mathematics

Article

Development of a Mathematical Model of Operation Reliability of Mine Hoisting Plants

Pavel V. Shishkin [1,*], Boris V. Malozyomov [2], Nikita V. Martyushev [3,*], Svetlana N. Sorokova [4], Egor A. Efremenkov [4], Denis V. Valuev [5] and Mengxu Qi [3]

1 Department of Transport and Technological Processes and Machines, Empress Catherine II Saint-Petersburg Mining University, 199106 Saint-Petersburg, Russia
2 Department of Electrotechnical Complexes, Novosibirsk State Technical University, 630073 Novosibirsk, Russia; borisnovel@mail.ru
3 Department of Advanced Technologies, Tomsk Polytechnic University, 634050 Tomsk, Russia; mensyuy1@tpu.ru
4 Department of Mechanical Engineering, Tomsk Polytechnic University, 634050 Tomsk, Russia; s_sorokova@tpu.ru (S.N.S.); egorefr@tpu.ru (E.A.E.)
5 Yurga Technological Institute (Branch), Tomsk Polytechnic University, 652055 Yurga, Russia; valuev@tpu.ru
* Correspondence: shishkinp@mail.ru (P.V.S.); martjushev@tpu.ru (N.V.M.)

Abstract: The work analyzes the performance assurance of mine hoisting machines, including the problem of the quality of performance of the functions. The quality of functioning allows evaluation of a set of properties of the process of lifting loads, designed to meet the given requirements in accordance with the purpose and evaluated performance indicators. In this case, the quality of the function depends not only on the elements that worked properly or failed during system functioning but also on the moments involving certain changes in the states of the system. The considered system of power supply of mine hoisting installations is rather complex with respect to reliability. The proposed approach allows this rather complex system to lead in terms of the form of a serial connection of elements, allowing for determining the influence of the functioning of its subsystems and electrical equipment on the technological process of cargo lifting in a coal mine. The presented mathematical concept of increasing the reliability and failure-free operation of mine hoisting plants with the help of the developed mathematical model of the mine hoisting plant allowed studying the reliability indicators of the hoisting plant operation and reserving the equipment most effectively to increase reliability. The determination of coupling coefficients in this study made it possible to analyze the impact of the reliability of electrical equipment and power supply systems on the operation of technological machines to improve the reliability of mining equipment and the efficiency of technical systems of mining equipment.

Keywords: mathematical modelling; forecasting; technical reliability; verifiability; mining equipment; operating efficiency

MSC: 62N05

Citation: Shishkin, P.V.; Malozyomov, B.V.; Martyushev, N.V.; Sorokova, S.N.; Efremenkov, E.A.; Valuev, D.V.; Qi, M. Development of a Mathematical Model of Operation Reliability of Mine Hoisting Plants. *Mathematics* **2024**, *12*, 1843. https://doi.org/10.3390/math12121843

Academic Editors: Sinan Xiao and Pan Wang

Received: 30 April 2024
Revised: 10 June 2024
Accepted: 12 June 2024
Published: 13 June 2024

1. Introduction

When analyzing the performance assurance of mine hoisting machines, a question arises about the quality of performance of the functions. The quality of functioning evaluates a set of properties of the process of lifting loads designed to meet the given requirements in accordance with the purpose and evaluated performance indicators [1,2]. The quality of function fulfillment depends not only on the elements, which in the process of the system functioning worked properly or failed, but also on the moments in time when some or other changes in the system states occurred. The output effect of the lifting system is the load flow. In this regard, the parameters of the load flow such as productivity or capacity of lifting and transport means serve as indicators of efficiency [3,4].

If simple systems have a deterministic analyzed parameter and are characterized by the presence of two states, operable or inoperable, it is very difficult to formulate the concept of failure for complex technical systems [5,6]. Complex CPS systems have structural redundancies that allow them to continue functioning after the failure of their individual elements or a group of elements. In the case of the failure of elements, the system of the lifting unit can function with the deteriorated qualitative indicators. Deterioration of performance indicators of the lifting installation sometimes occurs gradually, without identifying the moment of failure. In this case, the change of the investigated parameter is a function of time. Reliability indicators used for simple systems, as applied to the reliability assessment of complex systems such as hoisting systems, lose their significance [7,8].

The stoppage of mining machines due to poor power quality leads to economic losses. The main contributors to the poor quality of low voltage power are reactive power, which needlessly loads the power supply system; harmonic pollution, which leads to additional load on the network and reduces the efficiency of electrical installations; and load irregularity, especially in office buildings. Unbalanced loads can lead to excessive voltage asymmetry, which affects other loads connected to the same network, as well as to an increase in neutral current and megavoltage.

All these phenomena are potential causes of inefficient operation of mining electrical installations, system inoperability, reduced equipment life, and consequently, high cost of operating electrical installations. The quality of electric energy, which is understood to be the degree of compliance of its parameters with the established values, has a probabilistic character. The concept of "quality of electric power" reflects a set of properties that determine its consumer value as a product [9]. The deviation of indicators characterizing these properties from the specified ones for simple systems is constant and independent of time; for complex systems, it is a stochastic value [10].

The parameter of power consumption is the power consumption rate, which is understood to be a planned indicator of power consumption per unit of production of a set quality [11]. The real power consumption for lifting a unit of payload differs from the standardized one, which, naturally, causes changes in the parameters of cargo flows. The authors in [12–14] investigated the reliability of mining machines and showed that the use of new technologies and materials helped to increase the service life and efficiency of the equipment. They identified the main problem nodes and proposed innovative solutions to improve the reliability and safety of mining machines [15]. The results of the study can be useful for both manufacturers and users of machinery to improve production processes and reduce the risks of accidents [16]. At the same time, the reliability of both mining machinery, equipment, and conventional equipment largely depends on objective and subjective factors [17,18]. For mining equipment, objective factors are the action of the environment, and mechanical and other effects (wear, aging, load). Subjective factors depend on human action, such as the choice of scheme, design, modes of operation, maintenance, and repairs [19,20]. The impact of these factors leads to equipment failure. Studying the reliability of equipment operation is based on the fact that failure is a random event. To eliminate failure, the regularities of its development and the physical causes of its occurrence are considered [21].

Reliability is assessed using probabilistic categories. These probabilistic categories are introduced into calculation algorithms, and thus a unified methodological approach to solving reliability determination problems is obtained [22,23]. Of the many tasks of reliability determination, the most important ones can be singled out as the prediction of service life and residual service life and the probability of failure-free operation of the system and its elements [24,25].

The determining factor that is relied upon in the design and operation of the underground power supply system is the productivity of the mining machines (load flow).

Load flow is the final result of system functioning. The mathematical model of the process of load lifting can be represented as a random flow $Y(t)$, whose change, along with technological, mining-geological, and organizational factors, is determined by the reliability characteristics of electromechanical equipment, voltage quality, and technological parameters of the system, and reflects the change in the quality of power supply of lifting units in time [26].

The purpose of this work is to model the reliability and uptime of mine hoisting equipment, which allows us to measure changes in the performance of mining equipment. To achieve this goal, the following tasks were set: develop a mathematical model of the mine hoisting plant, allowing for studying the reliability performance of the hoisting plant and the most effective equipment redundancy.

2. Materials and Methods

The failures of subsystems and elements of mining machines obey the normal distribution law [27].

The normal distribution of a random variable (Gaussian distribution) is a probability distribution that in the univariate case is given by a probability density function that coincides with the Gaussian function [28]:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}, \quad (1)$$

where the parameter μ is the mean mathematical expectation of the distribution;

σ^2 is the distribution variance;

σ is the standard deviation.

1. The mathematical expectation of equipment failure is determined by the following formula:

$$L_o = \frac{\sum_{i=1}^{k} L_i \cdot m_i}{\sum_{i=1}^{k} m_i}, \quad (2)$$

where L_i is the mileage of degradation in the i-m period, km; m_i is the number of equipment failures in the i-m period; and k is the number of periods.

2. The failure in dispersive scattering is determined as:

$$D = \sigma^2 = \frac{\sum_{i=1}^{k} (L_i - L_o)^2 \cdot m_i}{\sum_{i=1}^{k} m_i} \quad (3)$$

3. The standard deviation or dispersion of failures is determined as follows:

$$\sigma = \sqrt{D} = \sqrt{\frac{\sum_{i=1}^{k} (L_i - L_o)^2 \cdot m_i}{\sum_{i=1}^{k} m_i}} \quad (4)$$

4. The coefficient of the variation is:

$$V = \frac{\sigma}{L_o} \quad (5)$$

Processing statistical information according to Formulas (1)–(4) and calculations of numerical characteristics of mining equipment failure allows for determining an important characteristic of failures when the maximum number of failures is observed [29].

Mathematical expectation of failures L_o reflects a state when the maximum number of failures of the equipment in use is maximized. The coefficient of the variation V and dispersion σ show the possible spread of failures contrary to their expectations.

Depending on the statistical information on the operation of new or old and reconditioned equipment, the distribution laws of the random value of serviceable equipment states can be described by distribution laws other than the normal distribution. This is a limitation of the proposed model.

3. The Mathematical Model of the Serviceability of Lifting Installations

Any production system is created for a certain functional purpose [30]. On this basis, it can be represented by an arbitrary total flow $Y_o(t)$. Its parameters are quantitatively specified at the design stage. In contrast to $Y_o(t)$, the parameters of the flow $Y(t)$ of the lifting system are realized in the process of operation.

The flow parameters $Y(t)$ take many values. By their value, they can be both more or less than similar parameters $Y_o(t)$. The values of parameters $Y(t)$ that are less than the flow parameters $Y_o(t)$ determine the area of matching parameters of the mine hoisting system. In practice, the quantitative representation of the target is provided in the form of the average value of flow parameters $Y_o(t) \to Yo$.

