the implementation of the system property under study, for example, reliability or failure, safety or occurrence of an accident, the creation of certain operation modes of the object, etc. The structure of the constructed circuit includes functional elements which are actually the various technological operations, subsystems, blocks, nodes, connections of various physical nature. In the most general case, the functional vertices of the functional integrity scheme reflect both the operability of certain functional elements (for the supply chain, these can be suppliers, manufacturing plants, warehouses, distributors, providers, etc.), and the need for the implementation of certain functions for example, customer orders).

Figure 1 shows a diagram of the functional integrity of a certain adaptive supply chain, taking into account the structural and functional reserve. Apexes 1-10 reflect the performance of individual product suppliers, manufacturing plants, transport enterprises involved in meeting the needs of consumers, represented by vertices 11-14. Vertices from 15 to 33 are fictitious and are used to describe the logical relationships of the functional elements of the supply chain.

For example, apex 33 ensures the customer satisfaction that is a successful operation (achievement of the goal) of the supply chain. So, if there is no need in customer orders despite the refusals of suppliers and manufacturers, the goal of the supply chain will be achieved. It should be noted that orders from consumers in the supply chain differ in the nature and the intensity of their receipt. Firstly, certain orders can be main or auxiliary. In other words, the orders may be inconsistent (that is, they may be executed one at a time), and individual orders may come in at the same time as others. Secondly, orders may consist of different fractions of the arrival time at a given time interval or may have different values of the arrival probability at a given interval, that is, they can have a deterministic or random dynamic nature. Therefore, it is required to analyse and to evaluate indicators of the structural and functional reliability of the supply chain in the conditions of joint and separate receipt of dynamic customer orders.

Using the program complex of logical and probabilistic modelling "Arbiter" [14], we obtain for the scheme of functional integrity of the supply chain a probabilistic polynomial of its successful functioning (1).

$$\Re(P_1, P_2, ..., P_n, P_{n+1}, ..., P_{n+m}, Q_1, Q_2, ..., Q_n, Q_{n+1}, ..., Q_{n+m}), \quad (1)$$

where $P_i(Q_i), i = 1, ..., n$ is probability of uptime (failure) of functional elements of the supply chain, and $P_{n+i}(Q_{n+i} = 1 - P_{n+i}), i = 1, ..., m$ can be interpreted either as the probability of receipt (non-receipt) of an order by the consumer, or the relative size (intensity) from 0 to 1 receipt (absence) of a sales order.

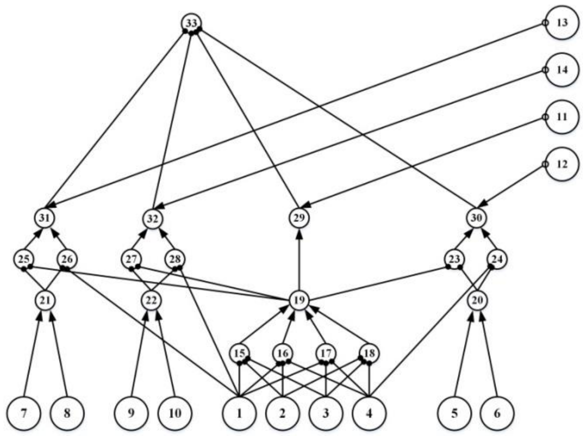

Figure 1. Supply chain functional integrity diagram

Let us denote the intensity of receipt of orders from customers of the supply chain through $\alpha_i = P_{n+i}, i = 1, ..., m$. Further, based on the assumption that all functional elements of the supply chain are homogeneous in the probability of no-failure operation $(P_1 = P_2 = ... = P_n = P)$, the probabilistic polynomial of the successful functioning of the supply chain (1) can be transformed to the following form (2)

$$\begin{aligned}\Re(P, \alpha_1, \alpha_2, ..., \alpha_m) &= \chi_0(\alpha_1, \alpha_2, ..., \alpha_m) + \chi_1(\alpha_1, \alpha_2, ..., \alpha_m)P + \\ &+ \chi_2(\alpha_1, \alpha_2, ..., \alpha_m)P^2 + ... + \chi_n(\alpha_1, \alpha_2, ..., \alpha_m)P^n\end{aligned} \quad (2)$$

By analogy with the concept of the structure genome introduced in [15-18], we will call vector $\vec{\chi}(\alpha_1, \alpha_2, ..., \alpha_m) = (\chi_0(\alpha_1, \alpha_2, ..., \alpha_m), \chi_1(\alpha_1, \alpha_2, ..., \alpha_m), \chi_2(\alpha_1, \alpha_2, ..., \alpha_m), ..., \chi_n(\alpha_1, \alpha_2, ..., \alpha_m))^T$ the parametric genome of the structure.

