THE CONTRIBUTIONS OF SELECTION FOR THE STRUCTURAL MODEL FOR THE RELIABILITY OF TECHNOLOGICAL MINING EQUIPMENT

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Abstract: The reliability of various mechanization means is determined by the level of reliability of the elements included in them and the interaction of these elements on which the resulting value for the failure flow parameter depends. The failure flow is understood as the sequence of failures of the object, occurring one after another at specific points in time. The reliability level of mechanized complexes considered as a system, as well as other means of mechanizing mining works, depends on the level of reliability of the component elements of the system, as well as on the connections between them, from the point of view of their influence on the functioning of the system. Mechanized complexes are multifunctional technical systems. The structural elements of the complexes used in mining operations, in addition to their primary function of mechanizing coal extraction (separating coal from the massif, loading, and transporting it beyond the working front), also serve the purpose of supporting mining operations, directing roof pressure, and ensuring work safety conditions at the working front.

Keywords: system reliability, mechanized complex, mean time between failures, structural reservation

1. COMPOSITION OF THE FLOW OF FAILURES IN OPERATION

For the quantitative characterization of the flow of failures in operation of repaired objects of various means of mechanization in mining works, the parameter of the flow of failures in operation is used, the size of which is determined on the basis of statistical data. The flow parameter of failures in operation characterizes the average number of object failures per unit of time, considered for the examined time point:

$$\lambda(t) = \frac{n(t+\Delta t)-n(t)}{\Delta t}, \tag{1}$$

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where: λ(t) - the parameter of the flow of failures, in hours^{-1}; n(t) and n(t+Δt) - the number of failures in the operation of the object at time t, respectively t+Δt.

For various means of mechanization of mining works (cutting combines, conveyors, mechanized support sections taken as a system) the successive interaction of the elements is characteristic (Fig. 1 a), in which the failure in the operation of any element is a necessary and sufficient condition for the failure in the operation of the entire system.

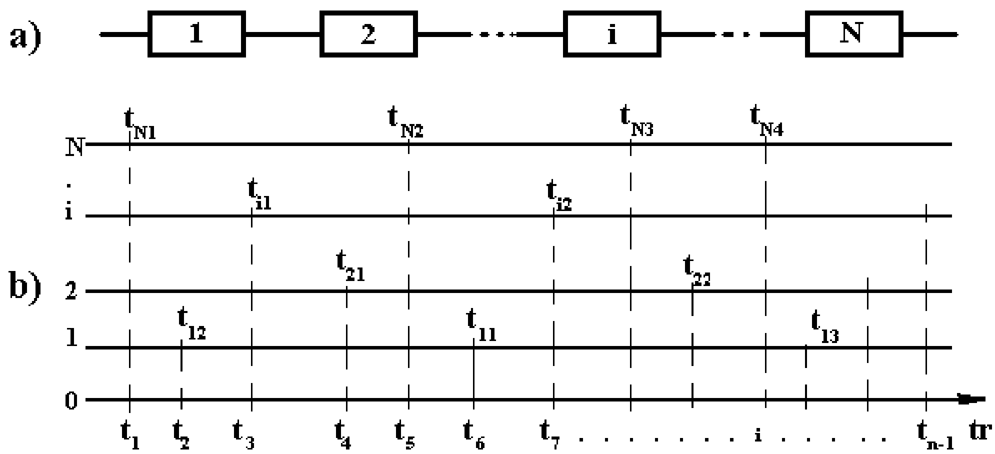

Fig. 1. Principle diagram (a) and diagram of the failure flow formation (b) at the successive interaction of elements

If the failure of each element is an independent random event and the probabilities of safe operation $k_i(t)$ during the given time t are known, then the probability of safe operation of the system, respectively the system reliability $R_s(t)$, is determined as the product of the reliability of the component elements:

$$R_s(t) = \prod_{i=1}^{n} R_i(t). \quad (2)$$

From relation (2) it denotes that with the increase in the number of elements that interact successively, the reliability of the system decreases.

With successive interaction, all elements work simultaneously and as can be seen from the diagram of the failure flow formation (Fig. 1 b), the resulting failure flow of the system, on the t axis, represents the maximum position of the failure flows of all elements. In this case, the operating time until failure T_0 (MTTF) of the system corresponding to time t' will be:

$$T_0 = \frac{t'}{n_1+n_2+\cdots+n_i+\cdots+n_n}, \quad (3)$$

where: n_1, n_2, ... n_i, ... n_n - represents the number of failures of the system's component elements.

