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RESEARCH ARTICLE

Reliability Allocation for Components at the Early Stages of Design

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ABSTRACT

At the early stages of machine design, reliability indicators must be assigned on a sound basis so that the designer can correctly identify critical components and ensure the required level of failure-free operation. Existing reliability allocation methods have limitations and internal inconsistencies, particularly when the exponential distribution is used. This paper proposes an alternative approach that enables a complete structural analysis — from the generalized characteristics of the system to individual components, including those whose failures are not sudden. At the same time, the method retains mathematical simplicity comparable to that of the exponential model.

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INTRODUCTION

Review of the Current State of Reliability Allocation for Technical Systems. Identification of Problems and Possible Solutions.

At the early stages of machine design specified by the Unified System for Design Documentation, including analysis of the technical specification [GOST 15.001–88, 1988; GOST 2.103–2013, 2015] and preparation of the technical proposal [GOST 2.118-2013., 2015], preliminary design [GOST 2.119–2013, 2018], and technical design documentation [GOST 2.120–2013, 2015], calculations must be performed to confirm the operability and reliability of the future product.

At the technical specification stage, two key parameters must be determined that are important both for the preparation of design documentation and for subsequent operation:

What probability of failure-free operation should be specified for the machine?

For what operating time should this probability be specified?

The operating time of a machine at the technical specification stage may be selected from different perspectives. Most machines are designed as repairable systems in which operating and repair cycles are repeated until the limiting state is reached. The required operating time may be specified for a nonrepairable system, until the first failure, or for a repairable system, within its service life. The warranty period is also important. The components of a technical system, as the sources of failures, determine the operating time between failures of the system and may be repairable or nonrepairable. Ideally, the operating times to failure of all components should be equal to or multiples of the selected system operating time. Therefore, the required or selected operating time should represent a period of failure-free operation.

Since the probability of failure-free operation decreases over time under any distribution law, the operating time of the technical system should be rationally minimized while remaining consistent with the operating logic of the system. It may correspond to a period of continuous operation during which a specific technical and economic cycle is completed, such as a single intended use, a scheduled trip, the amount of work specified by a contract, a season of construction, transport, or agricultural work, or the interval between scheduled maintenance operations.

MATERIALS AND METHODS

The calendar service life of the technical system and its required operating time are related as follows:

$$T = TK \times 365 \times Kyear \times 24 \times Kday \times DC, \text{ h}, \tag{1}$$

where TK is the calendar service life, years;

Kyear is the annual availability coefficient of the technical system;

Kday is the daily utilization coefficient of the technical system;

DC is the relative duty cycle, defined as the ratio of the operating time within a cycle to the total cycle duration.

A high level of failure-free operation can be achieved by reducing the required operating time. If the operating time must be substantially increased, maintaining the required reliability will require more frequent maintenance and the design of critical assemblies with higher production costs [Kovalev et al., 1991, Dalsky, 1975].

RESULTS AND DISCUSSION

The probability of failure-free operation of a machine may be specified on the basis of industry standards, competitive requirements, or other considerations, including the conventional reliability classes used in mechanical engineering. The data presented in [Volkov and Nikolaev, 1979; Androsov, 2000; Manshin and Manshina 2014; Pronnikov, 2002] can be summarized as shown in Table 1.

Table 1: Machine Reliability Classes

Reliability class	0	1	2	3	4	5
Allowable probability of failure-free operation	≤ 0,9	≥ 0,9	≥ 0,99	≥ 0,999	≥ 0,9999	1
Applicable product structural types	Complex transport, agricultura, and road construction machinery; technological machines and complexes	Machines and units	Units and mechanisms	Mechanisms, assembly units, and components	Assembly units and components of highly reliable machines	
Applicable machine types		Technological equipment for nonautomated production	Technological equipment for automated production	Mass-produced products	Material-handling machinery, aircraft, chemical processing machinery, medical equipment, and military equipment.	
General consequence of failure	A failure occurring during the specified period results in economic losses that are acceptable relative to the product cost and the cost of restoration.			Reputational damage and associated economic losses.	Accident, disaster, or failure to complete a critical mission.	
	An insignificant reduction in efficiency with high maintainability.	Economic losses due to insufficient maintainability.	Significant economic losses due to downtime and insufficient maintainability.			

