METHODS OF RELIABILITY MANAGEMENT IN SUPPLY CHAIN

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Abstract. The main problem of choosing an adequate method of managing the reliability of supply chains is that for both participants and consumers all the main properties of an effective supply chain (failure, economy and security of supply) are equally relevant. Therefore, it is necessary to jointly use the tools of reliability theory, planning methods built on the basis of operation research and risk management methods. The work considers mathematical models and methods for assessing and improving the reliability of supply chains and proposes an algorithm for calculating the reliability of supplies that corresponds to the exponential and normal laws of the distribution of failure intensity. According to the algorithm, on the example of the supply chain of spare parts of the "Sfera-Auto" enterprise, the reliability indicators of the supply chain were calculated, namely: failure time, failure intensity, average recovery time, recovery intensity and probability of failure-free delivery, and changes in the probability of failure-free operation P(t) chain. The results of the study showed that: the increase in the probability of failure-free operation P for the period (t) characterizes the higher reliability of the supply chain for any type of supply probability distribution; – the point values of the coefficient of failure of supply Kg and the value of supply reliability in supply P do not give a complete picture of the reliability of the supply chain, it is necessary to study the dynamics of these indicators; – it is necessary to choose a theoretical distribution for the failure intensity λ(t), because the exponential distribution, which is widely used for modeling the reliability of non-renewable systems, is not well suited for modeling the reliability of renewable systems.

Keywords: failure, cost effectiveness, supply chain, logistics costs, reliability.

Introduction

Management of reliability in a supply chain is usually associated with the choice of one or another tool or method for improving its reliability, which allows to achieve the continuity of its work under specific conditions. At the same time, to reduce production and logistics costs, it is necessary to use rather complex planning methods based on the research of the operations. Such methods are linear, non-linear or target programming, simulation modeling. To increase security, risk management methods such as risk distribution, diversification, and insurance should be applied.

The growing number of the scientific works devoted to the reliability, sustainability and security in the supply chains proves the exceptional relevance of this issue. In particular, various aspects of management of reliability in the supply chain are considered by H. Guo, W. Shengyu, Z. Yu [1], L. F. López-Castro, Elyn L. Solano Charris [2], M. Negri, E. Cagno, C. Colicchia, J. Sarkis [3], J. S. Rha [4], A. K. Sahu, N. K. Sahu, An. K. Sahu [5], O. Zagurskiy, L. Savchenko, I. Makhmudov, V. Matsiuk [6]. The impact of the pandemic on the sustainability and reliability of global supply chains was raised in the scientific works of I. Ali, A. Arslan, M. Chowdhury, Z. Khan, S. Y. Tarba [7], C. L. Karmaker, T. Ahmed, S. Ahmed, S. M. Ali, M. A. Moktadir, G. Kabir [8] and some other scientists. However, despite the number of studies of management of reliability in the supply chain, this issue remains one of the complex theoretical and insufficiently developed. The aim of the article is to develop mathematical models and methods of management of reliability in the supply chains.

Materials and methods

In a general sense, the supply chain model shows the actual multilateral relationship between producers integrated into a single exchange system and consumers. Accordingly, the supply chain can be effective only when all participating enterprises are in a normal state [9]. It is obvious that the attractiveness of the supply chain for the consumer is determined by a certain level of reliability, which has competitive advantages over the reliability of similar supply chains presented on the goods (services) market [10]. Therefore, for both participants and consumers, the quality of the supply chain is associated with a certain given (expected) reliability criterion, which depends on the following condition (Formula 1):

$$P_c \geq P_0 , \tag{1}$$

where P_c – level of reliability of all parts of the supply chain;
P_0 – required level of reliability.

In this case, reliability is understood as the ability to perform the required functions within a specific time frame.

That is, it is a set of criteria such as the efficiency of order fulfillment in terms of compliance with supply deadlines, the quality of the services provided, product range, total costs. However, the main obstacles to the reliability in the supply system are random disruptions in the supply (deviations of X_n from the normal behavior of X_0.) The change in the parameters of processes and/or the results of the interaction of the supply chain elements correspond to these deviations. Moreover, the random variable X_n has a stable distribution, characterized by function (2) [11], and violations, as a result of the influence of dangerous (force majeure) factors, can be compensated mutually.