If the durations of the *i-th* mismatches are equal to each other ($\theta_1 = \theta_2 = \theta_3 = \ldots = \theta_i = \ldots = \theta_n$), then the process of ensuring the operability of lifting units is expressed by the dependence:

$$Y(t) = f(P;U;W;D), \tag{6}$$

when

$$\left.\begin{aligned} P_c &= 1 - \sum_{i=1}^{n} \int_{\theta_i - 1}^{\theta_i} \overline{P}(t)dt; \\ U_c &= \int_{\theta_i - 1}^{\theta_i} U_i \cdot U(t)dt; \\ W_c &= \int_{\theta_i - 1}^{\theta_i} W_i \cdot W(t)dt. \end{aligned}\right\}, \tag{7}$$

where P is the probability of operation (availability factor) of the equipment; U and U_i are the voltage deviation for time t and at the i-th time interval, respectively; W and W_i are the power consumption by the considered electrical equipment for time t and at the i-th time interval, kWh; D_c is the dependence between the factors affecting the functioning of the hoist system. It is determined on the basis of the Э-transformation of flows.

The absolute value of the mismatch in general can be represented through the Э-transformation of the flows:

$$Э: [Y(t) - Y_o(t)]. \tag{8}$$

Then the operation of the hoist system can be shown as:

$$Y_c(t) = f(P_c; U_c; W_c; D_c), \tag{9}$$

where

$$\left.\begin{aligned} P_c &= 1-\sum_{i=1}^{n}\int_{\theta_i-1}^{\theta_i}\overline{P}(t)dt; \\ U_c &= \int_{\theta_i-1}^{\theta_i} U_i\cdot U(t)dt; \\ W_c &= \int_{\theta_i-1}^{\theta_i} W_i\cdot W(t)dt. \end{aligned}\right\} \tag{10}$$

In the case of specifying the period of study of the process under consideration, dependences (8) and (9) turn into equations describing the functioning of simple systems. The change in the parameters of the lifting system leads to a change in the intensity of cargo lifting per machine time (load flow parameters). On this basis, it is possible to use the relative change in the productivity of the lifting unit as an estimator [31]. Such change will be defined as:

$$Э:\left[\frac{Y_{\text{o}}}{Y_{\text{o}}}=\frac{Y}{Y_{\text{o}}}=\frac{Y}{Y+\Delta Y}\right], \tag{11}$$

where Y_{o} is the specified productivity of the lifting unit, t/h; $Y = Y_0 - \Delta Y$ is the actual productivity of the lifting unit, t/h; ΔY is the change of productivity, t/h.

According to expressions (6)–(10), the analysis and synthesis of the process of ensuring the operability of lifting units should be based on the real model of the mine system functioning. At the same time, the model, which does not take into account the peculiarities of the hoisting plant, does not meet the requirements for assessing the performance of complex systems.

The complex approach to the evaluation of the process of ensuring the serviceability of lifting units, based on the theory of random impulse flows, corresponds to the system approach to the design and operation of technical systems of a mining enterprise and allows evaluating the reliability of each technological link of a lifting unit step by step [32].

4. Influence of the Reliability of Individual Elements on the Operation of the Plant as a Whole

To evaluate the measures aimed at improving the efficiency of lifting units, it is necessary to know the impact of equipment reliability on mine productivity and load flow parameters. To solve the task, we will represent the work of a unit of equipment (element) by a random flow of the unit height of impulses $X_{\text{e}}(t)$. The pulse flow $X_{\text{f}}(t)$ serves as a mathematical model of the cargo flow. In this case, we will assume that equipment failures always cause the cessation of cargo flow from the mine [33].

The impact of the reliability of the lifting equipment unit operation on the load flow is determined by subtracting the flow describing the equipment operation $X_{\text{e}}(t)$ from the flow representing the load flow $X_{\text{f}}(t)$. As a result, the newly formed flow $X^{*}(t)$ represents the load flow obtained during the absolutely reliable operation of the considered piece of equipment. The load on the lifting unit in this case increases $x = 1+\dfrac{\overline{\mu}_{\text{e}}\cdot\overline{\theta}_{\text{e}}}{1-\overline{\mu}_{\text{f}}\cdot\overline{\theta}_{\text{f}}}$ times, and the change in the frequency and the average duration of the load will be equal to:

$$\Delta\overline{\mu} = \frac{\overline{\mu}^{*}}{\overline{\mu}_{\text{f}}}, \tag{12}$$

$$\Delta\bar{\tau} = \frac{\bar{\tau}^*}{\bar{\tau}_f}, \quad (13)$$

where $\bar{\mu}^*$, $\bar{\tau}^*$ are the frequency and average duration of cargo flow pulses in absolutely reliable equipment under consideration.

If we take into account the fact that the frequency is the ratio of probability to the average duration of pulses or pauses, respectively, then:

$$\lambda = 1 + \frac{\bar{P}_e}{P_f}, \quad (14)$$

$$\Delta\bar{\mu} = \frac{P_f\bar{\tau}_e - P_e\bar{\tau}_f}{P_f\bar{\tau}_e}, \quad (15)$$

$$\Delta\bar{\tau} = \frac{(P_f + P_e)\bar{\tau}_e}{P_f\bar{\tau}_e - P_e\bar{\tau}_f}. \quad (16)$$

In mining mines, placing redundant equipment, which is known as structural redundancy, next to non-redundant equipment, has become an active part of hoisting systems [34,35]. An important aspect of such redundancy is its influence on various components of hoisting plants, such as a braking system, compressors, oil pumps, electric motors, magnetic starters, and circuit breakers. Equipment redundancy is a system of interaction between operating and spare pumping stations that affects the equipment recovery time [36]. With this structural redundancy, the recovery time is reduced by optimizing organizational processes and reducing the failure recovery time. If the recovery time of the main equipment exceeds the time of switching to the standby equipment, then in this case the structural redundancy of the system becomes justified [37].

The solution to the problem of determining the impact on the lifting unit operation of the equipment reliability with reserve allows for considering the example of the compressor starters, providing the operation of the braking system of the lifting unit. For this system, we assume that the working starter function is the random pulse flow $X_e(t)$, and the joint operation of the starters is described by the pulse flow $Y_o(t)$. Since switching from the working compressor to the standby compressor takes place during maintenance and is always accompanied by stopping the lifting unit, the pulse frequency of the sought flow is equal to the frequency of the original flow [38]. The duration of pulses in the flows $X_e(t)$ and $Y_p(t)$ obey the same distribution law and the mean values of the flows also coincide. To determine the parameters describing the pauses $Y_p(t)$, we distinguish two types of pauses: the first type, q', corresponding to the time of switching to standby and requiring the replacement of starters, and the second type, pauses q'', whose duration is less than the time of switching to standby equipment and not requiring the replacement of starters [39]. The average duration of pauses of the first type q'_e can be determined from statistical data, using the arithmetic mean or density distribution of the replacement time of starters:

$$\bar{\mu}' = \bar{\mu}_e \int_{\theta_e}^{\infty} \beta_e(\theta)d\theta, \quad (17)$$

where $\bar{\mu}'$ is the probability frequency for the pause of flow $X_e(t)$;

$\beta_e(\theta)$ is the probability density function for the flow pause $X_e(t)$.

The frequency of the second type of pause is determined using the expression:

$$\bar{\mu}'' = \bar{\mu}_e \int_0^{\bar{\theta}_e} \beta_e(\theta) d\theta. \tag{18}$$

We will calculate the pause duration $\bar{\theta}''$ using the probability addition theorem [40]. Using this theorem will lead to the following expression for determining the probability of failure of the starter:

$$\bar{P}_e = \bar{\theta}'_e \cdot \bar{\mu}'_e + \bar{\theta}''_e \cdot \bar{\mu}''_e, \tag{19}$$

where $\bar{P}_e$ is the probability of failure for a working starter;

$\bar{\theta}'_e$ is the average value of the pause with a duration that is longer than the time required for a transfer to the standby equipment;

$\bar{\theta}''_e$ is the average value of the pause with a duration that is shorter than the time required to switch to the standby equipment.

To calculate the average value of $\bar{\theta}'_e$, we apply the δ-transformation. In addition, we will exclude from the analysis the durations of the source stream when their value is less than δ. We will also reduce the value of δ pauses whose duration is greater than δ. The expression for calculating $\bar{\theta}'_e$ will take the following form:

$$\bar{\theta}'_e = \frac{\int_{\bar{\theta}_e}^{\infty} (\theta_e - \bar{\theta}_e) \beta_e(\theta) d\theta}{\int_{\bar{\theta}_e}^{\infty} \beta_e(\theta) d\theta} + \bar{\theta}_e. \tag{20}$$

For the flow in question, the average pause duration $X_e(t)$ is equal to the average pause value $\bar{\theta}''_e$. The duration of pauses is calculated for those pauses that are shorter than the time of transition to the reserve.

Considering the above and based on the joint solution (17)–(20) with respect to $\bar{\theta}''_e$, we obtain:

$$\bar{\theta}''_e = \frac{\bar{\theta}_e - \int_{\bar{\theta}_e}^{\infty} \theta_e \beta_e(\theta) d\theta}{\int_0^{\bar{\theta}_e} \beta_e(\theta) d\theta} = \frac{\int_0^{\bar{\theta}_e} \theta_e \beta_e(\theta) d\theta}{\int_0^{\bar{\theta}_e} \beta_e(\theta) d\theta}. \tag{21}$$

The obtained expressions for the characteristics of $\bar{\theta}'_e$ and $\bar{\theta}''_e$ make it possible to express the distribution law using (9)–(13). It is also possible to calculate the average pause for the flow under study:

$$\bar{\theta}_{\text{p}} = \frac{\bar{\mu}'_e}{\bar{\mu}_e} \bar{\theta}_e + \frac{\bar{\mu}''_e}{\bar{\mu}_e} \bar{\theta}''_e, \tag{22}$$

If the pause duration for the original flow obeys an exponential distribution law, then the average duration will be:

$$\bar{\theta}_{\text{p}} = \bar{\theta}_e \left(1 - e^{-\frac{\bar{\theta}_3}{\bar{\theta}_e}} \right), \tag{23}$$

where $\overline{\theta}_e$ is the average pause of the stream $X_e(t)$.

The value $\overline{\theta}_e$ will indicate the operation of the starter.