Using the parametric genome of the supply chain structure, it is possible to calculate estimates of the structural and functional reliability of the supply chain, depending on the parameters $\alpha_1, \alpha_2, ..., \alpha_m$ of the intensity of customer orders.

So, in the case of a probabilistic description of the failure-free operation of functional elements for a homogeneous structure (the same probability of failure-free operation of functional elements), the function of the successful functioning of the supply chain, represented by the polynomial $\Re(P,\alpha_1,\alpha_2,...,\alpha_m)=$ $=\chi_0(\alpha_1,\alpha_2,...,\alpha_m)+\chi_1(\alpha_1,\alpha_2,...,\alpha_m)P+\chi_2(\alpha_1,\alpha_2,...,\alpha_m)P^2+$ $+...+\chi_n(\alpha_1,\alpha_2,...,\alpha_m)P^n$, changes its values in the interval [0,1]. Moreover, the closer the function graph to line $\Re(P,\alpha_1,\alpha_2,...,\alpha_m)=1$, the higher the structural and functional reliability of the supply chain. Therefore, as an indicator of structural and functional reliability in this case, it is proposed to use $F_{\text{homog}}(\vec{\chi}(\alpha_1,\alpha_2,...,\alpha_m))=\int_0^1 \Re(P,\alpha_1,\alpha_2,...,\alpha_m)dP$

Then, to calculate the indicator of the structural and functional reliability of the supply chain, you can use the parametric genome of the structure according to the following formula (3)

$$F_{\text{homog}}(\vec{\chi}(\alpha_1,\alpha_2,...,\alpha_m))=\int_0^1 \Re(P,\alpha_1,\alpha_2,...,\alpha_m)dP=$$
$$=\sum_{i=0}^{n}\chi_i(\alpha_1,\alpha_2,...,\alpha_m)\cdot\frac{1}{i+1}$$

or

$$F_{\text{homog}}(\vec{\chi}(\alpha_1,\alpha_2,...,\alpha_m))=\int_0^1 \Re(P,\alpha_1,\alpha_2,...,\alpha_m)dP=$$
$$=\vec{\chi}(\alpha_1,\alpha_2,...,\alpha_m)\cdot(1,\frac{1}{2},\frac{1}{3},...,\frac{1}{n+1})^T. \quad (3)$$

In the case of a heterogeneous structure (different probability of failure-free operation of functional elements), it can be used as an indicator of the structural and functional reliability of the supply chain

$$F_{\text{heterog}}(\vec{\chi}(\alpha_1,\alpha_2,...,\alpha_m))=$$
$$=\int_0^1...\int_0^1 \Re(P_1,P_2,...,P_n,\alpha_1,\alpha_2,...,\alpha_m)dP_1dP_2...dP_n$$

or using the parametric genome structure formula (4)

$$F_{\text{heterog}}(\vec{\chi}(\alpha_1,\alpha_2,...,\alpha_m))=$$
$$=\vec{\chi}(\alpha_1,\alpha_2,...,\alpha_m)\cdot(1,\frac{1}{2},\frac{1}{2^2},...,\frac{1}{2^n})^T. \quad (4)$$

In the case, when performing functions by functional elements included in the structure of the supply chain, it is not possible to identify a well-defined stochastic regularity of failure-free operation, then it is proposed to use a fuzzy-possibility approach to describing the behavior of functional elements, which is based on the concept of space with a measure of possibility [15-17].

So, as an indicator (5) of the structural and functional reliability of the supply chain with a fuzzy-possibility description of the behaviour of its functional elements, one can use [15-17] a fuzzy integral as far as possible

$$F_{\text{homogposs}}(\vec{\chi}(\alpha_1,\alpha_2,...,\alpha_m))=$$
$$=\sup_{\mu\in[0,1]}\min\{R(\mu,\alpha_1,\alpha_2,...,\alpha_m),\ g(\mu)\}= \quad (5)$$
$$=\sup_{\gamma\in[0,1]}\min\{\gamma,G(\{\mu|R(\mu,\alpha_1,\alpha_2,...,\alpha_m)\geq\gamma\})\}$$

For this indicator, it is necessary to determine the measure of possibility G and, if possible, its distribution function $g(\mu)$.

