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Reliability of parts and unrestorable components in the machine design[*]

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Надежность деталей и неремонтируемых узлов при проектировании машин[***]

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Введение. В статье рассматриваются вопросы нормирования показателей надежности на ранних стадиях проектирования машин. Такой подход обеспечивает соблюдение заданного уровня надежности при разработке деталей, критичных с точки зрения стабильной эксплуатации. Цель работы — исследовать проблемы проектирования в указанной сфере. Анализ методов нормирования надежности позволяет утверждать, что их недостаточно для проектирования. Кроме того, отмечены противоречия, связанные с использованием в проектировании экспоненциального закона надежности.

Материалы и методы. На стадии технического задания определены численные значения наработки и безотказности машины. Затем значения вероятностей безотказной работы или отказов системы и ее элементов представлены степенными выражениями. В них степени являются параметрами ранжирования показателей безотказности элементов системы.

*Результаты исследования***.** Синтезирован альтернативный подход к нормированию, который позволяет выполнить полный структурный анализ проекта. Таким образом, могут быть оценены показатели надежности всей системы или деталей, безотказность которых определяет надежность машин. Детали и другие элементы, отказы которых не внезапны, рассматриваются без применения экспоненциального закона. При этом сохраняется свойственная ему простота математических операций.

Обсуждение и заключения. Для проектирования с заданным уровнем надежности недостаточно числового значения вероятности безотказной работы (ВБР) машины в целом, принимаемого на стадии технического задания. Необходимы требуемые ВБР и наработки элементов системы, которые являются источниками отказов, развивающихся по разным законам. Полученные результаты могут быть использованы как при проектировании новых механических систем с заданным уровнем надежности, так и при модернизации машин.

Introduction. The issues on standardization of reliability indices in the early stages of machine design are considered. This approach maintains the target level of reliability when developing parts that are critical in view of stable operation. The work objective is to study design problems in this area. The analysis of the reliability regulation methods suggests that they are insufficient to design. Besides, there are some contradictions associated with the use of the exponential failure law in design.

Materials and Methods. At the stage of the task order, the numerical values of the operation time and reliability of the machine are determined. Then the values of the reliability probabilities or failures of the system and its elements are shown by exponential expressions. In them, degrees are the ranking parameters of the system reliability indices.

Research Results. The alternative approach to normalization is synthesized; it enables to complete a full structural analysis. Thus, the reliability indices of the entire system or parts, whose operational safety determines the machine reliability, can be assessed. Parts and other components, whose failures are not sudden, are considered without using the exponential law. This preserves the inherent simplicity of mathematical operations.

Discussion and Conclusions. The numerical value of the reliability probability (RP) of the machine as a whole, taken at the stage of the task order, is insufficient for the reliability target design. The specified RP and running time of the system elements, which are sources of failures developing according to different laws, are required. The results obtained can be used both in designing new mechanical systems with the reliability target, and in the modernization of machines.

Ключевые слова: надежность, вероятность, безотказность, наработка, машина, техническая система, элемент.

Keywords: reliability, probability, failure-free performance, running time, machine, technical system, element.

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Introduction. The conditions for launching mechanical products into manufacture and the unified system for design documentation (ESKD) [1–2] require considering the following engineering systems (ES) reliability parameters under the machine designing:
- durability - calendar time (T_k));
- reliability - probability of failure-free operation $P(t)$ ...);
- lifelength $t = T$ hours (probability of failure-free operation should be guaranteed for this period).

The given factors characterize the machine as a whole and are coordinated at the stage of the technical specifications (TS). The developer should affect the failsafety, which is the key feature of the reliability of nonrecoverable ES and forms the durability of the restorable ES during the workover intervals.

t lifelength is the argument of $P(t)$ reliability function. By any law of reliability, $P(t)$ monotonously decreases with increasing t. In virtue of this, to achieve the required reliability probability (RP), the lifelength must be efficiently minimized and selected according to the ES behavior [3].