$$\varphi(X_n) = \{\exp\{-/\gamma w/[1 - i sign(w)\beta \tan(\frac{\pi\alpha}{2}] + i\delta w\}, (\alpha \neq 1\} \ , \quad (2)$$

where $sign(w) = \frac{w}{/w/}$, $\alpha \in (0.2)$

Thus, the impact of disruptions on the interactions in the supply chain always manifests itself due to the reliability of the suppliers. Accordingly, the main properties of the supply chains due to their reliability are failure-free performance, cost effectiveness and security of supply. The main parameters of reliability in the supply are mean time between failures, failure rate, mean time to repair, repair rate and probability of failure-free supply. The listed indicators are taken in dynamics or comparison. They quite fully characterize the supply process, allow predicting the level of supply reliability and the duration of possible shortage situations. The procedure for the assessment of reliability in the supply chain is as follows (Fig. 1):

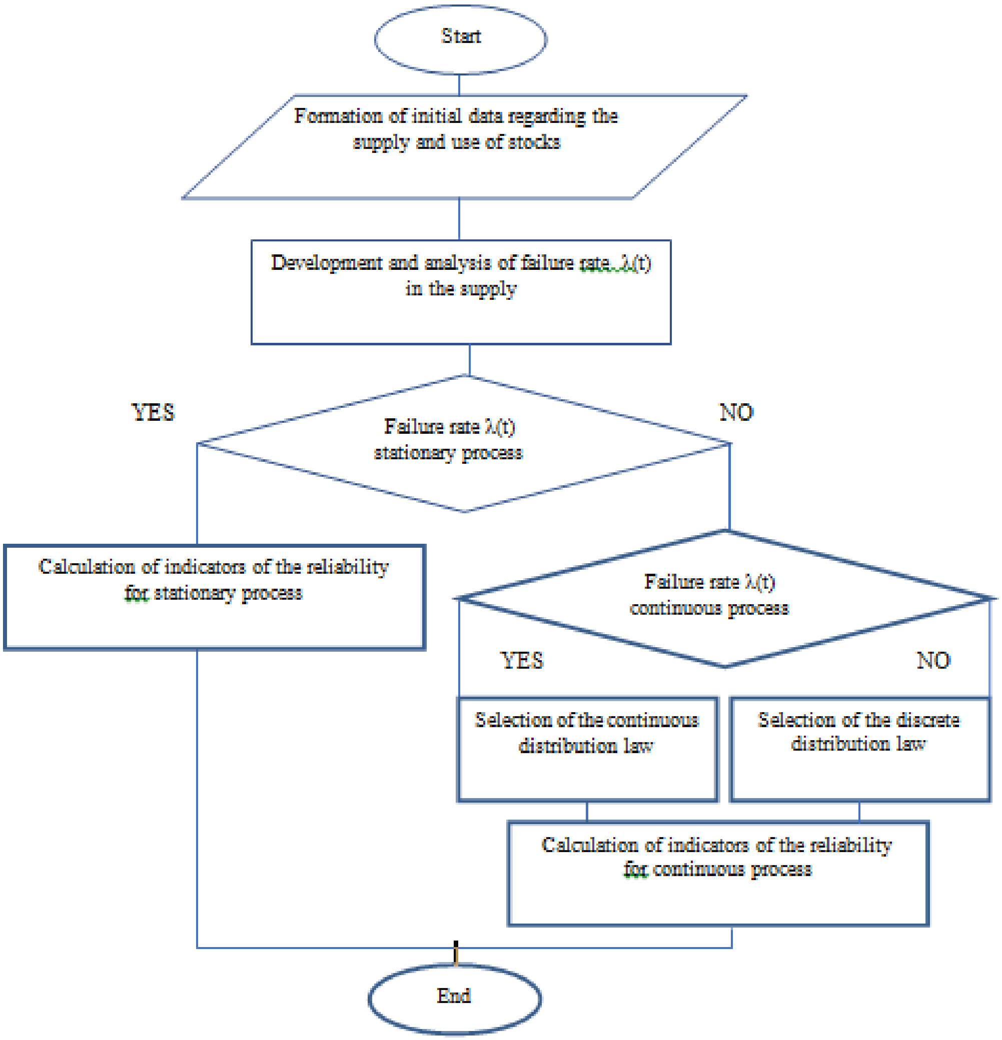

Fig. 1. **Assessment of reliability in a supply chain**

The procedure for the calculation of indicators of reliability in the supply chain under the exponential distribution of failure rate is shown in Table 1.