Knowing that:

$$T_{01} = \frac{t'}{n_1};\ T_{02} = \frac{t'}{n_2}; \dots; T_{0i} = \frac{t'}{n_i}; \dots;\ T_{0n} = \frac{t'}{n_n}, \tag{4}$$

we will have:

$$n_1 = \frac{t'}{T_{01}};\ n_2 = \frac{t'}{T_{02}}; \dots; n_i = \frac{t'}{T_{0i}}; \dots; n_n = \frac{t'}{T_{0n}}, \tag{5}$$

substituting in formula (3) we obtain:

$$T_0 = \sum_{i=1}^{n} T_{0i}. \tag{6}$$

Relations (2) and (6) allow to calculate the indicators of safe operation of the system depending on the indicators of safe operation of the component elements that act sequentially.

For complex machines and equipment, respectively mechanized complexes, which consist of a large number of elements, which individually have small values of the parameters of the flow of failures in operation, the flow of failures in operation will be close to the flow of elements after their running-in period.

The most important properties of the flow of failures in operation are: stability, the moment of failures and the absence of after action.

The stability of the flow means that the probability of the occurrence of any number "k" of failures in operation of the object in the time interval Δt does not depend on the position of this interval on the axis [0, t].

The moment of the flow of failures means the probability of the simultaneous occurrence of two or more failures in operation. It is negligible compared to the probability of the occurrence of a single failure in operation.

The absence of post action consists in the fact that the probability of occurrence of "k" failures in operation, in the time interval Δt, does not depend on the number of failures in operation that have occurred up to this time interval.

For the simplest flow of failures in operation, the size of the failure flow parameter $\lambda(t) = ct.$ is determined as the inverse of the size of the object's operation time until the failure $\lambda=1/T_0$.

In this case, for n elements that interact successively, taking into account formula (6) it results:

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

where: λ and λ_i - represent the parameters of the system outage flow and of component i, respectively, in hours^{-1}.

The random values of the system operation times between outages are subject to the exponential distribution law, the probability of system operation results from:

$$R(t) = e^{-\lambda \cdot t}. \tag{8}$$

Note: Formula (2) can also be used if the operation probabilities of the component elements that act successively within the system are known.

2. STRUCTURAL FORMULAS OF RELIABILITY

Considering a complex mechanized system, consisting of 3 elements, namely: felling combine (CA), mechanized support (SM) and scraper conveyor (TR). These 3 component elements are linked to work together within the system, these links can be: technological (< t >); kinematic (< f >) and constructive (< c >).

The basic structural formula for the mechanized complex taken as a system will be:

CA<t>TR<t>SM, (9)

To evaluate the influence of the technological link on the reliability level of the system, it can be considered in the form of parallel technological links (< II >), when the component elements operate in parallel (simultaneously), or in the form of successive technological links (< → >), when the system elements operate sequentially.

Taking into account the basic structural formula of the system (9), the following structural combinations can be obtained:

$$(CA \longrightarrow TR) \sqcup SM;$$

$$CA \sqcup TR \sqcup SM. \tag{10}$$

With the parallel technological connection of functional components, the flows of their failures in operation overlap (Fig. 1 b), so the calculation of the reliability indicators of the system with parallel technological connections should be done with the relations (2-8) corresponding to the successive interaction of the elements in the system.

In the case of the successive technological connection of functional machines, the flows of failures in operation continue one after another (Fig. 2).

In this case, the failure flow parameter of the machine system in each specific period of time is equal to the failure flow parameter of a single machine, and for a sufficiently large period of operation t of the system, we will have:

$$\lambda = \sum_{i=1}^{n} \lambda_i \cdot \frac{t_i}{t}; \tag{11}$$

$$t = \sum_{i=1}^{m} t_i$$

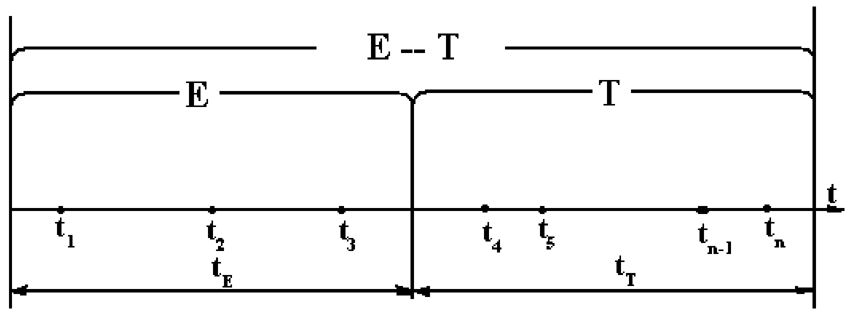

Fig. 2. Formation of the failure flow in the case of sequential operation of functional machines

where: m - represents the number of machines that work sequentially in time; ti - the working time of the machines in the period.