Parts and nonrepairable products, being worn out, determine the time between failures (TBF). Ideally, the TBF of the elements should be the same or at least be a multiple of the selected ES lifelength. In this case, T_k calendar time and the required T lifelength are related as follows:

$$T = T_k \cdot 365 \cdot K_{год} \cdot 24 \cdot K_{сут} \cdot ПВ\ ,\ ч, \qquad (1)$$

wher T_k is calendar life in years; $K_{год}$ is the coefficient of ES possible use p.a.; $K_{сут}$ is the coefficient of ES use per day; $ПВ$ is duty factor, which is the average ratio of on-time (acceleration time and steady-state motion time) to the ES workcycle time.

High RP is possible while reducing the required lifelength. If it needs to be significantly increased, failsafety will have to be maintained as follows:
- to perform maintenance more often;
- to budget disadvantage costs for ensuring the quality of products when designing key elements [4, 5].

The project RP can be selected from existing industry standards, from competitive conditions, and on other grounds, including the conventional reliability categories adopted for the engineering products (Table 1).

Table 1

Reliability categories of engineering products

Reliability category	0	1	2	3	4	5
RP acceptable value $P(t)$	≤ 0.9	≥ 0.9	≥ 0.99	≥ 0.999	≥ 0.9999	1

When considering the reliability categories, the following groups of the ES characteristics are taken into account [3, 6, 7].

1. According to the structural type of products. Technological complexes, machines, units, mechanisms and hierarchy (levels) of their assembly units and parts are considered. Under the sequential component interaction in most machines, the RP grows with the transition to the lower levels of the reliability structure diagram. Then the RP of the details under the structural analysis may approach the indices of 3-5 reliability categories.

2. According to the ES types. The projected level of RP directly depends on the level of the manufacturer's responsibility before the ES consumer. Undoubtedly, the highest level of RP is planned, for example, for aircraft, chemical machinery, medical equipment, military equipment, etc.

3. According to types of failure effects. The projected level of RP directly depends on the potential damage level in case of a machine failure (economic, environmental, reputational, etc.).

It is generally accepted [5, 6, 8–13] that the ES failures are presented as sudden. In this case, the RP is described by the exponential law

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

Here, λ failure rate in the period of normal operation after run-in is associated with $\breve{T}$ mean time between system failures

$$\lambda = 1/\breve{T} \qquad (3)$$

with failsafety parameters

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

From here, the ES mean time between failures (MTBF) can be calculated

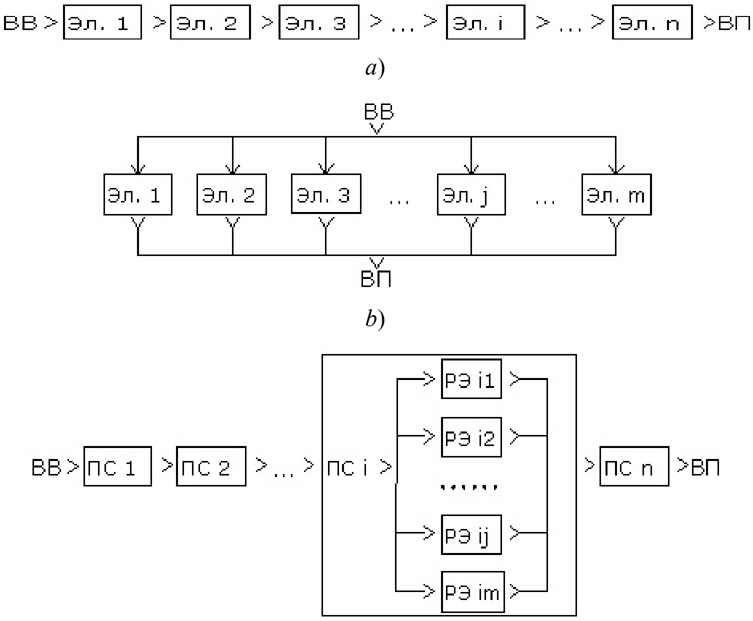
$$\breve{T} = -T/(\ln P(T))\ . \tag{5}$$

This algorithm for forming the ES reliability parameters has both protagonists and opponents [7, 10, 14]. Do all failures occur suddenly? How correct are the ES reliability parameters (3) - (5) arising from the exponential law?