It is widely assumed that failures of technical systems occur suddenly and that reliability can therefore be described by the exponential distribution [Volkov and Nikolaev, 1979; Androsov, 2000; Manshin and Manshina, 2014; Shubin and Ryumin, (2006); Androsov et al., 2013; Polovko and Gurov, 2006; Druzhinin, 1977; Manshin and Manshina, 2017; Gnedenko et al., 1965.]:

$$P(t) = e^{-\lambda t} \tag{2}$$

where the failure rate during the normal operating period, after the burn-in period, is related to the mean operating time between failures of the technical system, Ť:

$$\lambda = 1 / \check{T}, \tag{3}$$

and, taking into account the specified reliability parameters:

$$\lambda = (-\ln P(T)) / T \,, \tag{4}$$

from which the mean operating time between failures can be calculated:

$$\check{T} = (-T / \ln P(T)). \tag{5}$$

This procedure, applied at the technical specification stage, has both supporters and critics [Pronnikov, 2002; Polovko and Gurov, 2006; Khozyaev, 2014.]. A more substantiated approach would be to use as the initial value the mean operating time between failures, $\bar{T}$, obtained from prototype testing or from tests of comparable machines, and then determine the failure rate from Equation (4) and the required probability of failure-free operation from Equation (3) using the required operating time T. However, the question remains whether all failures observed during testing are truly sudden and whether the parameters in Equations (3)–(5), derived from the exponential model, are valid.

The machine reliability literature provides examples of bottom-up analysis – from the probability of failure-free operation of individual components to that of the entire system – for series, parallel, and combined reliability block diagrams (Figure 1).

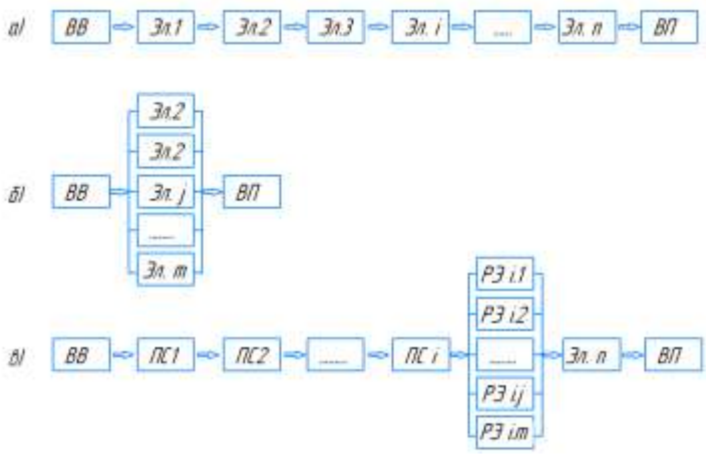

Figure 1: Reliability Block Diagrams of Technical Systems

(a) series interaction of components; (b) parallel interaction of components;
(c) combined interaction of subsystems (SS) or blocks (RC – redundant components).

The following designations are used in Figure 1: IA – input actions; OP – output parameters; RC – redundant components.

For the series connection shown in Figure 1a, the exponential distribution provides convenient mathematical expressions. If the probability of failure-free operation of the system P(t) and those of its component subsystems Pi(t) are related as follows:

$$P(t) = \prod_{i=1}^{n} P_i(t)\,, \tag{6}$$

then the failure rates of the system, λ, and the subsystems, λi, satisfy the following equation:

$$\lambda = \sum_{i=1}^{n} \lambda_i \,, \tag{7}$$

The failure rates may be allocated among the components according to different principles.