For monotone homogeneous structures, the graph of the polynomial of the possibility of failure-free operation $R(\mu,\alpha_1,\alpha_2,...,\alpha_m)$ has the form shown in Figure 3. Here the polynomial $R(\mu,\alpha_1,\alpha_2,...,\alpha_m)=\chi_0(\alpha_1,\alpha_2,...,\alpha_m)+$ $+\chi_1(\alpha_1,\alpha_2,...,\alpha_m)\mu+\chi_2(\alpha_1,\alpha_2,...,\alpha_m)\mu^2+...$ $...+\chi_n(\alpha_1,\alpha_2,...,\alpha_m)\mu^n$ is obtained from the polynomial $\Re(P,\alpha_1,\alpha_2,...,\alpha_m)$ by replacing the probability P of no-failure operation of functional elements with the possibility μ of no-failure operation of functional elements of the supply chain. As a measure of opportunity, we will use $G(\{\mu|R(\mu,\alpha_1,\alpha_2,...,\alpha_m)\geq\gamma\})=$ $=G(H_\gamma)=\sup_{A\subseteq H_\gamma}|A|=\sup_{R(\mu,\alpha_1,\alpha_2,...,\alpha_m)\geq\gamma}\{1-\mu\}$, where $|A|$ is the Lebegue measure. Therefore, in the case of monotone homogeneous structures, the distribution function of the measure of possibility is $g(\mu)=1-\mu$.

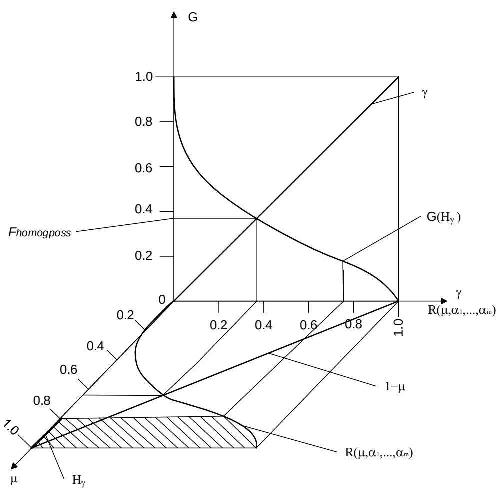

Figure 2. Graphic interpretation of finding the indicator of the possibility of failure-free operation of homogeneous structures

Then, for the considered case of a fuzzy-possibility description of the failure-free operation of functional elements of the supply chain, the indicator of the possibility of failure-free operation of a monotonic homogeneous structure can be calculated by the formula (6)

$$F_{\text{homogposs}}(\vec{\chi}(\alpha_1,\alpha_2,...,\alpha_m)) = 1-\mu_* \quad , \qquad (6)$$

where μ_* is a solution to the equation $\vec{\chi}(\alpha_1,\alpha_2,...,\alpha_m)\cdot(1,\mu_*,\mu_*^{\,2},...,\mu_*^{\,n})^T = 1-\mu_*$.

For non-monotone homogeneous structures, the uptime polynomial $R(\mu,\alpha_1,\alpha_2,...,\alpha_m)$ either does not preserve "0" $(R(0,\alpha_1,\alpha_2,...,\alpha_m)=1)$, or does not preserve "1" $(R(1,\alpha_1,\alpha_2,...,\alpha_m)=0)$.

The graphs of the polynomials of the failure-free operation are shown in Figure 3.

When $R(1,\alpha_1,\alpha_2,...,\alpha_m)=0$, the measure of possibility is

$$G(\{\mu | R(\mu,\alpha_1,\alpha_2,...,\alpha_m)\geq\gamma\}) = G(H_\gamma) =$$
$$= \sup_{A\subseteq H_\gamma}|A| = \sup_{R(\mu,\alpha_1,\alpha_2,...,\alpha_m)\geq\gamma}\{\mu^{\max}-\mu^{\min}\},$$

where $\mu^{\max} = \sup\{\mu | R(\mu,\alpha_1,\alpha_2,...,\alpha_m)\geq\gamma\}$ and $\mu^{\min} = \inf\{\mu | R(\mu,\alpha_1,\alpha_2,...,\alpha_m)\geq\gamma\}$.