How correct are the ES reliability parameters (3) - (5) arising from the exponential law? These questions arise when determining the failure rate (4) and the corresponding ES RP (3) regardless of the estimation technique:

- according to specified T lifelength and $P(T)$ RP;
- on $\breve{T}$ MTBF;
- according to $\breve{T}$ test results.

In the literature, structural analysis of the ES reliability of the ES, which transform the input effect (IE) into output parameters (OP), is usually referred to as a bottom-up network analysis from the RP components to the RP systems. Herewith, the following schematic structures are considered: sequential (Fig. 1, a), parallel (Fig. 1, b), and combined (Fig. 1, c).



a)

b)

c)

Fig. 1. Schematic structures of ES reliability under various types of component interaction (ВВ=IE; ВП=OP)

Under the sequential interaction of the ES components (see Fig. 1, a) whose failures are independent, the exponential law (2) represents a convenient mathematical model. If $P(t)$ system RP and components - $P_i(t)$ subsystems are in the ratio

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

then the failure rates of λ system and λ_i subsystems are in the ratio

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

and they are ranked depending on the accepted principle of intensity distribution over the components.

A hierarchical schematic structure developed from the nested levels of subsystems and components [3, 6, 8–12] enables, selectively or throughout the structure, to perform a top-down analysis [3, 9] (from ES RP to RP of components). The required values of the RP of components along with the required lifelength are the initial data for designing parts with the specified reliability level [15, 16].

The top-down analysis algorithm based on (2) enables to distribute the intensities and RP components over all nested levels of the schematic structures with equal success. This is the case for radioelectronic systems [10, 11]. But at the level of the mechanical system components [3], a contradiction arises: it is impossible to apply the exponential law if the development of degradation failure proceeds according to another law. The system failure will occur as a result of the sequential interaction not related to the exponential law. All the while, the development of a schematic structure for the ES reliability has sense if it serves as the basis for designing parts and selecting standardized components with the required RP for the selected lifelength.

When analyzing ES RP with parallel component interaction (see Fig. 1, b), the following conditions are considered:

- components are constantly on,
- their failures are independent,
- each of *m* components has $P_j(t)$ RP,
- each of the *m* components is able to accept an input effect and convert it into an output parameter of the ES (see Fig. 1, b).

In this case, the ES failure will occur after the failure of the last functional component. The probability of system failure through the component failure probability:

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

From the property

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

The system survival probability through the component RP:

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

For homogeneous components

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

If the goal is to provide the specified ES RP, and homogeneous redundant components are taken into account, then using the expression of the exponential law (2) gives a simple failure rate calculation of components or *m* number of components only in the ratio (11). For more complex relations (10) and combined structures (see Fig. 1, c), examples using the exponential law are not given.

Simple division into components is impossible in respect to complex structures with multidirectional component interaction with dependent failures. Performance and reliability parameters should be determined for the system as a whole, and in this case, it may be necessary to carry out a large amount of analytics and experimental works. A graphic representation of such diagrams [7, 9] is accompanied by a reference to the complexity of the functioning model and the cumbersome reliability calculations (for example, a complex closed interdependent operation of IC engine units or of jet engine).

Main Part. For the design ES implementation under any kind of interaction, it is necessary to produce parts that make up the assembly units, and then – functional modules (mechanisms, units, power boxes, control modules, etc.). The modern modular principle of building machines provides for modular operations: development, assembly and debugging, modification and modernization, repair, replacement, etc. Parts and other components are at the lower level of the hierarchical design system consisting of nested blocks. Using it as a reliability structure diagram, it is necessary to find the criterion for RP distribution over components. We should consider not $P(t)$ function, but its numerical value $P(T)$. In this case, it is possible to substitute the specified T lifelength, and to use it under the distribution of the RP numerical values over components as the replacement cost criterion for base units in the event of their failures. The replacement cost may include:

- costs of materials used for the repair, products, diagnostics and repair work;
- failure effects estimated in money equivalent (renewal of other damaged components in case of dependent failures, ES idle time losses, insurance compensation for repayment, etc.).