The duration of flow pauses characterizes the joint operation of the components of the lifting unit. Changing the duration of these pauses, in relation to pauses $X_e(t)$, changes the probability of pulses of the studied flow. The probability of pauses of the investigated flow also changes. Calculation of the probability values of these pauses and pulses is carried out using the average values of pauses and pulses $Y_p(t)$. They are calculated in a manner similar to Equations (17)–(19). In the case of the exponential distribution for the pauses of the initial flow, the following is true:

$$\overline{P}_{\text{p}} = \overline{P}_e \left(1 - \exp\left(-\frac{\overline{\theta}_3}{\overline{\theta}_e}\right)\right), \tag{24}$$

where $\overline{P}_{\text{p}}$ is the pause probability of the desired flows;

$\overline{P}_e$ is the probability of the pause of the original streams.

The proposed approach is applicable in cases of redundancy, when the working equipment of the hoisting plant is automatically replaced by the reserve when it fails. To assess the reliability of a group of hoisting plant equipment with a reserve, it is reasonable to study their joint operation, including from one to three units of equipment [41]. The increase in the reliability of the reserve requires the provision of two or three units of equipment identical in parameters. The units of equipment belonging to the same group are themselves connected in series in terms of reliability [42]. Despite the presence of three units of equipment, failures in the process of operation can lead to stoppages of the lifting complex. However, the use of redundant units of equipment allows them to be activated during the recovery of a faulty unit for a longer period of time than when switching to redundant equipment [43,44].

In the case of only one piece of equipment, its reliability and impact on the hoist and load flow are considered according to similar techniques (8)–(13). For the joint operation of two or three pieces of equipment, the total impulse flows $Y_1(t)$, $Y_2(t)$ and $Y_3(t)$ are used (Figure 1). The characteristics of such flows are calculated on the basis of reliability parameters of individual equipment units, which show the working and non-working periods of the equipment group caused by failures.

In the analysis, the calculation should be performed with respect to the stoppages of the group units. The simultaneous stoppage of equipment of the group units, regardless of their number, always causes failure of the group as a whole.

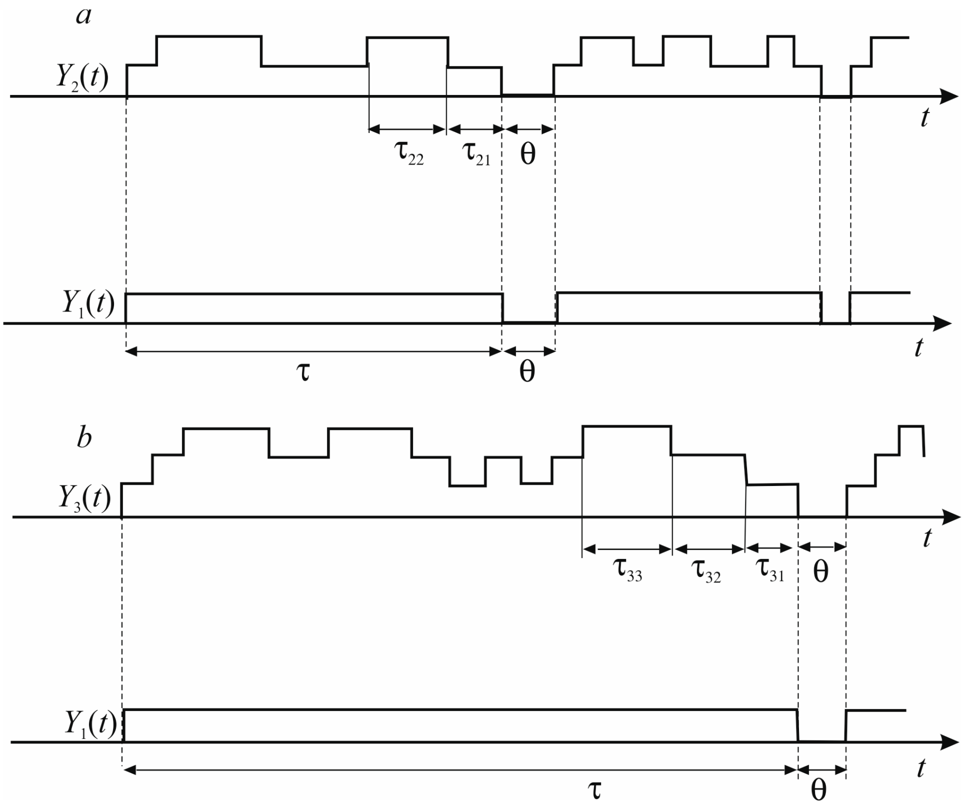

Figure 1. Graphical representation of the joint functioning of two and three units of equipment of the CMP: (**a**)—joint functioning of two units of equipment; (**b**)—joint functioning of three units of equipment.

The average pause of the flow $X_g(t)$ describing the work of the group is equal to the average duration of the non-working states of the group. Its value is expressed by the equation:

$$\overline{\theta}_g = \left(\sum_1^n \frac{1}{\overline{\theta}_i} \right)^{-1}, \tag{25}$$

where n is the number of units of the complex group; $\overline{\theta}_i$ is the average equipment recovery time of the *i-th* unit.

The probability of non-operational states of the group caused by equipment failures is as follows:

$$\overline{P}_g = \prod_1^n \overline{P}_i, \tag{26}$$

where P_i is the probability of failures of the equipment of the *i-th* unit.

The group pause frequency is calculated similarly to (19). The distribution law of the pause duration can be found through the distribution laws of the equipment recovery time [45].

The non-operational states of a group are characterized by a number of average parameters. These parameters allow us to determine the periods of operation of this group. These are the periods to which the impulses τ_g of the flows $X_g(t)$ correspond.

The probability of pulses $X_g(t)$ is the opposite of the probability of pauses. For any random flow, the frequency of pauses is equal to the frequency of pulses. Taking into account all the above, the average duration of hydraulic system operation periods can be determined using the expression:

$$\overline{\tau}_g = \frac{1-\prod_1^n \overline{P}_i}{\left(\prod_1^n \overline{P}_i\right)\sum_1^n \frac{1}{\overline{\theta}_i}}. \tag{27}$$

One of the key aspects in analyzing the characteristics of pulses $X_g(t)$ is to identify the laws of their distribution. To achieve this goal, it is necessary to find out the parameters of pulses and to determine the number of coincidences in each of them. Parameters of coincidences, when a unit of the group works together, can be calculated either by means of calculations or on the basis of time observations. In certain cases, when there are three pieces of equipment in a group if two of them fail, normal operation of the group is not guaranteed. This may result in the cessation of cargo flow into the system [46]. Similar to the group reliability assessment, in this context based on random impulse flows, the group reliability characteristics are also investigated (Figure 2).

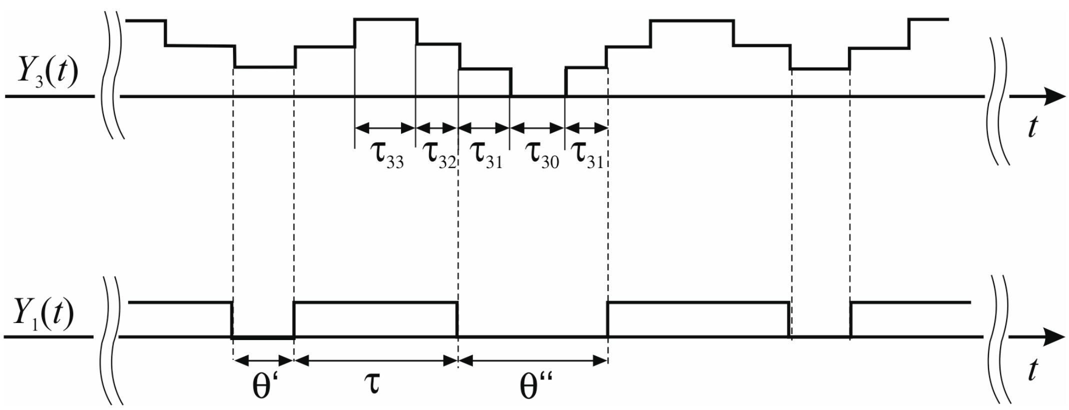

Figure 2. Graphical representation of the joint operation of three pieces of equipment and the hydraulic system with operating states caused by simultaneous switching on of at least two pieces of equipment of the CPSU.

Periods of non-operational states of the group due to stoppages of units caused by equipment failures are as follows:

$$\overline{P}_g = P_{30} + P_{31} = \overline{P}_1\overline{P}_2\overline{P}_3 + (\overline{P}_1)\overline{P}_2\overline{P}_3 + \overline{P}_1(1-\overline{P}_2)\overline{P}_3 + \overline{P}_1\overline{P}_2(1-\overline{P}_3), \tag{28}$$

where P_{30} and P_{31} are failure probabilities of three and two units out of three, respectively; $\overline{P}_1, \overline{P}_2, \overline{P}_3$ are failure probabilities of the equipment of the first, second, and third units.

Taking into account the low probability of simultaneous failure of several units of equipment [47], the situation of coincidence of operation of two units, leading to the coincidence of failure of three units, is presented through the coincidence link of operation of one unit. Each coincidence moment τ30 is accompanied by two coincidence moments τ_{31}. The frequency of these coincidences allows us to determine the frequency of pauses in the flow $X_g(t)$. Knowing the frequency of pauses in the flow allows finding the frequency of periods of the operation of the group:

$$\overline{\mu}_g = \overline{\mu}_{31} - \overline{\mu}_{30}, \tag{29}$$

where $\overline{\mu}_{31}, \overline{\mu}_{30}$ is the frequency of coincidences corresponding to failures of two and three units out of three.

Calculations (13)–(19) allow us to find other characteristics of the group performance, namely the frequency s and the probability P. A very important aspect of the methodology in this context is to analyze the distribution of the pause $X_g(t)$ arising from coincidences of failures of two and three units. The frequency of pauses q′ caused by coincidences τ_{31} is calculated as the difference between $(\overline{\mu}_{31} - 2\overline{\mu}_{30})$. Their distribution is determined by the duration of τ_{31}. The pauses q'' caused by coincidences τ_{30} and τ_{31} have frequency s'. The distribution q″ is generated from the distributions of the single coincidence τ_{30} and double coincidences τ_{31}. After determining the frequencies and distributions q' and q''', it is possible to calculate the periods of non-operation of the hoist equipment group according to formula (22).