A hierarchical reliability block diagram containing nested levels of subsystems and components [Volkov and Nikolaev, 1979; Manshin and Manshina, 2014; Shubin and Ryumin, 2006; Androsov et al., 2013; Druzhinin, 1977; Manshin and Manshina, 2017] enables top-down analysis of the probability of failure-free operation [Manshin and Manshina, 2014; Androsov et al., 2013] – from the system as a whole to individual components. The resulting probabilities of failure-free operation of the components, together with the specified operating time, serve as input data for designing components with a specified reliability level [Manshin and Manshina 2014].

The top-down analysis algorithm works effectively for allocating failure rates and probabilities among hierarchical levels. However, a contradiction arises at the component level: if a component failure develops gradually according to a different distribution law rather than the exponential distribution, application of the exponential model becomes invalid. A component failure occurring in accordance with the physical law governing damage accumulation will nevertheless cause the failure of higher-level subsystems and the entire technical system, but this event will not be described by the exponential distribution.

For the parallel interaction shown in Figure 1b, the following conditions are assumed: the components operate continuously, their failures are independent, and each of the m components has a probability of failure-free operation Pj(t) and is capable of receiving an input action and generating an output parameter. In such a system, system failure occurs after the last operable component has failed. The probability of system failure is:

$$\mathrm{F}(t) = \prod_{j=1}^{m} F_j(t) \tag{8}$$

and, using the completeness property of the set of events

$$\mathrm{P(t) + F(t) = 1}, \tag{9}$$

we obtain:

$$\mathrm{P}(t) = 1 - \prod_{j=1}^{m} [1 - P_j(t)] \tag{10}$$

For identical components:

$$\mathrm{P(t)=1-[1-P_j(t)]^m} . \tag{11}$$

The exponential distribution provides a simple calculation of failure rates or the required number of components only for identical redundancy, as expressed by Equation (11). For more complex relationships described by Equation (10) and for combined structures shown in Figure 1c, examples of applying the exponential model are rarely provided.

The literature also lacks examples of structural analysis involving dependent failures and complex multidirectional relationships between components that hinder structural decomposition. Graphical representations of such systems [Androsov, 2000; Pronnikov, 2002] are accompanied by comments on the complexity of the operating model and the cumbersome nature of the calculations, for example, in the case of closed-loop operation of internal combustion engine units.

To solve the problem of allocating the probability of failure-free operation at the early design stages, these difficulties can be avoided by referring to the physical structure of the machine. As a more specific hierarchy, the machine structure can be divided into structural blocks. The lowest level of this hierarchy consists of components and standard products. If this structural arrangement is used as the reliability block diagram, the restoration cost of a component following failure may be adopted as the criterion for allocating the probability of failure-free operation. The restoration cost may include the costs of materials, products, diagnostics, and repair work, as well as the monetary value of the consequences of failure, including downtime losses, insurance payments, and other costs shown in Table 1.

The aim of this study is to develop a method for the top-down analysis of reliability block diagrams that is free from the contradictions described above. The proposed reliability block diagram should serve as a tool for allocating the probabilities of failure-free operation of individual components on the basis of the specified probability of failure-free operation of the system at the early design stages. The selected operating time and balanced values of the probability of failure-free operation of the components then provide the basis for designing the system with a specified level of failure-free operation.

The reliability block diagram must satisfy the following requirements:

To simplify complex functional relationships, the diagram is constructed on the basis of the machine structure.

The mathematical model must be suitable for calculations at the early design stages.

The model must not rely on the exponential distribution and must use only the fundamental reliability properties expressed by Equations (6), (10), and (11).

The criterion for ranking the probabilities of failure-free operation of components is their restoration cost following failure, including, where necessary, the monetary value of the consequences of failure.

The method must be equally applicable to series, parallel, and combined structures.