The technological connection itself is not a source of failure in operation, although it influences the method of calculating the reliability of the machine system.

The kinematic connection is achieved by connecting functional machines that are technologically correlated and retain their individuality, the connection leading to the formation of the system called a mechanized complex.

The connection of machines requires the correlation of the speeds and directions of mutual movement of functional components in the common work process and can be achieved only on the basis of a parallel technological connection.

The constructive connection is achieved by replacing the basic elements, coordinated on the basis of the parallel technological connection and the kinematic correlation of the components and it leads to the formation of the mining system which, in correlation with the machine construction, we will call the mining aggregate (or, in a broader context, the extraction aggregate).

Unlike the technological connection, the kinematic and constructive connections are material connections, therefore, knowing the successive interaction of the elements in the system (when they work in parallel) on the reliability, they participate together with the functional machines in the evaluation of the size of the parameter of the flow of failures in operation of the means of mechanization of mining works:

$$\lambda = \sum_{i=1}^{n} \lambda_{ni} + \sum_{j=1}^{k} \lambda_{lj}, \tag{12}$$

where: n - represents the number of functional elements of the mechanized complex; k - the number of material connections (kinematic and constructive) between the functional elements; λ_{ni} - the parameter of the flow of failures in operation of the i element; λ_{lj}- the parameter of the flow of failures in operation of the j kinematic or constructive connections.

The number and type of functional elements, as well as the type of connection between them, are determined by structural formulas of the reliability of mechanization means.

The structural formulas of reliability for different cases are as follows:

For mechanized semi-complexes, respectively the system in which there are kinematic and technological connections between the functional elements:

CA||TR<f> SM ; CA<f>TR||SM ; CA||SM<f> TR. (13)

For mechanized complexes with a complete set of functional elements and with elements related to them:

CA<f>TR<f>SM ; CA<f>TR ; CA<f>SM ; TR<f>SM. (14)

For mining semi-aggregates, where between the functional elements there are both kinematic and technological or constructive connections:

CA||TR<c>SM ; CA<c>TR||SM ; CA||SM<c>TR; (15)

CA<f>TR<c> SM ; CA<c> TR<f> SM ; CA<f>SM<c>SM. (16)

For mining aggregates with a complete set of functional elements n with their related elements:

CA<c>TR<c>SM ; CA<c> TR ; CA<c>SM ; TR<c>SM. (17)

For the means of mechanization of mining works, described by the structural reliability formulas (13-17), the expressions for determining the operating time until the occurrence of failures in operation MTBF and the probability of safe operation R(t) of the system have the form:

$$MTBF = \left[\sum_{i=1}^{n} \frac{i}{T_0(n_i)} + \sum_{j=1}^{k} \frac{i}{T_0(l_j)}\right]^{-1}; \tag{18}$$

$$R(t) = \sum_{i=1}^{n} R_{ni}(t) \cdot \sum_{j=1}^{k} R_{lj}(t), \tag{19}$$

where: $T_0(n_i)$ and $R_{ni}(t)$ - represent the average operating time until the occurrence of failures, respectively the probability of safe operation of functional elements i; $T_0(l_j)$ and $R_{lj}(t)$ - the average operating time until the occurrence of failures, respectively the probability of safe operation of the kinematic link or constructive link; n and k - the number of functional elements, respectively of material connections.

Relations (18) and (19) for k = 0, can also be used to calculate the values of reliability indicators of systems with parallel technological connections.

3. ANALYSIS OF STRUCTURAL STATES AND DETERMINATION OF RELIABILITY OF MEANS OF MECHANIZATION OF WORKS

Depending on the work scheme and constructive features, at different moments of time a different number of structural elements of the complex can function. Different structural states are determined by the need to perform not only basic operations, but also auxiliary mechanized operations, not overlapping with the process of extraction of useful substances, to be performed permanently with the help of maintaining the supporting function of the working space, as well as the need to operate the conveyor for the evacuation of coal from niches, transportation of materials and spare parts to the mine.