In order to optimize the process of operation of the SNU systems, temporary redundancy, which is based on the use of excess time, is actively used [48,49]. This mechanism of temporary redundancy is implemented with the help of accumulators, which are represented in the form of hoppers at mines. Hoarders, by performing the function of temporary redundancy, help to reduce the impact of failures in the sub-bunker chain on the ore lifting process. They allow the flow of the material from the longwall face to continue even after the sub-bunker conveyors have stopped, until the hopper is filled with the material [50]. Therefore, the hopper provides temporary redundancy of the under-hopper conveyor equipment, which eliminates the stoppage of the material flow due to failures in the conveyor equipment, whose failure duration is shorter than the hopper filling time, and reduces the material flow downtime caused by failures, whose duration is longer than the hopper filling time [51,52].

In order to assess the impact of temporary redundancy on the operation of lifting equipment and the material flow characteristics, the reliability of the equipment subjected to temporary redundancy is replaced by a single equivalent element. It is important that this equivalent element has a similar impact on the operation of the process machines as the group of equipment does, which it replaces [53]. Provided that the failure of any piece of equipment causes the conveyors to stop, their reliability is related sequentially, and by modeling the operation of each piece of equipment as a random flow, we can define the characteristics of this equivalent element. The operation of the hoisting plant, as determined by the reliability of the sub-bunker conveyor equipment, will be illustrated by flow $X_\delta(t)$. Pauses in the flow $X_\delta(t)$, corresponding to downtime of the hoisting plant, occur only in case of conveyor equipment failure, whose duration exceeds the time of filling the hopper with the material. For the hopper volume V and the average capacity of the lifting machine in machine time, the value of δ can be determined using the equation:

$$\delta = \frac{V}{p_{\mathrm{f}}\overline{q}_{\mathrm{f}}}, \tag{30}$$

where p_{f} is the probability of the mine cargo's arrival.

The presence of a hopper in the system of operation of the conveyor section reduces the frequency of its stops for the lifting unit. When excluding equipment failures with the duration $\theta_e < \delta_1$, the frequency of pauses $X_\delta(t)$ will be equal to:

$$\overline{\mu}_\delta = \overline{\mu}_e \int_{\delta}^{\infty} \beta_e(\theta) d\theta, \tag{31}$$

where $\overline{\mu}_e$ is the frequency of the recovery time distribution for the equivalent element and $\beta_e(\theta)$ is the density distribution of the recovery time for the equivalent element.

The average duration of time delays for equipment recovery using δ-transformations will be defined as:

$$\theta_\delta = \frac{\int_\delta^\infty (\theta_e + \delta)\beta_e(\theta)d\theta}{\int_\delta^\infty \beta_e(\theta)d\theta}, \tag{32}$$

where θ_e is the time required to recover the equivalent element.

The probability of pauses $X_\delta(t)$ for stopping the lifting unit due to failure of the conveyor equipment will be determined by taking into account expressions (6), (31) and (32). It will be equal to:

$$\overline{P}_\delta = \overline{\mu}_e \int_\delta^\infty (\theta_e + \delta)\beta_e(\theta)d\theta. \tag{33}$$

Considering (19), we can similarly find the average parameters that will characterize the operating states of the lifting unit.

Pauses $\theta_e > \delta$ of the flow $Y_e(t)$ can be expressed through the sum of time components, the sum of idle time of the lifting rig, and the time to fill the hopper with the load. The distribution of these time costs with respect to their components will be two-dimensional. Then, the distribution of durations of stoppages caused by plant failures will be defined as:

$$\beta_\delta(\theta) = \frac{\beta_e(\theta_\delta + \delta)}{\int_\delta^\infty \beta_e(\theta)d\theta}, \tag{34}$$

for the case when $\theta_\delta \geq 0$.

The law of distribution of the trouble-free operation duration for the lifting unit will not change when the initial flow of the hopper input pulse duration obeys the exponential distribution [54]. In this case, for one switching on of the lifting unit, the duration of its operation will increase. The duration of this work is determined by the formula:

$$\overline{\tau}_\delta = \left[\exp\left(-\frac{V}{P_f \overline{q}_f \overline{\theta}_e}\right)\right]^{-1}, \tag{35}$$

where τ is the average operating time of the hoisting unit during a single switch-on (without the hopper).

The hoist system is designed with reliability in mind, combining both series and parallel connections of equipment [55]. To ensure continuous operation, structural redundancy is used to compensate for equipment failures and maintain the technological process. The integration of storage tanks into the transport system mitigates the impact of failures on the hoisting plant operation and material flow [56]. Consequently, the occurring failures have different degrees of influence on the system operation and material handling parameters. Obviously, the hoisting plant belongs to the category of complex systems and has redundancy as well as performance reserve. It has characteristic features of complex systems, such as the interaction between equipment, the complexity of functions performed, the ability to be divided into subsystems, and the presence of a control system, etc. [57,58]. The use of random impulse flow theory in analyzing the influence of individual equipment elements helped to evaluate their influence on the plant operation and to represent the system as a serial connection [59]. Taking into account the probability of downtime of the lifting unit caused by equipment failures in accordance with relations (31)–(34), it is possible to determine the following:

$$\overline{P}_{\text{c}} = \sum \overline{P} + \sum \overline{P}_r + \sum \overline{P}_{ps} + \overline{P}_\delta, \tag{36}$$

where $\overline{P}$ is the probability of downtime due to failure of critical equipment (any failure of this equipment leads to stoppage of the entire hoisting unit);

$\overline{P}_\delta$ —probability of downtime due to failure of the sub-bunker transport system;

$\overline{P}_{ps}$ —probability of downtime due to failure of pumping station subsystems;

$\overline{P}_r$ —probability of downtime due to redundant equipment;

Based on Equation (36) and taking into account expressions (24), (28) and (33) for the lifting unit, the probability of failure is defined as:

$$\overline{P}_{\text{c}} = \sum_1^n \overline{P}_i + \sum_1^k \overline{P}_j \left[1 - \exp\left(-\frac{\overline{\theta}_r}{\overline{\theta}_j} \right) \right] + \prod_1^m \sum_1^s \overline{P}_j + \sum_1^r \overline{P}_\eta \exp\left(-\frac{V}{P_f \overline{q}_f} \sum_1^r \frac{1}{\overline{\theta}_\eta} \right) \tag{37}$$

where $\overline{P}$ is the probability of failure of the equipment under study;

$\overline{\theta}$ is the average recovery time of the equipment under study;

P_f is the probability of the cargo's arrival;

$\overline{\theta}_r$ is the average duration of standby redundant equipment;

$\overline{q}_f$ is the average capacity of the used lifting unit, in tons per day;

V is the volume of the hopper used at the site, m^3;

n is the number of equipment units causing stoppage of the hoisting unit in use;

m is the number of subsystems under study;

r is the number of transport line equipment to the hopper;

k is the number of equipment provided with reserve;

S is the number of subsystem equipment.

The stopping frequency for the investigated lifting unit will be equal to:

$$\overline{\mu}_{\text{c}} = \sum_1^n \overline{\mu}_i + \left(\prod_1^m \sum_1^s \overline{P}_j \right) \sum_1^m \sum_1^s \frac{1}{\overline{\theta}_j} + \sum_1^r \overline{\mu}_\eta \exp\left(-\frac{V}{P_f \overline{q}_f} \sum_1^r \frac{1}{\overline{\theta}_\eta} \right), \tag{38}$$

where μ is the failure rate of the considered unit of equipment.

Taking into account expressions (37) and (38), the average duration of stops of the hoisting unit is equal to:

$$\overline{\theta}_{\text{c}} = \frac{1}{\overline{\mu}_{\text{c}}} \left\{ \begin{array}{l} \left(\sum_1^n \frac{1}{\overline{\theta}_i} \right)^{-1} \sum_1^n \overline{\mu}_i + \sum_1^k \overline{\theta}_j \left[1 - \exp\left(-\frac{\overline{\theta}_r}{\overline{\theta}_j} \right) \right]^{-1} \sum_1^k \overline{\mu}_j + \\ + \prod_1^m \sum_1^s \overline{P}_r \left(\sum_1^r \frac{1}{\overline{\theta}_\eta} \right)^{-1} \sum_1^r \overline{\mu}_\eta \exp\left(-\frac{V}{P_f \overline{q}_f} \sum_1^r \frac{1}{\overline{\theta}_\eta} \right) \end{array} \right\}. \tag{39}$$

Based on the calculated values of probabilities and frequencies, the average operating time (time-in-operation coefficient) of the hoisting unit is analyzed. The determination of regularities of the distribution of operating time and recovery time indicators is reduced to calculations. The use of the theory of random impulse flows helped to simplify the complex system of the hoisting plant in the context of reliability, presenting it in the form of a serial connection [60]. The operability of the lifting unit was assessed on the basis of reliability indices of individual components of the equipment, and the implementation of measures to improve the reliability of the system was analyzed [61,62].

5. The Impact of Power Supply Reliability on the Operation of the Mine Hoisting Plant

The efficiency of hoisting plant operation is influenced by the electrical equipment of both the hoisting plant itself and the main transport equipment [63]. In addition, the distribution of recovery time of electrical equipment of underground power supply systems is described not only by the exponential law. It has been established that exponential distribution is inherent in the equipment of advanced mines with a high level of labor organization and qualification of operating personnel [64,65]. On average, for mines, for example, in the Kuzbass basin, the logarithmic-normal distribution is characteristic. At the lagging mines, the recovery time obeys the truncated-normal law. Therefore, the method discussed in the previous section should be extended to the general case of assessment of the power supply provided for hoisting plants [66].