Representation of the Numerical Value of an Object's Probability of Failure-Free Operation

Any number A in the interval 0 < A < 1 can be represented in various ways. One possible representation is the power form:

$$A = B^x, \tag{12}$$

where exponent x is obtained from the logarithmic equation log A = x log B:

$$x = \log A / \log B. \tag{13}$$

Since the value of A does not depend on the choice of base B, either common logarithms (B = 10) or natural logarithms (B = e) may be used. Therefore:

$$x = \log A, \text{ for } B = 10, \tag{14}$$

$$x = \ln A / \ln 10, \text{ for } B = 10, \tag{15}$$

$$x = \ln A, \text{ for } B = e, \tag{16}$$

where Equations (14) and (15) yield the same numerical result, and x is a negative real number in all cases.

Since the probability of failure-free operation of a technical object also lies within the interval 0 < P(t) < 1, it can be represented in the form of Equation (12). Taking B = 10, we obtain:

$$P(t) = 10^x, \tag{17}$$

where, according to Equation (14), log P(t) = x log 10:

$$x = \log P(t). \tag{18}$$

The following section considers the "simplest and most important case" [18] — the calculation of system reliability.

Probability of Failure-Free Operation of Components in Series Interaction.

For the series system shown in Figure 1a with independent failures, Equation (6) applies. Applying the representation in Equation (17) to all factors gives:

$$10^x = 10^{x1}\ 10^{x2}\ ..\ 10^{xn},$$

from which:

$$x = x_1 + x_2 + .. + x_n. \tag{19}$$

The possible combinations of x_i in Equation (19) are constrained by the restoration costs C_i: the more expensive a component is to restore, the higher its probability of failure-free operation should be. Therefore, the sequence x_1, x_2, ..., x_n corresponds to the sequence of reciprocal values $1/C_1$, $1/C_2$, ..., $1/C_n$. This relationship can be expressed using sums.:

$$1 = \frac{x_1}{x} + \frac{x_2}{x} + \ldots + \frac{x_n}{x}, \text{ and } 1 = \frac{\frac{1}{C_1}}{\sum \frac{1}{C_i}} + \frac{\frac{1}{C_2}}{\sum \frac{1}{C_i}} + \ldots + \frac{\frac{1}{C_n}}{\sum \frac{1}{C_i}}.$$

Term-by-term equality yields the restoration-cost weighting coefficient:

$$a_i = \frac{\frac{1}{C_i}}{\sum \frac{1}{C_i}}, \tag{20}$$

and therefore:

$$x_i = x\, a_i. \tag{21}$$

The units used to express cost are irrelevant because Equation (20) uses ratios.

Example 1, involving a series system with three components, is presented in Table 2.

The probabilities of failure-free operation of the components of a technical system with series interaction, as shown in Figure 1a, were calculated using the following input data: system probability of failure-free operation P(t) = 0.9; number of components n = 3; component restoration costs C_1 = 5,000, C_2 = 3,000, and C_3 = 2,000 arbitrary units.

Table 2: Calculation of Component Probabilities of Failure-Free Operation for Series Interaction

Object	Restoration Cost C_i, arbitrary units	Reciprocal Cost $1/C_i$	Weighting Coefficient a_i, Equation (20)	Exponent x_i, Equation (21)	Probability of Failure-Free Operation $P_i(t)$, Equation (17)
Technical system				−0,04576	0,9
Component 1	5000	0,0002	0,193548	−0,00886	0,979814
Component 2	3000	0,000333	0,322581	−0,01476	0,966584
Component 3	2000	0,0005	0,483871	−0,02214	0,950297
Check sums and products		$\Sigma(1/C_i)$	Σa_i	Σx_i	$P(t)= \prod P_i(t)$
		0,001033	1	−0,04576	0,9