In the process of operation of mechanized means there can be different structural states. The logical formulas of possible structural states of mechanized complexes or other extraction systems can be obtained from the structural formulas of reliability of the corresponding mechanization means, as a result of the assessment of the additional structural state with a reduced number of functional elements working simultaneously.

Thus, for the system having the structural formula of reliability CA || TR || SM the logical formula of possible structural states can be: CA and TR and SM or TR and SM or SM.

The logical link "and" in these expressions for the possible structural states of mechanization components replaces the conventional notation for parallel technological links (||) in the structural reliability formulas, indicating the simultaneous operation of different system components. The link "or" signifies the sequential occurrence of different structural states over time.

The probability of the safe operation of the felling system, considering various possible structural states, can be determined as the sum of the products of the probabilities of each structural state and the probability of safe operation of the system in the corresponding state:

$$R(t) = \sum_{i=1}^{S} K_{ti} \cdot \prod_{i=1}^{n_i} R_{ni}(t) \cdot \prod_{i=1}^{k} R_{li}(t_i), \quad (20)$$

where: S - represents the number of possible structural states; K_{ti} - the stationary probability of the system being in structural state i, representing the fraction of time of existence in this structural state; n_i - the number of functional elements working simultaneously in state i; $R_{ni}(t_i)$ - the probability of safe operation of the functional element in state i; K - the number of material connections between the functional elements in structural state i; $R_{li}(t_i)$ - the probability of safe operation of the kinematic or constructive connection in the structural state i.

4. STRUCTURAL RESERVATION

From formulas (2-5) it follows that with the increase in the number of elements that interact successively, as a result of the increase in the complexity of technical systems in mining, the reliability of the systems decreases.

One of the main means of ensuring the working capacity, respectively of maintaining reliability in the event of failures in the functioning of one or more elements, is reservation.

In the construction of machines, equipment, and mining installations, load reservation is used to ensure the ability of the elements to bear the forces acting on them. This includes ensuring a power reserve for engines, a reserve for the forces developed by advancing mechanisms, a reserve for the resistance of elements, and the use of couplings with limiting torque, safety valves, etc. The use of intermediate silos in transport systems allows, for a certain period, for stationing during failures of certain elements, thereby achieving temporary reservation.

The system consists of n elements with the same functional destination that work in parallel (fig. 3 a) is also called a system with active redundancy.

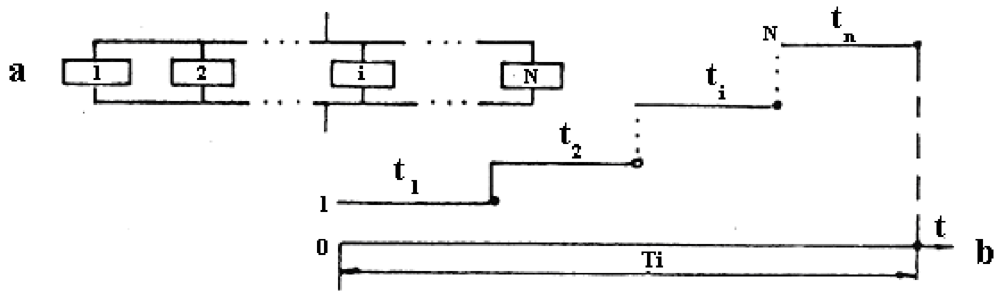

Fig. 3. Schematic diagram (a) and formation diagram (b) of the failure flow in systems with active redundancy (active reserve)

In an active redundant system, the function is performed by n elements that are simultaneously in operation; m elements are, however, sufficient to perform the function ($m<n$). In the case of systems with reserve elements that are not in operation, the function being performed by a single element, the system is called a system with passive redundancy (reserve). At the time of failure, the load is taken over by the reserve unit.

In the case of parallel connection of elements, the probability of system failure $F_s(t)$ is equal to the product of the probabilities of failure of the component elements $F_i(t)$.

$$F_s(t) = \prod_{i=1}^{n} F_i(t), \tag{21}$$

where: n - represents the number of elements connected in parallel.