This study objective is to develop a top-down analysis method for reliability structure diagrams, which eliminates the above-mentioned contradictions. The ES reliability structure diagram should be a tool for the distribution of component RP for the specified ES RP in the initial stages of the project. Then the selected lifelength and the balanced component RP will be the initial data for the design with the given reliability level. For this, the structure diagram should meet a number of requirements.

1. The structure diagram should be based on the construct structure. This will simplify complex functional component relationships.
2. The structure diagram should contain a mathematical reliability model available for calculations in the early stages of the project.
3. The reliability model of according to the structure diagram should be based not on the exponential law, but only on the fundamental reliability properties of the technical objects and systems (6), (8) - (11).

4. The criterion for ranking the component RP should be the cost of the component renewal in case it fails. It can be considered as a monetary equivalent of compensation of damage from failure.

5. The top-down structural analysis should be applied equally efficiently for both sequentially interacting and redundant reliability diagrams, as well as for the combined ones.

Alternative representation of numerical value of object RP. While t time has $P(t)$ value of the reliability function argument, it is a function decreasing by any of the known laws or obtained statically. After selecting the required $t = T$ lifelength, RP receives $P(t) = P(T)$ value within $0 < P(T) < 1$ limits. Such a value can be represented in a variety of ways from which the exponential expression is selected

$$P(T) = B^X . \tag{12}$$

X determined by the ratio

$$X = lg\ (P(T))\ /\ lg\ B. \tag{13}$$

Taking the base value of $B = 10$ degree, we obtain the expression of the numerical RP value:

$$P(T) = 10^X , \tag{14}$$

from which

$$X = lg\ P(T). \tag{15}$$

X exponent is called the ranking parameter of the ES RP. In the annex to the system components, X_i exponents are also referred to as the ranking parameters of the component RP. Further in this presentation, “the simplest and most important case” [13] of the system reliability is considered.

ES component RP under their sequential interaction. Consider the ES reliability structure diagram with the sequential component interaction (see Fig. 1, a) whose failures are independent. In this case, the system failure under the failure of any of n components at $t = T$ time is expressed through the component RP according to (6):

$$P(T) = \prod_{i=1}^{n} P_i(T) .$$

In (6), product can be obtained by a variety of $P_i(T)$ combinations and types of their presentation. Applying (14) for the numerical values of $P(T)$ system RP and its components, $P(T) = P_1\ (T) \times P_2(T) \times ... \times P_n(T)$ product can be represented as follows:

$$10^X = 10^{X1} \times 10^{X2} \times ... \times 10^{Xn} ,$$

whence the connection between the system ranking parameter and the components:

$$X = X_1 + X_2 + ... + X_n . \tag{16}$$

From the set of X_i possible combinations in (16), those ones following from C_i renewal costs of failed components are selected. At this, components with a higher renewal cost should have larger $P_i(t)$ RPs. That is, at the cost of C_1, C_2, …, C_n components restoring, the set of $1/C_1$, $1/C_2$, ..., $1/C_n$ inverse values should be associated with the set of X_1, X_2, ..., X_n components’ ranking parameters.

The indicated ratio can be written as sums

$$1 = \frac{\frac{1}{C_1}}{\Sigma\frac{1}{C_i}} + \frac{\frac{1}{C_2}}{\Sigma\frac{1}{C_i}} + ... + \frac{\frac{1}{C_n}}{\Sigma\frac{1}{C_i}} ,$$

in which the accepted conditions for X_i ranking parameter are obtained from the termwise equality of the summands:

$$\frac{X_{\text{i}}}{X} = \frac{\frac{1}{C_i}}{\sum\frac{1}{C_i}} .$$

The right-hand side of this equality is called the “weight coefficient of the renewal cost of sequentially interacting components”:

$$a_i = \frac{\frac{1}{C_i}}{\sum\frac{1}{C_i}} . \tag{17}$$

X_i ranking parameter values that meet the ranking condition:

$$X_i = Xa_i . \tag{18}$$

The unit of measuring the renewal cost does not matter, since the cost relations are used in (17). The top-down analysis of the ES component RP with sequential interaction is considered in Example 1. The system presented below contains three components for simplicity. However, any number of components is possible for the algorithm based on (14–18).