Probability of Failure-Free Operation of Components in Parallel Interaction

For the parallel system shown in Figure 1b, system failure occurs when all components have failed, as expressed by Equation (8). By analogy with Equation (17), the failure probability is represented as:

$$F(t) = 10^{y}, \tag{22}$$

then Equation (8) gives: $10^{y} = 10^{y1}\ 10^{22}\ ..\ 10^{ym}$,

$$y = y_1 + y_2 + .. + y_m. \tag{23}$$

In this case, components with higher restoration costs should have lower probabilities of failure and therefore higher probabilities of failure-free operation. Thus, the sequence y_1, y_2, ..., y_m corresponds to the sequence of costs C_1, C_2, ..., C_m. The weighting coefficient is derived in the same manner:

$$b_j = \frac{C_j}{\sum C_j}, \tag{24}$$

$$y_j = y\, b_j. \tag{25}$$

Example 2, involving a parallel system with three components, is presented in Table 3. The failure probabilities and probabilities of failure-free operation of the components of a technical system with parallel interaction, as shown in Figure 1b, were calculated using the following input data: system probability of failure-free operation P(t) = 0.9; number of components m = 3; component restoration costs C_1 = 5,000, C_2 = 3,000, and C_3 = 2,000 arbitrary units.

Table 3: Calculation of Failure Probabilities and Probabilities of Failure-Free Operation for Parallel Interaction

Object	Restoration Cost C_j, arbitrary units	Weighting Coefficient b_j, Equation (24)	Exponent y_j, Equation (25)	Failure Probability $F_j(t) = 10^{yj}$	Probability of Failure-Free Operation $P_j(t)=1-F_j(t)$
Technical system			−1	0,1	0,9
Component 1	5000	0,5	−0,5	0,316228	0,683772
Component 2	3000	0,3	−0,3	0,501187	0,498813
Component 3	2000	0,2	−0,2	0,630957	0,369043
Check sums and products	ΣC_j	Σb_j	Σy_j	$Ft)=\Pi F_j(t)$	$P(t)=1-F(t)$
	10000	1	−1	0,1	0,9

Example 3, involving the combined structure shown in Figure 1c, is presented in Tables 4 and 5. The probabilities of failure-free operation of the components of the combined technical system shown in Figure 1c were calculated using the following input data: the number of subsystems interacting in series is n = 3; the number of components interacting in parallel within subsystem SS3 is m = 4; the system probability of failure-free operation is P(t) = 0.95; the subsystem restoration costs are C1 = 5,000, C2 = 8,000, and C3 = 12,000 arbitrary units; the restoration costs of the components interacting in parallel are C3.1 = 3,000, C3.2 = 4,000, C3.3 = 5,000, and C3.4 = 6,000 arbitrary units.

Table 4: Calculation of Subsystem Probabilities of Failure-Free Operation for the Series Section

Object	Restoration Cost C_i, arbitrary units	$1/C_i$	Weighting Coefficient a_i, Equation (20)	Exponent x_i, Equation (21)	Probability of Failure-Free Operation $P_i(t)$, Equation (17)	
Technical system				−0,022276	0,95	
SS 1	5000	0,000200	0,489796	−0,010911	0,975190	
SS 2	8000	0,000125	0,306122	−0,006819	0,984421	
SS 3	12000	0,000083	0,204082	−0,004546	0,989587	◄
Check sums and products		$\Sigma(1/C_i)$	Σa_i	Σx_i	$P(t)=\prod P_i(t)$	
		0,000408	1	−0,022276	0,95	

◄ — symbol indicating the subsystem selected for further top-down analysis.

For SS3, which has a parallel structure:

P3(t) = 0.989587,

F3(t) = 1 − P3(t) = 1 − 0.989587 = 0.010413,

y = log F3(t) = log 0.010413 = −1.982407.