The reliability of the system will be:

$$R_s(t) = 1 - F_s(t) = 1 - \prod_{i=1}^{n} F_i(t) = 1 - \prod_{i=1}^{n}(1 - R_i(t)). \quad (22)$$

For systems composed of elements with the same reliability working in parallel, relation (22) becomes:

$$R_s(t) = 1 - [1 - R_i(t)]^n, \quad (23)$$

where: $R_i(t)$ - represents the reliability of element i.

The failure rate of the system with active redundancy is determined by the relationship:

$$\lambda_s(t) = \frac{f(t)}{R_s(t)} = -\frac{dR_s(t)}{R_s(t)dt} \quad (24)$$

and the average uptime:

$$MTBF_s = \int_0^{\infty} R_s(t)dt; \quad (25)$$

$$MTBF_s = \frac{1}{\lambda_1} + \frac{1}{2\cdot\lambda_2} + \cdots + \frac{1}{n\cdot\lambda_n} \quad (26)$$

and when $\lambda_i=\lambda$, the expression becomes:

$$MTBF_s = \frac{1}{\lambda} \cdot \sum_{i=1}^{n} \frac{1}{i}. \quad (27)$$

In the case of schemes with passive redundancy (fig. 4), the function is performed by one or more elements.

If one of these elements fails, the load is taken over by the reserve unit. As long as they are in reserve, the elements do not work, therefore it can be assumed that during this period they won't fail. Theoretically, we can consider that passive redundancy provides higher reliability than positive redundancy. In practice, however, we must look with caution, because:

- the probability of coupling failure can be important;

- the active elements working in parallel have a lower load, which leads to a lower failure rate per element;

- the reserve element has a probability of not starting when it is necessary to put it into operation.

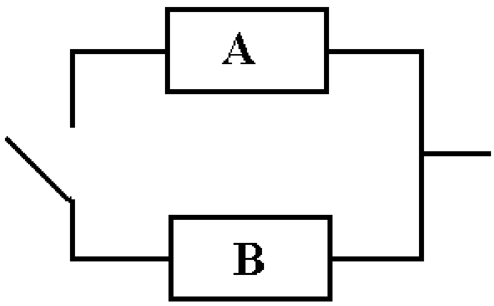

Fig. 4. Schematic diagram of passive reservation systems

Systems with passive redundancy can present the following types of failures:

- absence of switching (switching is not performed);

- absence of contact (on a faulty unit);

- failure of all elements (active and passive).

We consider the system in figure 4 with element A active and element B spare, and the switch is perfectly reliable. In this case, the system reliability is:

$$R_s = 1 - (1 - R_A) \cdot (1 - R_B) = R_A + R_B \cdot (1 - R_A).$$

If there is a second reserve element C, we have:

$$R_s = R_A + R_B \cdot (1 - R_A) + R_C \cdot R_A + R_B \cdot (1 - R_A) \cdot R_A + R_B \cdot (1 - R_B).$$

In general:

$$R_s = R_i + \sum_{i=2}^{n}\left[R_i \cdot \prod_{j=1}^{i-1}(1 - R_j)\right]. \tag{28}$$

If the switch is not perfectly reliable, then the following quantities must be introduced into the formulas:

p_a - the probability that, when actuated, the switch will perform the switching (switches on demand);

p_b - the probability that, in the absence of an actuation, the switch will not perform the switching (not switch on its own initiative);

p_c - the probability of the switch in terms of transmitting the energy flow.

The system in figure 4 operates in the following cases: A and B are operating; B is faulty or A is faulty; B is not operating. The situations are mutually exclusive, so that the probabilities can be added:

$$R_s = R_A \cdot R_B \cdot p_a + R_A \cdot p_b \cdot p_c \cdot (1 - R_B) + R_B \cdot p_b \cdot p_c \cdot (1 - R_A). \tag{29}$$

If p_a=p_b=p_c=1, the switch is perfectly reliable and the result is R_s=R_A+R_B·(1-R_A).

The ratio of the number of reserve elements to the number of basic elements, which can also be reserved, is called the reservation factor.

If for the total number of elements n of the system, the number of basic elements is m, then the reservation factor is given by the relation:

$$K_r = \frac{n-m}{m}, \tag{30}$$

where: r - represents the number of reserve elements.

Reservation with a reservation factor equal to unity is called doubling. At a reservation factor K_R<1, a reservation with fractional multiplicity takes place. In this case, the reservation ensures a smaller number of eliminated failures than at kr>1, but it is more economical.