Example 1. Calculation of the ES component RP with sequential interaction (see Fig. 1, a). Initial data:

- system RP: $P(T) = 0.9$;
- number of components: $n = 3$;
- renewal costs of components (in c.u.): $C_1 = 5000$, $C_2 = 3000$, $C_3 = 2000$.

Ranking parameter for ES RP (15): $X = lg\,P(T) = lg\,0.9 = -0.04576$.

The results of the step-by-step calculation of the component RP are presented in Table 2.

Table 2

Calculation of ES component RP with sequential interaction

Object	C_i, c.u.	$1/C_i$	a_i (17)	X_i (18)	$P_i(T)$ (14)
ES				–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
Checksums and products		$\sum(1/C_i)$	$\sum a_i$	$\sum X_i$	$P(T) = \prod P_i(T)$
		0.001033	1	–0.04576	0.9

ES component RP under their parallel interaction. Consider the following case: system crash under the failure of all elements with $F(T)$ probability at $t = T$ moment of time corresponding to the selected lifelength. Then, the basic property of parallel component interaction (see Fig. 1, b), according to (8), is expressed through $F_j(T)$ component failure rate:

$$F(T) = \prod_{j=1}^{m} F_j(T).$$

Taking by the analogy with (14)

$$F(T) = 10^{Y}, \tag{19}$$

where Y is determined from logarithmic equation $lg\,(F(T)) = Y\,lg10$:

$$Y = lg\,F(T). \tag{20}$$

Y exponent is called the ranking parameter of the ES failure rate. When engaged the system components, Y_j exponents are called the ranking parameters of the component failure rate. The conditions (8, 19) can be represented by $10^{X} = 10^{Y1} \times 10^{Y2} \times \ldots \times 10^{Yn}$ product, whence

$$Y = Y_1 + Y_2 + \ldots + Y_n. \tag{21}$$

From Y_j set of possible combinations in (21), those ones following from C_j renewal costs of failed components are selected. At this, components with a higher renewal cost should have lower failure rate (which also means large RP). That is, at the cost of C_1, C_2, ..., C_m components restoring, the set of $C_1, C_2, \ldots, C_m$ costs should be associated with the set of $Y_1, Y_2, \ldots, Y_m$ exponents.

The indicated ratio can be written as sums

$$1 = \frac{Y_1}{Y} + \frac{Y_2}{Y} + \ldots + \frac{Y_m}{Y} \text{ и } 1 = \frac{C_1}{\sum C_j} + \frac{C_2}{\sum C_j} + \ldots + \frac{C_m}{\sum C_j}.$$

Here, the selected conditions for the exponents at Y_j are obtained from the termwise equality of the summands: $\frac{Y_j}{Y} = \frac{C_j}{\sum C_j}$.

The right-hand side of the equality is called the “weight coefficient of the renewal cost under parallel component interaction”:

$$b_j = \frac{C_j}{\sum C_j}. \tag{22}$$

Y_j ranking parameter values fitting the above relation:

$$Y_j = Yb_j. \tag{23}$$

The top-down analysis of the failure rate and ES component RP with the parallel component interaction is considered in Example 2. The system contains three components.

Example 2. Calculation of the failure rate and ES component RP with parallel interaction (see Fig. 1, b). Initial data:

- system RP: $P(T) = 0.9$;
- component number: $m = 3$;
- component renewal costs (in c.u.): $C_1 = 5000$, $C_2 = 3000$ и $C_3 = 2000$.

We calculate the system reliability indices. System failure probability from (9):

$$F(T) = 1 - P(T) = 1 - 0.9 = 0.1.$$

Ranking parameter values for the system failure probability from (20):

$$Y = lg\, F(T) = lg\, 0.1 = -1.$$

The results of the step-by-step calculation are presented in Table 3.