Table 5: Calculation of the Components of Parallel Subsystem SS3

Object	Restoration Cost $C_{3\cdot j}$, arbitrary units	Weighting Coefficient b_j, Equation (24)	Exponent y_j, Equation (25)	Failure Probability $F_{3\cdot j}(t) = 10^{y3.j}$	Probability of Failure-Free Operation $P_{3\cdot j}(t) = 1 - F_{3\cdot j}(t)$
SS3			−1,982407	0,010413	0,989587
Component 3.1	3000	0,166667	−0,330401	0,467303	0,532697
Component 3.2	4000	0,222222	−0,440535	0,362631	0,637369
Component 3.3	5000	0,277778	−0,550669	0,281405	0,718595
Component 3.4	6000	0,333333	−0,660802	0,218372	0,781628
Check sums and products	ΣC_j	Σb_j	Σy_j	$F3(t)=\prod F_{3.j}(t)$	$P_3(t)=1-F_3(t)$
	18000	1	−1,982407	0,010413	0,989587

Example 4 — top-down analysis of a combine harvester (Figures 2 and 3, Table 6).

Figure 2: Process diagram of the RSM-181 TORUM-740 combine harvester

(units: 1 – harvesting unit; 2 – running gear; 3 – controls; 4 – threshing unit; 5 – engine unit; 6 – chopper)

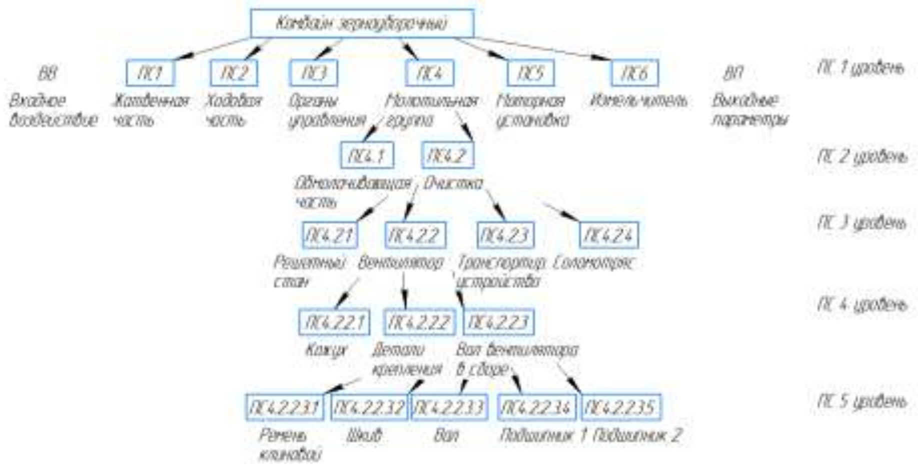

Figure 3. Reliability Block Diagram of the Combine Harvester
(hierarchy: levels from SS1–SS6 to components 4.2.2.3.1–4.2.2.3.5)

The following assumptions were adopted for the combine harvester:

– The system probability of failure-free operation is P(t) = 0.8.

– All subsystems and components are connected in series.

– The restoration costs are presented in Table 6.

The required operating time, taking into account the seasonal operation of the combine harvester — 50 days per year, Kday = 0.9, and DC = 1 — is:

T = 50 × 24 × 0.9 × 1 = 1,080 h.

The calculations were performed sequentially for each hierarchical level using Equations (18)–(21), as presented in Table 6. The following probabilities of failure-free operation were obtained for the final components over an operating time of 1,080 h:

– V-belt: 0.999990.

– Bearing 1, located near the pulley: 0.999991.

– Bearing 2: 0.999986.

– Shaft: 0.999998; it should be calculated using a fatigue model [Manshin and Manshina, 2014].

Table 6: Calculation of the Probabilities of Failure-Free Operation of the Subsystems and Components of the RSM-181 TORUM-740 Combine Harvester