In the case of mining units, for example: ventilation installations, water discharge installations and some elements of the hydraulic drives of mechanized supports, elements of energy supply systems are doubled.

In scraper conveyors, the drive system can have a reservation factor $k_r<1$. The same reservation factor can also be used for the working elements of mining cutting machines.

As reservation methods (Fig. 5) we can encounter total reservation, separate for each element and in a group, the most effective in terms of increasing the reliability of the system is separate reservation for elements.

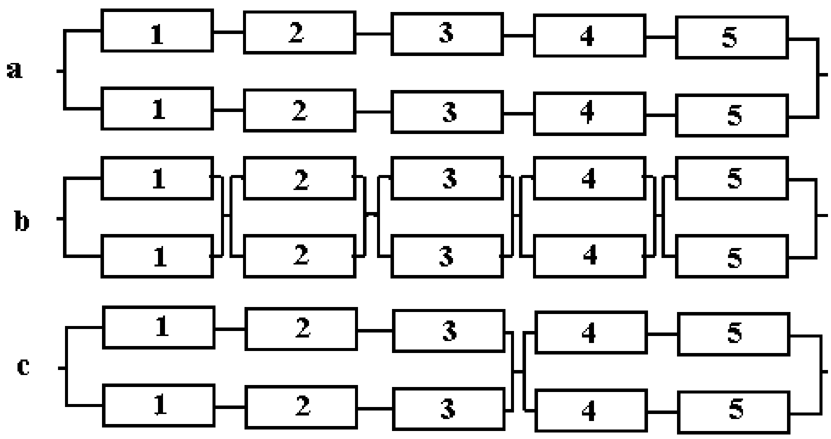

Fig. 5. Reservation schemes a) total; b) separate by elements; c) separate in group

In practical applications we can frequently encounter systems in which the interaction of elements in the system is combined (fig. 6).

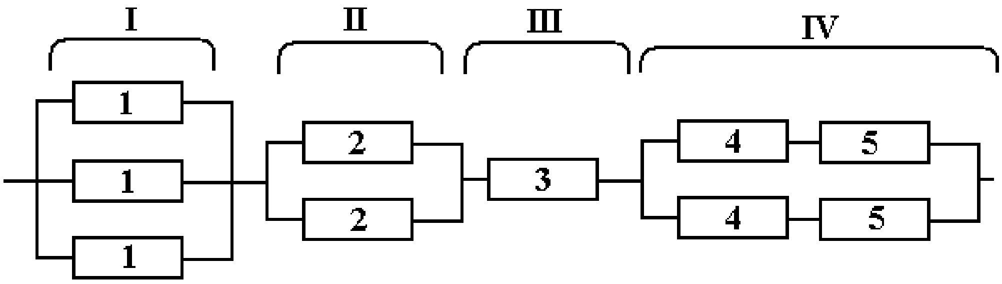

Fig. 6. Combined interaction of elements in the system

For this case, the reliability of the system will be:

$$R(t) = R_I(t) \cdot R_{II}(t) \cdot R_{III}(t) \cdot R_{IV}(t),$$

where: $R_I(t) = 1 - (1 - R_1)^3$; $R_{II}(t) = 1 - (1 - R_2)^2$; $R_{III}(t) = R_3$; $R_{IV}(t) = 1 - (1 - R_4 \cdot R_5)^2$.

5. CONCLUSIONS

For various means of mechanization of mining works (cutting machines, conveyors, mechanized support sections taken as a system) the structural model with successive connection of elements is characteristic, in which case the reliability of the system, the failure rate of the system, is determined by the classical relations (2) and (6).

Within the complex mechanized system, the cutting machine, mechanized support and the conveyor are connected for joint work, the connections can be technological, kinematic and constructive. For various means of mechanization, the structural formulas of reliability are presented (relations 13-17) and the expressions for determining the mean time of good operation (MTBF) and the reliability of the system (relations 18 and 19).

The probability of safe operation of the cutting system, with the evaluation of various possible structural states, can be determined as the sum of the products of the probabilities of each structural state and the probability of safe operation of the system in the corresponding structural state (relation 20).

Structural redundancy systems can be active or passive, both representing possibilities for increasing system reliability. For both systems, calculation relationships for determining the average uptime and reliability are presented.

Considering that one of the specific features of mining equipment is the limited space, redundant systems can only be used at the level of benchmarks, at most certain subassemblies.

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