In order to evaluate the impact of the power supply system on the operation of mining machines, where each failure of electrical equipment leads to machine stoppage, it is necessary to determine the parameters of joint operation of the system [67]. For a series of connections of equipment, the frequency of stoppages is equal to the sum of frequencies of electrical equipment failures, i.e.:

$$\bar{\mu}_{\text{ser}} = \sum_{i=1}^{n} \bar{\mu}_i = \sum_{i=1}^{n} \frac{1}{\bar{\tau}_i + \bar{\theta}_i}. \quad (40)$$

The average duration of machine stoppage over the time interval under consideration, using the failure rates of electrical equipment and the values of the average time of its recovery, is calculated as follows:

$$\theta_{\text{ser}} = \frac{1}{\bar{\mu}_{\text{ser}}} \sum_{i=1}^{n} \bar{\mu}_i \bar{\theta}_i. \quad (41)$$

Taking into account Formulas (40) and (41), and similarly to (22), the probability of operation, stoppages, and MTBF are determined by the expressions:

$$\left.\begin{aligned} \bar{P}_{\text{ser}} &= \sum_{i=1}^{n} \bar{P}_i; \\ P_{\text{ser}} &= 1 - \sum_{i=1}^{n} \bar{P}_i; \\ \bar{\tau}_{\text{ser}} &= \frac{1 - \sum_{i=1}^{n} \bar{\mu}_i \bar{\theta}_i}{\sum_{i=1}^{n} \bar{\mu}_i}. \end{aligned}\right\} \quad (42)$$

By investigating the partitioning of pulses into components and analyzing the distribution laws of MTBF and recovery time, we can find similar solutions to those described in [68,69].

When studying the impact of the reliability of electrical equipment using structural redundancy on load flow parameters, we determine the average duration and frequency of pauses whose length is shorter than the time of switching to standby via θ_r–θ' and μ', and large θ_r–θ'' and μ''.

Taking into account (17)–(22), the probability of interruptions in power supply for machines caused by failure of electrical equipment with reserve will be generally less than the probability of failures of electrical equipment without reserve by:

$$\Delta \overline{P} = \overline{P}_e - \overline{P}_{\text{p}} = \overline{P}_e \int_{\overline{\theta}_r}^{\infty} \beta_e(\theta) d\theta, \tag{43}$$

where $\overline{P}_e$, $\beta_e(\theta)$ are the probability and density of the distribution of failures of the considered unit or group of equipment.

Then, the probability of machine stoppages caused by power interruptions will be equal to:

$$\overline{P}_{\text{p}} = \overline{P}_e - \overline{P}_e \int_{\overline{\theta}_r}^{\infty} \beta_e(\theta) d\theta = \overline{P}_e \int_{0}^{\infty} \beta_e(\theta) d\theta. \tag{44}$$

Reducing the probability of $\overline{P}_{\text{э}}$ is carried out by reducing the duration of interruptions in the power supply of hoisting installations. The assessment of the influence of electrical equipment failures on the operation of hoisting installations can also be performed by the pause durations of the flow describing the operation of the hoisting installation [70]. The average duration of pauses of the required flow is determined based on expression (22); taking into account (20), (17), (18), and (44), it will be equal to:

$$\overline{\theta}_{\text{p}} = \overline{\theta}_e - \overline{\theta}_e \int_{\overline{\theta}_r}^{\infty} \beta_e(\theta) d\theta = \overline{\theta}_e \int_{0}^{\infty} \beta_e(\theta) d\theta. \tag{45}$$

Using Equations (44) and (45), based on similar dependencies, the calculation of the probability and average duration of flow pulses, which describe the operation of the plant, is made. The integrals in Formulas (44) and (45) reflect the level of independence of the lifting unit operation from possible failures in the electrical equipment. Their values indicate the degree of reduction in the duration of downtime of the lifting rig due to failures in the electrical equipment when equipped with redundancy in relation to the stoppages of lifting rigs caused by failures in the electrical equipment without redundancy. Similarly, let the integral be the coupling coefficient of the structural redundancy. Then:

$$K_{\text{c}} = \int_{0}^{\overline{\theta}_r} \beta_e(\theta) d\theta. \tag{46}$$

Taking into account the coupling coefficient, we express the parameters of the hoisting unit operation due to the reliability of the electrical equipment with structural redundancy in the form of:

$$\left.\begin{aligned} \overline{P}_r &= \overline{P}_e K_{\text{c}}; \\ \overline{\theta}_r &= \overline{\theta}_e K_{\text{c}}; \\ P_r &= 1 - \overline{P}_e K_{\text{c}}; \\ \overline{\tau}_r &= \overline{\tau}_e + \overline{\theta}_e (1 - K_{\text{c}}). \end{aligned}\right\} \tag{47}$$

By introducing temporary redundancy into the system, created, for example, by introducing a transport chain storage hopper, the frequency of machine stoppages will be reduced by:

$$\Delta \overline{\mu} = \overline{\mu}_e \int_{0}^{\overline{\theta}_r} \beta_e(\theta) d\theta = \left(1 - \overline{\mu}_e \int_{0}^{\overline{\theta}_r} \beta_e(\theta) d\theta \right), \tag{48}$$

where $\overline{\mu}_e$ is the frequency of the distribution of flow pauses corresponding to the recovery time of electrical equipment of the sub-bunker system;

$\beta_e(\theta)$ is the density distribution of flow pauses corresponding to the recovery time of the same system;

δ is the time required to fill the hopper.

Exclusion of failures with duration $\overline{\theta}_e < \delta$ leads to an increase in the value of the probability of machine operation by the value determined by the expression:

$$\Delta\overline{P} = \overline{\mu}_e \int_0^\delta \theta_e \beta_e(\theta) d\theta. \tag{49}$$

The average duration of operation of the above hopper system equipment per one switching on becomes equal to:

$$\overline{\tau}_\delta = \frac{1 - \overline{\mu}_e \int_\delta^\infty (\theta_e - \delta)\beta_e(\theta) d\theta}{\overline{\mu}_e \int_\delta^\infty \beta_e(\theta) d\theta}. \tag{50}$$

Similarly to (46), in expressions (48)–(50), let us denote the integral as follows:

$$K_{pr} = \int_\delta^\infty \beta_e(\theta) d\theta \tag{51}$$

and call it the time redundancy coupling coefficient.

In this case, K_{pr} shows how many times the probability of pauses of the flow representing the operation of the lifting unit is less than the pauses of the flow describing the operation of the equipment of the sub-bunker system.

Then, taking into account (45), the characteristics of the flow describing the operation of machines in the case of temporary redundancy of electrical equipment are as follows:

$$\left.\begin{aligned} P_\delta &= 1 - \overline{P}_e K_{pr}; \\ \overline{\mu}_\delta &= \overline{\mu}_e K_{pr}; \\ \overline{\tau}_\delta &= \overline{\tau}_e K_{\mathrm{pr}}^{-1} - \overline{\theta}_e (1 - K_{pr}^{-1}). \end{aligned}\right\} \tag{52}$$

The law of the distributions of pulse durations and pauses of the flow describing the operation of the lifting unit when introducing temporary redundancy in the power supply system is determined in accordance with the schedule of its operation.

Along with structural and temporary redundancy, preventive maintenance is one of the most important means of improving equipment reliability and the efficiency of system operation. The probability and frequency of failures decrease in the case of application. The mean time between failures (MTBF) and the probability of operation increase [71]. At mining enterprises, there are special shifts or inter-shift times for maintenance and elimination of equipment failures, which makes it possible to ensure the probability of failure-free operation of systems close to one by the beginning of the main shifts [72].

Carrying out repair and preventive maintenance of electrical equipment with inter-repair periods T_p will cause a decrease in the frequency $\overline{\mu}_e$ of its failures to the value of:

$$\overline{\mu}_{\text{rpm}} = \overline{\mu}_e \int_0^{T_p} X_e(\tau) d\tau. \tag{53}$$

where $X_e(\tau)$ is the probability density of MTBF values of the power supply system under study.

Taking into account the fact that failures are an event opposite to operable states of the equipment, the probability of operation is equal to:

$$P_{\text{rpm}} = \frac{\overline{\tau}_e + \overline{\theta}_e \left(1 - \int_0^{T_r} \alpha_e(\tau) d\tau\right)}{\overline{\tau}_e + \overline{\theta}_e}, \tag{54}$$

and the mean time between failures is as follows:

$$\overline{\tau}_{\text{rpm}} = \frac{\overline{\tau}_e + \overline{\theta}_e \left(1 - \int_0^{Tr} \alpha_e(\tau) d\tau\right)}{\int_0^{T_r} X_e(\tau) d\tau}. \tag{55}$$

Equations (53)–(55) are a function of the integral that shows how many times repair and preventive maintenance reduces the number of failures. Let us denote it by the coefficient of the coupling of repair and preventive maintenance efficiency:

$$K_{\text{rpm}} = \int_0^{T_r} X_e(\tau) d\tau. \tag{56}$$

Then, the expressions representing the parameters of the considered system will take the form:

$$\left.\begin{aligned} \overline{\mu}_{\text{rpm}} &= \overline{\mu}_e K_{\text{rpm}}; \\ P_{\text{rpm}} &= P_e + \overline{P}_e (1 - K_{\text{rpm}}); \\ \overline{\tau}_{\text{rpm}} &= \frac{\tau_e + \overline{\theta}_e (1 - K_{\text{rpm}})}{K_{\text{rpm}}} \end{aligned}\right\} \tag{57}$$

The operation of redundant systems is mainly determined by the frequency of changeover from the main to the standby electrical equipment. When the working system stops, the standby system is switched on automatically or, as a last resort, by maintenance personnel. Since the equipment is not absolutely reliable, even the presence of two redundant systems does not guarantee the exclusion of all failures. As a result, the operating time of the hoist system is shortened. The delay time can be longer than the time between failures of the power supply systems. As a result, the frequency of switching on the hoisting systems will not be equal to the frequency of electrical equipment interruptions. Its value will be equal to:

$$\overline{\mu}_{\text{otm}} = \overline{\mu}_{\text{obb}} \left(1 - \int_0^{\overline{V}} x(\tau_{\text{obb}}) d\tau_{\text{obb}}\right), \tag{58}$$

where $\bar{\mu}_{\text{obb}}$, $\bar{\tau}_{\text{obb}}$ are the frequency and average duration of operation between breaks of electrical equipment.