Object	Cost C_i	$1/C_i$	Weighting Coefficient. a_i, (20)	Exponent x_i (21)	Probability of Failure-Free Operation $P_i(t)$, (17)	
Technical system				–0,096910	0,8	
SS 1	200000	0,000005	0,110294	–0,010689	0,975689	
SS 2	300000	0,000003	0,073529	–0,007126	0,983726	
SS 3	120000	0,000008	0,183824	–0,017814	0,959811	
SS 4	500000	0,000002	0,044118	–0,004275	0,990204	◄
SS 5	150000	0,000007	0,147059	–0,014251	0,967717	
SS 6	50000	0,000020	0,441176	–0,042754	0,906245	
Check sums and products		$\Sigma(1/C_i)$	Σa_i	Σx_i	$P(t)=\Pi P_i(t)$	
		0,000045	1,000000	–0,096910	0,800000	
Analysis of the Probability of Failure-Free Operation of the Selected Level 1 Subsystem						
SS 4	500000			–0,004275	0,990204	
SS 4.1	150000	0,000007	0,700000	–0,002993	0,993132	
SS 4.2	350000	0,000003	0,300000	–0,001283	0,997051	◄
Check sums and products		$\Sigma(1/C_i)$	Σa_i	Σx_i	$P(t)=\Pi P_i(t)$	
		0,000010	1,000000	–0,004275	0,990204	
Analysis of the Probability of Failure-Free Operation of the Selected Level 2 Subsystem						
SS 4.2	350000			–0,001283	0,997051	
SS 4.2.1	120000	0,000008	0,163934	–0,000210	0,999516	
SS 4.2.2	80000	0,000013	0,245902	–0,000315	0,999274	◄
SS 4.2.3	50000	0,000020	0,393443	–0,000505	0,998839	
SS 4.2.4	100000	0,000010	0,196721	–0,000252	0,999419	
Check sums and products.		$\Sigma(1/C_i)$	Σa_i	Σx_i	$P(t)=\Pi P_i(t)$	
		0,000051	1,000000	–0,001283	0,997051	
Analysis of the Probability of Failure-Free Operation of the Selected Level 3 Subsystem						
SS 4.2.2	80000			–0,000315	0,999274	
SS 4.2.2.1	15000	0,000067	0,235294	–0,000074	0,999829	
SS 4.2.2.2	5000	0,000200	0,705882	–0,000223	0,999487	
SS 4.2.2.3	60000	0,000017	0,058824	–0,000019	0,999957	◄
Check sums and products		$\Sigma(1/C_i)$	Σa_i	Σx_i	$P(t)=\Pi P_i(t)$	
		0,000283	1,000000	–0,000315	0,999274	
Analysis of the Probability of Failure-Free Operation of the Selected Level 4 Subsystem						
SS 4.2.2.3	60000			–0,000019	0,999957	
SS 4.2.2.3.1	7000	0,000143	0,237624	–0,000004	0,999990	◄
SS 4.2.2.3.2	10000	0,000100	0,166337	–0,000003	0,999993	
SS 4.2.2.3.3	30000	0,000033	0,055446	–0,000001	0,999998	◄
SS 4.2.2.3.4	8000	0,000125	0,207921	–0,000004	0,999991	◄
SS 4.2.2.3.5	5000	0,000200	0,332673	–0,000006	0,999986	◄
Check sums and products		$\Sigma(1/C_i)$	Σa_i	Σx_i	$P(t)=\Pi P_i(t)$	
		0,000601	1,000000	–0,000019	0,999957	

CONCLUSION

A method for the top-down analysis of machine reliability block diagrams was developed and tested using numerical examples. Its algorithm corresponds to the sequence of design stages – from the probability of failure-free operation of the machine as a whole to the probabilities of failure-free operation of individual components. Selecting the required operating time and allocating the probabilities of failure-free operation among components at the early design stages make it possible to design the system at subsequent stages with a specified level of failure-free operation.

To account for complex functional relationships, the reliability block diagram may be constructed on the basis of the actual physical structure of the machine.

The proposed mathematical models of reliability block diagrams are simple, suitable for calculations at the early design stages, equally effective for series, redundant, and combined structures, and convenient for algorithm development and programming.

The models eliminate the need to use the exponential distribution. The analysis of the probability of failure-free operation is based solely on fundamental reliability properties common to all technical objects and retains a unified algorithm at every hierarchical level, including the component level.

The restoration cost of a component following failure was selected as the criterion for ranking component probabilities of failure-free operation.

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