Table 1

Indicators of reliability in the supply chain under the exponential distribution of failure rate and the procedure for their calculation

Indicators	Calculation
1. Delay time for deliveries	$\Delta T_d = D_r - D_{pl}$
2. Amount of underdelivery	$\Delta V = V_{pl} - V_r$
3. Average number of daily deliveries	$V = \sum V/T$
4. Conditional delay time in case of underdelivery	$T_d = \Delta V/v$
5. Total number of delays	$\sum T_d = \sum t_d + \sum t'_d$
6. Mean time between failures T_{bf}	$T_{bf} = (T - \sum T_d)/n$
7. Failure rate λ	$\lambda = 1/T_d$
8. Mean time to repair	$T_r = \sum T_d/n$
9. Repair rate	$\eta = 1/T_r$
10. Delivery readiness index (failure-free supply) K_{read}	$K_{read} = (T - \sum T_d/T)$
11. Reliability of provision of raw materials	$P = K_{read} \times e^{-\lambda c}$ $(0 < P \leq 1)$

For the normal distribution, the reliability function (failure-free operation) is calculated by the Formula 3.

$$P(t) = \int_t^{\infty} \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{(x-m)^2}{2\sigma^2}} dx = 0.5 - \Phi_0(\frac{t-m}{\sigma}, \quad (3)$$

where $t = \Delta t$ – interval length, days;

$m = T_0$ – mean time between failures, days;

$\sigma = \sigma T$ – root-mean-square deviation between failures, days;

$\Phi_0 = \frac{1}{\sqrt{2\pi}} \int_0^t e^{\frac{x^2}{2}} dx$ – Laplace function, the values of which are summarized in the table.

This takes into account a number of conditions:

- exceeding of the size of the delivery batch against the planned one does not compensate for the violation of the delivery time;
- in the case when the delivery time is violated and there is an underdelivery, then two types of delay are considered: by date and due to underdelivery;
- if the delivery did not take place within the specified timeframe, then in this case the conditional delay is determined by the entire volume of delivery of the undelivered batch;
- deliveries made before the planned deadline are considered delivered on time.

Results and discussion

Let us apply this method for the calculation of reliability in the conditions of a pandemic in the supply chain of spare parts based on the data of "Sfera-Avto" enterprise in 2021, shown in Table 2.

Table 2

Calculation of reliability in the supply of materials under the exponential distribution of the failure rate

Indicator	**Data**												**∑ or average**
Month of delivery	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	
Interval length Δt, d.	31	28	31	30	31	30	31	31	30	31	30	31	365
Total number of interval lengths $\sum \Delta t$, d.	31	59	90	120	151	181	212	243	273	304	334	365	
Delay time t_d, d.	0	0	5	10	17	13	0	0	3	0	16	15	79

Table 2 (continued)

Indicator	**Data**												**∑ or average**
Conditional delay time t'_d, d.	0	0	0	0	0	0	7	20	11	30	0	0	68
Total delay time $t_d + t'_d$, d.	0	0	5	10	17	13	7	20	14	30	16	15	147
Amount of planned delivery V_{pl}, kg	600	600	600	600	600	600	600	600	600	600	600	600	7200
Amount of actual delivery V_{ac}, kg	600	600	600	800	1000	640	460	200	380	0	720	1200	7200
Amount of underdelivered goods ΔV, kg	0	0	0	200	400	40	-140	-400	-220	-600	120	600	0
Stock usage rate v, $kg \cdot d^{-1}$.	20	20	20	20	20	20	20	20	20	20	20	20	20
Number of failures $n(t, t + \Delta t)$,	0	0	1	1	1	1	1	1	1	1	1	1	10
Mean time between failures T_{bf}, d.	31	28	26	20	14	17	24	11	16	1	14	16	21,8
Mean time to repair T_d, d.	0	0	5	10	17	13	7	20	14	30	16	15	14.7
Failure rate $\lambda(t)$	0.032	0.036	0.038	0.05	0.071	0.059	0.04	0.091	0.063	1	0.071	0.063	0.04587
Availability $K_{read}(t)$	1	1	0.839	0.667	0.452	0.567	0.77	0.355	0.533	0.032	0.467	0.516	0.59726
Downtime $K_{simple}(t)$	0	0	0.161	0.333	0.548	0.433	0.23	0.645	0.467	0.968	0.533	0.484	0.40274
Probability of failure-free operation $P(t)$	0.968	0.965	0.807	0.634	0.420	0.534	0.74	0.324	0.501	0.012	0.435	0.485	0.57048

Figure 2 shows the dynamic change of the probability of failure-free operation *P(t)*, which corresponds to the exponential distribution of the failure rate.