Partial overlap in the timing between operating delays reduces the τ_{otm} operating time of the machines. Overlapping occurs between breaks of the shorter duration $\bar{V}$ and switching on the hoisting machines with a delay in operating hours between breaks of the longer duration $\bar{V}$. In order to calculate the density distribution of the values τ_{otm}, we remove from the analysis the hours of operation $\tau_{\text{rpm}} < \bar{V}$ and reduce the hours of operation $\tau_{\text{rpm}} > \bar{V}$ by the value $\bar{V}$. In this case, we obtain an expression of the form:

$$\alpha(\tau_{\text{otm}}) = \frac{\alpha(\tau_{\text{otm}} + \bar{V})}{1 - \int_0^{\bar{V}} x(\tau_{\text{obb}}) d\tau_{\text{obb}}}, \tag{59}$$

where $\tau_{\text{otm}} + \bar{V} = \tau_{\text{obb}}$.

According to (42) and (59), the average operating time of the lifting units per switch-on is:

$$\tau_{\text{otm}} = \frac{\int_{\bar{V}}^{\bar{\infty}} (\tau_{\text{obb}} - \bar{V}) x(\tau_{\text{obb}}) d\tau_{\text{obb}}}{1 - \int_0^{\bar{V}} x(\tau_{\text{obb}}) d\tau_{\text{obb}}}. \tag{60}$$

The duration of stoppages of hoisting systems θ_{otm} is determined by interruptions in equipment operation and delays in the load arrival.

Delays in switching on the lifting units are caused by unloading the working bodies of conveyors, rail cars, intermediate storage hoppers, etc. Delays shorten the operating time of machines, increasing the number and duration of stops. Similarly to (46), (51), and (56), let us introduce the concept of the delay coefficient:

$$K_{\text{otm}} = \int_0^{\bar{\theta}_{\text{o}}} x(\tau_{\text{obb}}) d\tau_{\text{obb}}. \tag{61}$$

The dependencies representing the operation of the lifting units in this case will be as follows:

$$\left.\begin{aligned} \bar{\mu}_{\text{otm}} &= \bar{\mu}_{\text{obb}}(1 - K_{\text{otm}}); \\ \bar{\theta}_{\text{otm}} &= \frac{\bar{\theta}_{\text{obb}} + \bar{V}}{1 - K_{\text{otm}}}; \\ \bar{\tau}_{\text{otm}} &= \frac{1 - \bar{\mu}_{\text{obb}}(\bar{\theta}_{\text{obb}} + \bar{V})}{\bar{\mu}_{\text{obb}}(1 - K_{\text{otm}})}. \end{aligned}\right\} \tag{62}$$

There are two possible cases of load shifting from the operating equipment to the standby equipment that occur during the operation of the standby equipment.

The first case of such switching occurs when the operating equipment fails. In the second case, an independent switchover from the main equipment to the standby equipment is performed. The equipment is switched on after a certain period of operation of the main equipment, and if the main equipment fails, the standby equipment is switched on. Switching on the standby equipment occurs in parallel. That is, there is no waiting for the end of the main equipment operation.

Interruptions in operation occur in case of repair, preventive maintenance or failure of the operating power supply system. The interruption of the operation is also possible in case of failure of the backup system. This occurs when the MTBF τ_{op} of the redundant system does not cover the duration of the interruptions θ_o of the power supply of the working system. The average duration of such events P_{op} is equal to:

$$\bar{\tau}_{\text{op}} = \frac{\int_0^{\bar{\theta}_o} x(\tau_{\text{op}})\tau_{\text{op}} d\tau_{\text{op}}}{\int_0^{\bar{\theta}_o} x(\tau_{\text{op}}) d\tau_{\text{op}}}, \tag{63}$$

where $x(\tau_{\text{op}})$ is the distribution density of the standby power system pulses corresponding to the MTBF.

The probability of occurrence of MTBF $\tau_{op} < \theta_o$ for the standby system and power interruptions of the working system is calculated using the formula:

$$P_{\text{c}} = \bar{P}_{\text{o}} P_{\text{op}}. \tag{64}$$

The probability P_c characterizes the events that precede power interruptions. These events occur when the systems under consideration are functioning together. The frequency of interruptions in the operation of these systems will be defined as:

$$\bar{\mu}_{\text{obb}} = \frac{\bar{P}_{\text{o}}}{\bar{\tau}_{\text{op}} + \bar{\theta}_{\text{op}}} \int_0^{\bar{\theta}_o} x(\tau_{\text{op}}) d\tau_{\text{op}}. \tag{65}$$

By analogy with the coupling coefficients of structural and temporary redundancy, preventive maintenance, and delays, let us denote the integrals of Formulas (60) and (65) by K_{cont} and call it the coupling coefficient of the control strategy:

$$K_{\text{cont}} = \int_0^{\bar{\theta}_o} x(\tau_{\text{op}}) d\tau_{\text{op}}. \tag{66}$$

It shows how many times the probability of the hoist system stopping because of power interruptions is reduced by applying the first system operation control strategy.

The parameters characterizing the operation of the power supply system for the control strategy, when the standby equipment is switched on only in case of failure of the working one, will be equal to:

$$\left.\begin{aligned} \bar{P}_{\text{op}} &= \bar{P}_{\text{p}} K_{\text{cont}}; \\ \bar{\theta}_{\text{op}} &= \bar{\theta}_{\text{p}} K_{\text{cont}}; \\ \bar{\tau}_{\text{op}} &= \frac{(1 - P_{\text{p}} K_{\text{cont}})\bar{\theta}_{\text{p}}}{\bar{P}_{\text{p}}}. \end{aligned}\right\} \tag{67}$$

The integral parameters in the distribution density of the equipment recovery time in the system are described by various formulas. These parameters include the coupling coefficients of structural and time redundancy. The type of formulas for their determination depends on the distribution function of the sub-equipment recovery time and is characterized by the specific distribution law $\beta(\theta)$. These are exponential, logarithmic-normal, truncated-normal, and other laws. The coupling coefficients of preventive maintenance, delays, and the control strategy are described by the Weibull law. This is due to the fact that the durations of the operating time to failure of mine electrical equipment obey, as statistical studies [73] have shown, the Weibull law. In Figure 3, the dependences show the change in the control coefficient K_{cont} for different values of β. At the same time, the efficiency of repair and preventive maintenance, the control strategy turns out to be a variable value based on the ratio of:

$$Strategy = f\,\frac{T_r}{\overline{\tau}_e}\left(\frac{\overline{\theta}_{\text{o}}}{\overline{\tau}_{\text{op}}}\right). \tag{68}$$

It is also influenced by the asymmetry parameter of the distribution β Weibull law. The larger the asymmetry parameter, the more reasonable it is to carry out the maintenance at small values of the ratio $\frac{T_r}{\overline{\tau}_e}$. The linearity of K_{cont} is seen to increase along with the decrease.

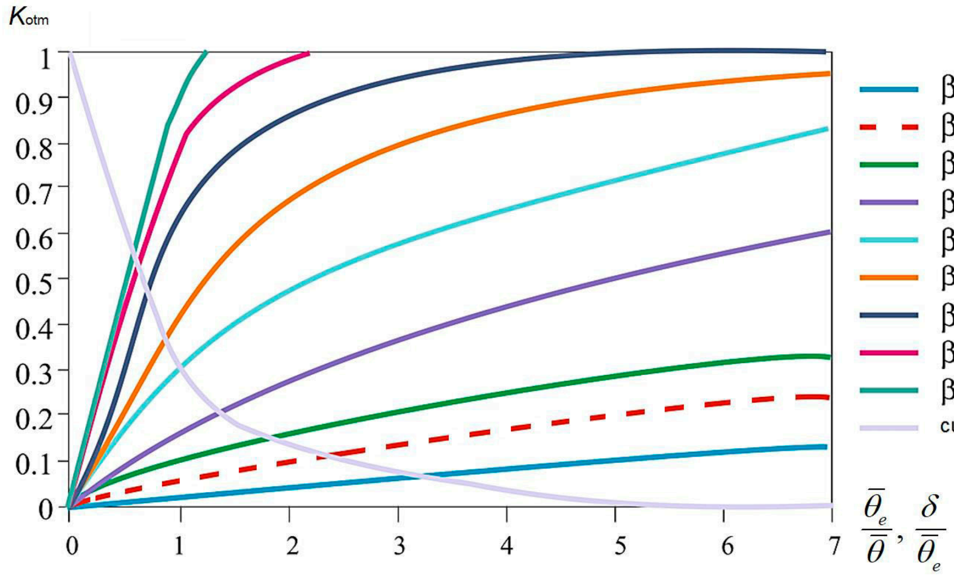

Figure 3. Graphs of coupling coefficients in case of MTBF distribution according to the Weibull law and recovery time according to the exponential law.

6. Discussion

In nature, the effect of K_{otm} delays on machine uptime is similar to the effect of temporary redundancy on equipment failures. The difference is that the delays overlap the time between failures. At the same time, the duration of the delays is less than $\overline{V}$ and reduces the time between failures with the duration greater than $\overline{V}$. In relation to the overlapping of failures with temporary redundancy, the interruption of operating hours is insignificant. There is no significant impact on the process flow of such interruptions. With the exponential law, the coupling coefficient of structural redundancy is shown in dependence 7 above at $\beta = 1$ (Figure 3). The coupling coefficient of temporal redundancy is shown in dependence 3 (Figure 3). The highest redundancy efficiency is achieved when the increment of the coupling coefficient value is in the range from 0 to 0.6 (for structural redundancy) and from 1 to 0.3 (for temporary redundancy). This change in the coupling coefficient corresponds to the change of values for the relation $\frac{\overline{\theta}_e}{\overline{\theta}}, \frac{\delta}{\overline{\theta}_e}$ from 0 to 0.8. The parameters of the log-normal distribution law are the mathematical expectation of the quantity under study and the mean square deviation of the quantity under study. If the truncated-normal law is used, a normalizing factor is added to the specified mathematical expectation and quadratic deviation. It is rather difficult and time-consuming to determine the coupling coefficients analytically. A simpler way to determine the coupling coefficients is to use graphical integration. Graphs of coupling coefficients were plotted using expressions (46)–(67) (Figure 4). The graphs are plotted for the coupling coefficients of structural and temporary redundancy under the logarithmic-normal distribution law.