When $R(0,\alpha_1,\alpha_2,...,\alpha_m)=1$, the measure of possibility is

$$G(\{\mu | R(\mu,\alpha_1,\alpha_2,...,\alpha_m)\geq\gamma\}) = G(H_\gamma) =$$
$$= \sup_{A\subseteq H_\gamma}|A| = \sup_{R(\mu,\alpha_1,\alpha_2,...,\alpha_m)\geq\gamma}\{1-(\mu^{\max}-\mu^{\min})\},$$

where $\mu^{\max} = \sup\{\mu | R(\mu,\alpha_1,\alpha_2,...,\alpha_m)\leq\gamma\}$ and $\mu^{\min} = \inf\{\mu | R(\mu,\alpha_1,\alpha_2,...,\alpha_m)\leq\gamma\}$.

The graphical interpretation of finding the indicator of the possibility of failure-free operation in this case is shown in Figure 3.

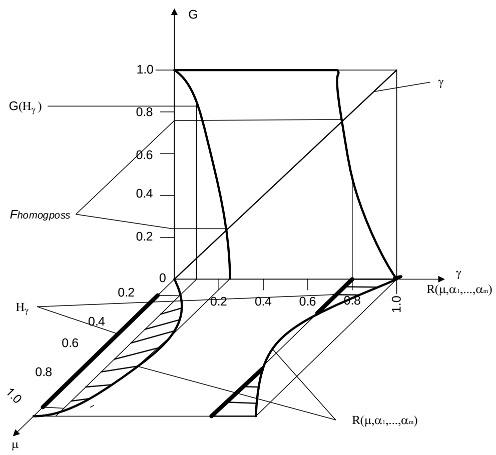

Figure 3. Graphical interpretation of finding the indicator of the possibility of failure-free operation of non-monotonic homogeneous structures

To study the structural and functional reliability of the supply chain, it is advisable to use the capabilities of the general logical-probabilistic method [14] and introduce some "weights" of orders that would take into account the above differences. The weighting factors are proposed to be introduced as follows. The weighting factor is found as the ratio of the average total duration of the order receipt during the considered time interval of the supply chain operation to the value of this interval.

3 Research of structural and functional reliability of the supply chain

Fragment of the polynomial of the circuit functional integrity of the circuit shown in Figure 2 has the following form

$$\Re(P,\alpha_1,\alpha_2,...,\alpha_m) = P^4(1-P)^6(1-\alpha_2)(1-\alpha_4) +$$
$$+P^2(1-P)^3(1-\alpha_1)(1-\alpha_2)\alpha_3(1-\alpha_4)+...$$
$$...-4P^5(1-\alpha_1)(1-\alpha_2)\alpha_3(1-\alpha_4).$$

To study the structural and functional reliability of the supply chain, we will use formulas (3), (4), (5). In this case, we will assume that all orders can be fulfilled both individually and jointly.

The calculation results for $\alpha_i \in \{0, 0.2, 0.4, 0.6, 0.8, 1\}, i=1,...,4,$ are shown in Figure 4.

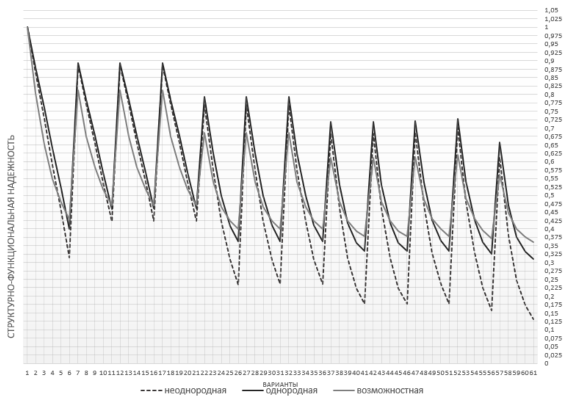

Figure 4. Structural and functional reliability of the supply chain

Variant №1 corresponds to the absence of orders $(\alpha_1=0;\alpha_2=0;\alpha_3=0;\alpha_4=0)$. Variants from №2 to №6 reflect a gradual increase from 0.2 to 1.0 in the intensity of order 1 (the apex of the functional integrity diagram №11) with a step of 0.2. Variants from No. 7 to No. 11, from No. 12 to No. 16, from No. 17 to No. 21 correspond to an increase in the intensity of orders 2, 3, 4 (apexes No. 12, No. 13, No. 14).