Table 3

Calculation of ES component RP with parallel interaction

Object	C_j, c.u.	b_j (22)	Y_j (23)	$F_j = 10^{Y_j}$	$P_j(T) = 1 - F_j(T)$
ES			–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
Checksums and products	$\sum C_j$	$\sum b_j$	$\sum Y_j$	$F(T) = \prod F_j(T)$	$P(T) = 1 - \prod (1 - P_j(T))$
	10000	1	–1	0.1	0.9

Example 3. Probability calculation of the nonfailure operation of the combined ES components (see Fig. 1, c). Initial data:

- number of sequentially interacting subsystems: $n = 3$;
- number of parallel interacting elements of SS 3: $m = 4$;
- system RP: $P(T) = 0.95$;
- renewal costs of subsystems (in c.u.): $C_1 = 5000$, $C_2 = 8000$, $C_3 = 12000$;
- renewal costs of parallel component interaction (in c.u.): $C_{3,1} = 3000$, $C_{3,2} = 4000$, $C_{3,3} = 5000$, $C_{3,4} = 6000$

We calculate the system reliability indices. Ranking parameter for ES RP from (15):

$$X = lg\, P(T) = lg\, 0.95 = -0.022276.$$

The results of the step-by-step calculation are presented in Table 4.

Table 4

Calculation of ES component RP with sequential interaction

Object	C_i, c.u.	$1/C_i$	a_i (17)	X_i (18)	$P_i(T)$ (14)	
ES				–0.022276	0.95	
Subsystem (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	◀*
Checksums and products		$\sum(1/C_i)$	$\sum a_i$	$\sum X_i$	$P(T) = \prod P_i(T)$	
		0.000408	1	–0.022276	0.95	
*◀ — subsystem selection mark for further top-down analysis.						

From Table 4, RP of the SS 3 subsystem: $P_3(T) = 0.989587$. Failure rate of SS 3 (8): $F_3(T) = 1 - P_3(T) = 1 - 0.989587 = 0.010413$. The ranking parameter for the failure rate of SS 3 (22): $Y = \lg F_3(T) = lg 0.010413 = -1.982407$.

The results of the step-by-step calculation are presented in Table 5.

Table 5

Calculation of SS 3 component RP with parallel interaction

Object	C_j, c.u.	b_j (22)	Y_j (23)	$F_j = 10^{Y_j}$	$P_j(T) = 1 - F_j(T)$
SS 3			–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
Checksums and products	$\sum C_j$	$\sum b_j$	$\sum Y_j$	$F(T) = \prod F_j(T)$	$P(T) = 1 - \prod (1 - P_j(T))$
	18000	1	–1.982407	0.010413	0.989587

The required lifelength of the ES and all its elements (1) should be considered, so that the component RP calculated in Tables 2–5 will be the initial data for the calculation and selection of components with the specified reliability level.

It is necessary to determine the obtained resources by the corresponding reliability models with the calculated RPs (Tables 2, 3, 5). To do this, the dimensions and design parameters of the components (parts, standard and other nonrestorable items) obtained at the stage of preliminary design are considered. Then, measures can be taken to approximate the obtained and specified resources [15, 16].

Conclusion. The technique of top-down analysis of the machine reliability structure diagram is developed and tested on numerical examples. Its algorithm coincides with the sequence of design stages: from the machine RP – to the RP of its parts. The selection of the required lifelength and RP distribution over the parts at the initial stages of the project provide the design with the specified reliability level. The structure diagram can be based on the construct structure. This ensures a universal approach to the formation of structure reliability diagrams under various types of component interaction. The criterion for ranking the RP components is the component renewal in case of its failure. At any level of the structure diagram, it includes the monetary equivalent of the costs of materials, products, repairs, damage from failure. They are known with sufficient accuracy at the initial stage of machine development.

The need to use the exponential law under the normalization of reliability and the development of its structure diagrams is eliminated. The RP analysis relies only on the reliability fundamental properties that are common to all technical objects and systems. The analysis algorithm is maintained at all levels of the structure diagrams including part levels.

Mathematical models of the structure diagrams are simple, available for calculations in the early project stages, and equally efficient for sequentially interacting, redundant and combined reliability diagrams. They provide convenient possibilities for algorithmization, programming, and data correction.

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