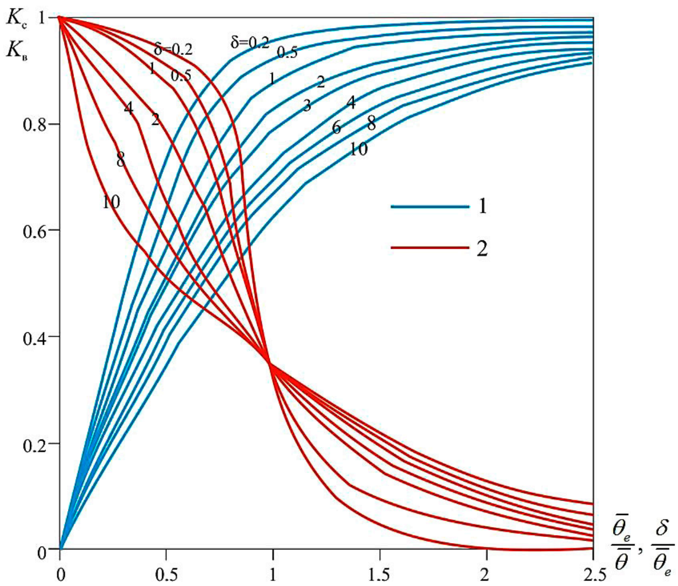

Figure 4. Graphs of structural and temporary redundancy coefficients under the logarithmic-normal law of recovery time distribution: 1—structural redundancy; 2—temporary redundancy.

The use of coupling coefficients makes it possible to analyze and establish the correlation between the reliability of power supply systems, the reliability of electrical equipment, and the operating modes of technological machines. Comparison of the coupling coefficients of these systems allows evaluation of their interrelation and influence on each other in the context of general reliability and efficiency of technical system functioning. The reliability of the mine's system functioning depends on the nature of the operation and the degree of interaction with the equipment of its own and other systems. Then, the E-transformation of flows due to the unreliable functioning of power supply systems can be represented in the general form:

$$(P_c;\ \overline{\tau}_c;\overline{\mu}_c) = Э:[(K_c + K_{pr} + K_{\text{rpm}} + K_{\text{otm}} + K_{cont})\cdot(P_i;\ \overline{\tau}_i;\overline{\mu}_i)], \quad (69)$$

where $P_c;\ \overline{\tau}_c;\overline{\mu}_c$ are reliability parameters of the system taking into account failure-free performance of its equipment.

Considering the coupling coefficients, we determine the working characteristic of the reliability parameters under study:

$$\left.\begin{aligned}
&P_{\mathrm{c}}=1-K_{\mathrm{c}1}K_{\mathrm{pr}1}K_{\mathrm{rpm}1}K_{cont1}(1-K_{otm1})\frac{P_1}{\overline{\tau}_1}(\overline{\theta}_1+\overline{\nu}_1)-\\
&-\sum_2^n K_{\mathrm{c}i}K_{\mathrm{pr}i}K_{\mathrm{rpm}i}K_{conti}(1-K_{otmi})\frac{P_i}{\overline{\tau}_1}(\overline{\theta}_1+\overline{\nu}_1);\\
&\overline{\tau}_{\mathrm{c}}=1-K_{\mathrm{c}1}K_{\mathrm{pr}1}K_{\mathrm{rpm}1}K_{cont1}(1-K_{otm1})\frac{P_1}{\overline{\tau}_1}(\overline{\theta}_1+\overline{\nu}_1)-\\
&-\sum_2^n K_{\mathrm{c}i}K_{\mathrm{pr}i}K_{\mathrm{rpm}i}K_{conti}(1-K_{otmi})\frac{P_i}{\overline{\tau}_1}(\overline{\theta}_1+\overline{\nu}_1)\times\\
&\times\left[K_{\mathrm{pr}1}K_{\mathrm{rpm}1}K_{cont1}(1-K_{otm1})\frac{P_1}{\overline{\tau}_1}+\sum_2^n K_{\mathrm{c}2}K_{\mathrm{pr}i}K_{\mathrm{rpm}i}K_{conti}(1-K_{otmi})\frac{P_i}{\overline{\tau}_i}\right]^{-1};\\
&\overline{\mu}_{\mathrm{c}}=K_{\mathrm{pr}1}K_{\mathrm{rpm}1}K_{cont1}(1-K_{otm1})\frac{P_1}{\overline{\tau}_1}+\sum_2^n K_{\mathrm{pr}i}K_{\mathrm{rpm}i}K_{conti}(1-K_{otmi})\frac{P_i}{\overline{\tau}_i}.
\end{aligned}\right\}\quad(70)$$

where P_1, $\overline{\tau}_1$, $\overline{\theta}_1$ are reliability parameters for the used electrical equipment;

K_{c1}, K_{pr1}, K_{rpm1}, K_{cont1}, K_{otm1} are electrical equipment coupling factors.

The coupling coefficients are shown for electrical equipment, the influence of failures of which is to be established. The influence of its failures on the operation of mine hoisting installations is established.

P_i, $\overline{\tau}_i$, $\overline{\theta}_i$ are parameters of the *i-th* unit of equipment of the SNU systems;

K_{ci}, $K_{\mathrm{pr}i}$, K_{rpmi}, K_{conti} are communication coefficients of the *i-th* unit of the equipment of the SNU systems.

The considered power supply system is quite complex in terms of reliability. The proposed approach allows this rather complex system to be brought in the form of a sequential connection of elements for this system to determine the influence of the functioning of its subsystems and electrical equipment on the technological process of cargo lifting in a coal mine.

The impact of the proposed approach on complex coal mine power systems has been analyzed. The key aspects of the approach have been highlighted, allowing the complexity of the system to be reduced to a series of elements. This allows the impact of system operation and electrical equipment on the coal mine lifting process to be determined in more detail. The results of the study will provide a deeper understanding of the relationship between electrical supply reliability and mining machine performance that will measure the effect of process improvements and contribute to improved safety in mining.

Coal mine power supply systems are extremely complex and are characterized by the presence of many components: power sources (transformers, generators), power transmission lines (aboveground, underground), switchgears (panels, stations), and electrical equipment (electric motors, pumps, fans). This complexity is due to the requirements for high reliability due to the need to ensure continuous operation of mine equipment, which is critical to the safety of miners and environmental protection. The proposed approach to improving equipment reliability allows for simplifying the analysis of a complex power supply system by representing it as a series of connection of elements. This is achieved by dividing the system into subsystems (underground and aboveground power lines, switchgears), establishing links between the subsystems, simplifying the connection scheme and functional dependencies, and determining the influence of subsystems and electrical equipment. The model of the power supply system allows for determining the impact of subsystems and electrical equipment on the technological process of cargo lifting in a coal mine by assessing the impact of subsystem and equipment failures on the operation of electric lifting equipment, the impact of power supply interruptions on the rate of cargo lifting, the interdependence between the reliability of power supply and mine productivity.

Key aspects of this approach include breaking down a complex system into controllable components, establishing the relationships between these components, simplifying the wiring diagram to facilitate analysis, and analyzing failures and the impact on the lifting process. The results of the study highlight the relationship between power supply reliability and mining machine performance, allowing us to evaluate the effect of improving production processes by improving power supply reliability and safety in mining by minimizing the risks associated with power outages and improving the management of mining equipment operation.

7. Conclusions

1. When analyzing the performance assurance of mine hoisting machines and the quality of performance of the functions under consideration, it is proposed to assess the quality of technical system functioning through a set of properties of the cargo lifting process, which meet specified requirements in accordance with the purpose and evaluated performance indicators. In this case, the quality of function fulfillment depends not only on the elements, which in the process of system functioning worked correctly or failed, but also on the moments of time when some or other changes of system states occurred. The proposed approach allowed for bringing the complex system of power supply of mine hoisting installations to the form of the sequential connection of system elements. For this system, the influence of the functioning of its subsystems and electrical equipment on the technological process of cargo lifting in a coal mine was determined.

2. The coefficients of the relationship between the time-to-failure distribution and the recovery time of the technical system were determined, allowing for the prediction of the state of technical system elements at any point of its life cycle, including the most important conditions, such as operation, repair, and maintenance.

3. The presented mathematical concept of increasing the reliability and failure-free operation of mine hoisting plants with the help of the developed mathematical model allowed investigation of the reliability indicators of the hoisting plant operation and reserving the equipment most effectively to increase reliability. The determination of coupling coefficients in this study made it possible to analyze the impact of the reliability of electrical equipment and power supply systems on the operation of technological machines to improve the mining equipment reliability and the most effective equipment redundancy.

Author Contributions: Conceptualization, B.V.M. and N.V.M.; methodology, S.N.S. and E.A.E.; software, M.Q.; validation, S.N.S. and E.A.E.; formal analysis, P.V.S.; investigation, D.V.V.; resources, D.V.V.; data curation, D.V.V.; writing—original draft preparation, P.V.S.; writing—review and editing, B.V.M. and N.V.M.; visualization, M.Q. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data presented in this study are available from the corresponding authors upon reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Carlo, F.D. *Reliability and Maintainability in Operations Management*; Massimiliano, S., Ed.; InTech: London, UK, 2013.
2. Dhillon, B.S. *Mining Equipment Reliability, Maintainability, and Safety*; Springer: London, UK, 2008.
3. Kumar, U.; Klefsjo, B. Reliability analysis of hydraulic systems of LHD machines using the power law process model. *Reliab. Eng. Syst. Saf.* **1992**, *35*, 217–224.
4. Troy, D. The Importance of Efficient Mining Equipment. Available online: https://industrytoday.com/importance-efficientmining-equipment/ (accessed on 12 February 2023).