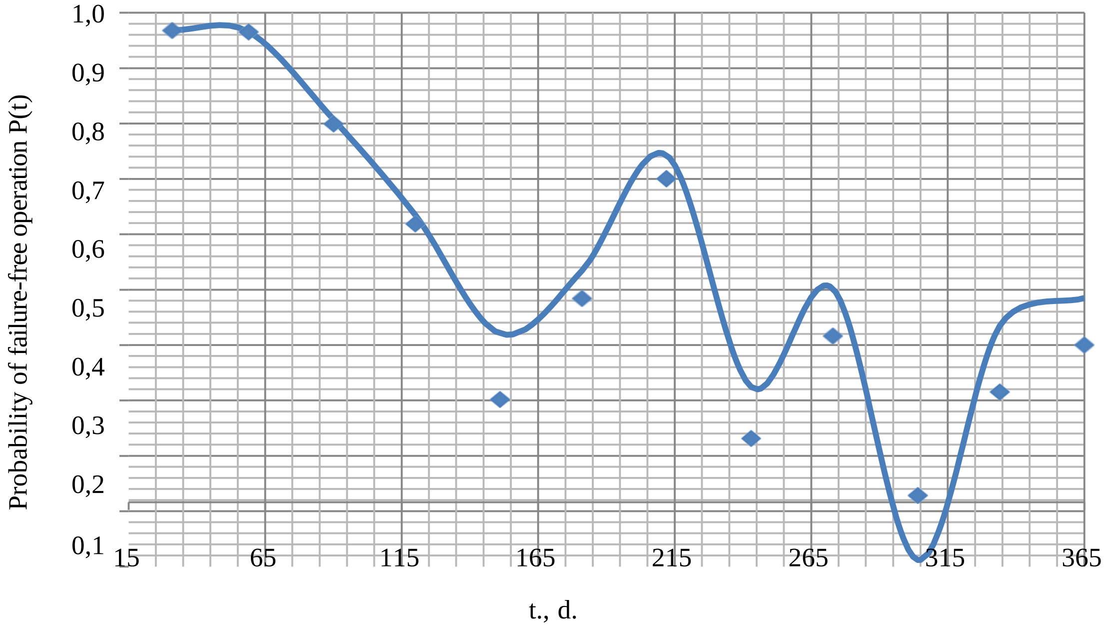

Fig. 2. **Dynamic change of probability of failure-free operation *P*(*t*) under exponential distribution of the failure rate**

The analysis of the dynamic changes in the failure rate $\lambda(t)$ (see Table 2 and Fig. 2) shows that the occurrence of failures is a non-stationary process. Therefore, firstly, it is necessary to study the dynamics of the parameters of the reliability in the supply chain. Secondly, the distribution of this indicator is sharp-edged, asymmetric. It has a number of local extrema and does not agree well with the exponential distribution. Therefore, in order to calculate the parameter of reliability in the supply chain of materials, it is necessary to choose the most appropriate distribution law.

The assessment of the amount of underdelivered goods ΔV shows that the problems with the supply at the enterprise have started in July, when the amount of underdelivered goods ΔV was 140 units, and reached a maximum in October, when there were no deliveries of goods, and ΔV = -600 units. Therefore, the trade or the production process at this enterprise during the specified timeframe could be interrupted due to the lack of the necessary material.

The analysis of the dynamic changes in the availability $K_a(t)$ and downtime $K_d(t)$ (see Table 2) shows that the indicators vary over a wide range during the entire planned timeframe T. Availability $K_a(t)$ reaches its maximum in January and in February, and the minimum in October, while downtime $K_d(t)$ has reverse dynamics.

The results of the calculation of the downtime $K_d(t)$ show that in August, October and November the enterprise could be idle for most of the time due to the lack of necessary material. At the same time, the data given in Table 2 do not give the answer to the question about the most critical value of the total delay that leads to the stoppage of the production or trade process $t_{on} + t'_{on}$. Therefore, it is necessary to know the value of the safety stock in order to calculate an invalid value of the total delay $t_{on} + t'_{on}$.

The analysis of the dynamic changes in the probability of failure-free operation $P(t)$ under the exponential distribution of the failure rate (see Fig. 2) shows that this indicator changes in a wide range of values from 0.968 in January to 0.012 in October. The dynamics of this indicator fully corresponds to the dynamics of the change in the availability $K_a(t)$ (see Table 2) but differs slightly from its value.

The assessment of the dynamic changes in the probability of failure-free operation $P(t)$ under the normal distribution of failure rate (see Fig. 3) shows that the dynamics of this indicator corresponds to the dynamic changes of availability $K_a(t)$ and the probability of failure-free operation $P(t)$ under exponential distribution (See Table 2). However, it is significantly different in value.