Further options from No. 22 to No. 26, from No. 27 to No. 31, from No. 32 to No. 36 reflect the structural and functional reliability of a gradual increase in the joint receipt of two orders 1 and 2, 1 and 3, 1 and 4, respectively. Then the options for the joint receipt of three orders are located (1, 2, 3; 1, 2, 4; 1, 3, 4; 2, 3, 4). And finally, options from 57 to 61 - a joint receipt of four orders. It should be noted that with the individual receipt of orders, the structural and functional reliability of the supply chain is higher than with the joint receipt of these orders. In addition, it can be seen from the graphs that the structural and functional reliability has a piecewise linear relationship with changes in the intensities of the receipt of individual orders. Moreover, for a homogeneous supply chain, it is impossible to clearly identify the best option for the joint receipt of orders, in contrast to a heterogeneous system.

In Figure 5 shows the changes in the values of indicators of the structural and functional reliability of the supply chain during the transition from joint to separate receipt of orders. Let us comment on the results obtained.

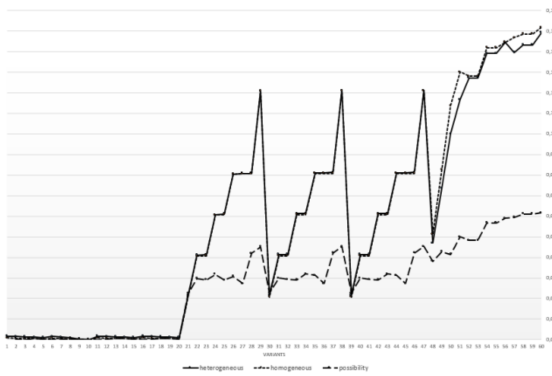

Figure 5. Increments of values of indicators structural and functional reliability of the supply chain with separate receipt of orders

The first 20 options reflect a single receipt of orders with a gradual increase in intensity. It should be noted that in this case, the values of the indicators $F_{\text{heterog}}(\vec{\chi}(\alpha_1,...,\alpha_4))$, $F_{\text{homog}}(\vec{\chi}(\alpha_1,...,\alpha_4))$, $F_{\text{homogposs}}(\vec{\chi}(\alpha_1,...,\alpha_4))$ do not change for the indicated variants, since there is an individual receipt of orders.

Variants from No. 21 to No. 29, from No. 30 to No. 38, from No. 39 to No. 47 reflect changes in the structural and functional reliability of the supply chain with a gradual increase in the intensity of uniform separate and joint receipt of two orders 1 and 2, 1 and 3, 1 and 4 respectively. Variants from No. 48 to No. 56 - a gradual increase in the intensity of the uniform separate and joint receipt of three orders (2, 3, 4; 1, 2, 3; 1, 2, 4; 1, 3, 4). Then there are variants from No. 57 to No. 60 - a gradual increase in the intensity of uniform separate and joint receipt of four orders.

It should be noted that with the joint receipt of several orders (two, three, four), the feasible assessment of the reliability of a homogeneous structure increases only by $4-6\%$. The probabilistic assessment of the reliability of a homogeneous or heterogeneous structure can increase for two orders by a maximum of 12%, for three and four orders - by a maximum of $14.5-15.2\%$. Moreover, the maximum value is achieved with the uniform use of these orders.

4 Conclusions

Within the framework of this article, a methodology and technology for assessing the reliability and survivability of the supply chain in the event of more or less serious fluctuations in demand are proposed. The proposed approach to the study of the structural and functional reliability of the supply chain under the conditions of changing customer orders is based on the parametric genome of the structure. The analysis of the above results showed that when creating and designing a supply chain, it is necessary to take into account various options (joint-incompatible, equivalent-unequal, homogeneous-heterogeneous) of dynamic customer orders, which significantly affect the reliability and survivability of the supply chain.

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