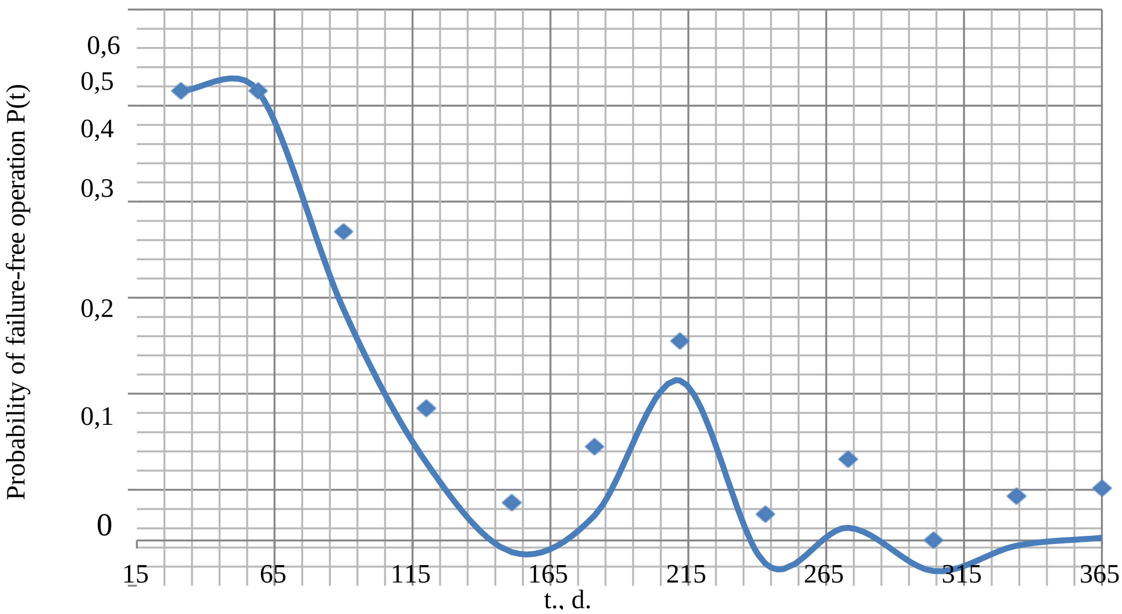

Fig. 3. **Dynamic changes in probability of failure-free operation *P*(*t*) under normal distribution of the failure rate**

Thus, when we consider the average time interval per month Δt = 30.4 days, the reliability function is $P_{(30.4)}$ = 0.149. Obviously, the higher value of the probability of failure-free operation $P(t)$ means higher reliability of supply. However, in developing the reliability indicators of supply, it is necessary to take into account such peculiarities of the supply process as:

- the failure rate $\lambda(t)$ of the supply. It can be both a stationary process and a non-stationary process. It can have trends, seasonality, random bursts. Therefore, the calculation of the reliability in the supply chain can be both static and dynamic;

- the delays in the supply of goods can be both continuous and discrete (for example, its dynamic changes can be rare). Therefore, it is necessary to choose the best distribution law of the probability of failure rates $\lambda(t)$: continuous (exponential, normal, Weibull, gamma distribution) or discrete (Poisson, binomial).

In order to ensure a stable and efficient operation of the supply chain in a competitive environment, manufacturing companies should actively respond to changes in the supply conditions, including the design of the supply chain and the recovery strategy.

Conclusions

1. The critical analysis of mathematical models and methods for management of the reliability in the supply chain shows that the technical approach to the assessment and improvement of the reliability is predominant. According to this approach, the criterion of reliability is the probability of failure-free operation of the supply chain that should be equal to one, including the restrictions on the cost of logistics or time of logistics cycle.
2. In recent years, the economic approach to management of reliability in the supply chain has become widespread. The main criterion is the production or logistics costs which are minimized, including the restrictions on the probability of failure-free operation in the supply chain. Thus, these two approaches to management of the reliability in the supply chain supplement each other.
3. The considered example of calculation of the reliability in the supply shows that, firstly, the main values of failure-free supply K_g and the amount of reliability of supply P do not give a full idea about the reliability of deliveries. It is necessary to research the dynamics of these indicators. Secondly, it is necessary to select an appropriate theoretical distribution for the failure rate $\lambda(t)$, since the exponential distribution, which is widely used to model the reliability of the non-restored systems, is poorly suited to model the reliability of the renewable systems. Thirdly, the reliability of the supply in the normal distribution does not correspond to the classical understanding of reliability. Thus, it cannot be the probability of the failure-free operation of a supplier during a specified timeframe t. Therefore, it is necessary to continue the study in this field.

Author contributions

Conceptualization, formal analysis and writing – Zagurskiy O.; original draft preparation methodology and project administration – Pivtorak M. ; methodology – Demin O.; data curation and visualization – Kolosok I..; funding acquisition – Bondariev S.

All authors have read and agreed to the published version of the manuscript.

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