5. Abramovich, B.N.; Bogdanov, I.A. Improving the efficiency of autonomous electrical complexes of oil and gas enterprises. *J. Min. Inst.* **2021**, *249*, 408–416. https://doi.org/10.31897/PMI.2021.3.10.
6. Amy, H. What Is Equipment Reliability and How Do You Improve It? Available online: https://nonstopreliability.com/equipment-reliability/ (accessed on 15 October 2020).
7. Meshkov, A.A.; Kazanin, O.I.; Sidorenko, A.A. Improving the efficiency of the technology and organisation of the longwall face move during the intensive flat-lying coal seams mining at the Kuzbass mines. *J. Min. Inst.* **2021**, *249*, 342–350. https://doi.org/10.31897/PMI.2021.3.3.
8. Nazarychev, A.N.; Dyachenok, G.V.; Sychev, Y.A. A reliability study of the traction drive system in haul trucks based on failure analysis of their functional parts. *J. Min. Inst.* **2023**, *261*, 363–373.
9. Norris, G. The True Cost of Unplanned Equipment Downtime. Available online: https://www.forconstructionpros.com/equipment-management/article/21104195/the-true-cost-of-unplanned-equipment-downtime (accessed on 3 December 2019).
10. Kumar, U. Reliability Analysis of Load-Haul-Dump Machines. Ph.D. Thesis, Lulea tekniska universitet, Lulea, Sweden, 1990.
11. Provencher, M. A Guide to Predictive Maintenance for the Smart Mine. Available online: https://www.mining.com/a-guide-topredictive-maintenance-for-the-smart-mine/ (accessed on 16 April 2020).
12. Koteleva, N.; Korolev, N. A Diagnostic Curve for Online Fault Detection in AC Drives. *Energies* **2024**, *17*, 1234. https://doi.org/10.3390/en17051234.
13. Glazunov, V.V.; Burlutsky, S.B.; Shuvalova, R.A.; Zhdanov, S.V. Improving the reliability of 3D modelling of a landslide slope based on engineering geophysics data. *J. Min. Inst.* **2022**, *257*, 771–782. https://doi.org/10.31897/PMI.2022.86.
14. Vasilyeva, N.; Golyshevskaia, U.; Sniatkova, A. Modeling and Improving the Efficiency of Crushing Equipment. *Symmetry* **2023**, *15*, 1343. https://doi.org/10.3390/sym15071343.
15. Stanek, E.; Venkata, S. Mine power system reliability. *IEEE Trans. Ind. Appl.* **1988**, *24*, 827–838.
16. Nevskaya, M.A.; Raikhlin, S.M.; Vinogradova, V.V.; Belyaev, V.V.; Khaikin, M.M. A Study of Factors Affecting National Energy Efficiency. *Energies* **2023**, *16*, 5170. https://doi.org/10.3390/en16135170.
17. Collins, E.W. Safety evaluation of coal mine power systems. In Proceedings of the Annual Reliability and Maintainability Symposium, Philadelphia, PA, USA, 27 January 1987; Sandia National Labs: Albuquerque, NM, USA, 1987.
18. Zhukovskiy, Y.; Buldysko, A.; Revin, I. Induction Motor Bearing Fault Diagnosis Based on Singular Value Decomposition of the Stator Current. *Energies* **2023**, *16*, 3303. https://doi.org/10.3390/en16083303.
19. Samanta, B.; Sarkar, B.; Mukherjee, S.K. Reliability assessment of hydraulic shovel system using fault trees. *Min. Technol. Trans. Inst. Min. Metall. Sect. A* **2002**, *111*, 129–135.
20. Kunshin, A.; Dvoynikov, M.; Timashev, E.; Starikov, V. Development of Monitoring and Forecasting Technology Energy Efficiency of Well Drilling Using Mechanical Specific Energy. *Energies* **2022**, *15*, 7408. https://doi.org/10.3390/en15197408.
21. Roy, S.K.; Bhattacharyya, M.M.; Naikan, V.N. Maintainability and reliability analysis of a fleet of shovels. *Min. Technol. Trans. Inst. Min. Metall. Sect. A* **2001**, *110*, 163–171.
22. Abdollahpour, P.; Tabatabaee Moradi, S.S.; Leusheva, E.; Morenov, V. A Numerical Study on the Application of Stress Cage Technology. *Energies* **2022**, *15*, 5439. https://doi.org/10.3390/en15155439.
23. Coetzee, J.L. The role of NHPP models in the practical analysis of maintenance failure data. *Reliab. Eng. Syst. Saf.* **1997**, *56*, 161–168.
24. Ilyushina, A.N.; Pershin, I.M.; Trushnikov, V.E.; Novozhilov, I.M.; Pervukhin, D.A.; Tukeyev, D.L. Design of Induction Equipment Complex using the Theory of Distributed Parameter Systems. In Proceedings of 2023 5th International Conference on Control in Technical Systems, 2023, CTS 2023, Saint Petersburg, Russian, 21–23 September 2023; pp. 79–82. https://doi.org/10.1109/CTS59431.2023.10288909.
25. Skamyin, A.N.; Dobush, I.V.; Gurevich, I.A. Influence of nonlinear load on the measurement of harmonic impedance of the power supply system. In Proceedings of the 2023 5th International Youth Conference on Radio Electronics, Electrical and Power Engineering, 2023, REEPE 2023, Moscow, Russian, 16–18 March 2023. https://doi.org/10.1109/REEPE57272.2023.10086795.
26. Hall, R.A.; Daneshmend, L.K. Reliability Modelling of Surface Mining Equipment: Data Gathering and Analysis Methodologies. *Int. J. Surf. Min.* **2003**, *17*, 139–155.
27. Malozyomov, B.V.; Martyushev, N.V.; Sorokova, S.N.; Efremenkov, E.A.; Qi, M. Mathematical Modeling of Mechanical Forces and Power Balance in Electromechanical Energy Converter. *Mathematics* **2023**, *11*, 2394. https://doi.org/10.3390/math11102394.
28. Golik, V.I.; Brigida, V.; Kukartsev, V.V.; Tynchenko, Y.A.; Boyko, A.A.; Tynchenko, S.V. Substantiation of Drilling Parameters for Undermined Drainage Boreholes for Increasing Methane Production from Unconventional Coal-Gas Collectors. *Energies* **2023**, *16*, 4276. https://doi.org/10.3390/en16114276.
29. Efremenkov, E.A.; Qi, M. Mathematical Modeling the Performance of an Electric Vehicle Considering Various Driving Cycles. *Mathematics* **2023**, *11*, 2586. https://doi.org/10.3390/math11112586.
30. Klyuev, R.V.; Karlina, A.I. Improvement of Hybrid Electrode Material Synthesis for Energy Accumulators Based on Carbon Nanotubes and Porous Structures. *Micromachines* **2023**, *14*, 1288. https://doi.org/10.3390/mi14071288.
31. Rao, K.R.; Prasad, P.V. Graphical methods for reliability of repairable equipment and maintenance planning. In Proceedings of the Annual Symposium on Reliability and Maintainability (RAMS), Philadelphia, PA, USA, 22–25 January 2001; pp. 123–128.
32. Kumar, R.; Vardhan, A.; Kishorilal, D.B.; Kumar, A. Reliability analysis of a hydraulic shovel used in open pit coal mines. *J. Mines Met. Fuels* **2018**, *66*, 472–477.

33. Sinha, R.S.; Mukhopadhyay, A.K. Reliability centred maintenance of cone crusher: A case study. *Int. J. Syst. Assur. Eng. Manag.* **2015**, *6*, 32–35. https://doi.org/10.1007/s13198-014-0240-7.
34. Gharahasanlou, A.N.; Mokhtarei, A.; Khodayarei, A.; Ataei, M. Fault tree analysis of failure cause of crushing plant and mixing bed hall at Khoy cement factory in *Iran. Case Stud. Eng. Fail. Anal.* **2014**, *2*, 33–38. https://doi.org/10.1016/j.csefa.2013.12.006.
35. Kang, J.; Sun, L.; Soares, C.G. Fault Tree Analysis of floating offshore wind turbines. *Renew. Energy* **2019**, *133*, 1455–1467.
36. Tuncay, D.; Nuray, D. Reliability analysis of a dragline using fault tree analysis. *Bilimsel Madencilik Derg.* **2017**, *56*, 55–64.
37. Patil, R.B.; AMhamane, D.; Kothavale, P.B.; SKothavale, B. Fault Tree Analysis: A Case Study from Machine Tool Industry. In Proceedings of the An International Conference on Tribology, TRIBOINDIA-2018, Mumbai, India, 13–15 December 2018.
38. Iyomi, E.P.; Ogunmilua, O.O.; Guimaraes, I.M. Managing the Integrity of Mine Cage Conveyance. *Int. J. Eng. Res. Technol. (IJERT)* **2021**, *10*, 743–747.
39. Relkar, A.S. Risk Analysis of Equipment Failure through Failure Mode and Effect Analysis and Fault Tree Analysis. *J. Fail. Anal. Prev.* **2021**, *21*, 793–805.
40. Li, S.; Yang, Z.; Tian, H.; Chen, C.; Zhu, Y.; Deng, F.; Lu, S. Failure Analysis for Hydraulic System of Heavy-Duty Machine. *Appl. Sci.* **2021**, *11*, 1249.
41. Jiang, G.-J.; Li, Z.-Y.; Qiao, G.; Chen, H.-X.; Li, H.-B.; Sun, H.-H. Reliability Analysis of Dynamic Fault Tree Based on Binary Decision Diagrams for Explosive Vehicle. *Math. Probl. Eng.* **2021**, *2021*, 5559475.
42. Kabir, S. An overview of fault tree analysis and its application in model based dependability analysis. *Expert Syst. Appl.* **2017**, *77*, 114–135.
43. Tynchenko, V.S.; Bukhtoyarov, V.V.; Wu, X.; Tyncheko, Y.A.; Kukartsev, V.A. Overview of Methods for Enhanced Oil Recovery from Conventional and Unconventional Reservoirs. *Energies* **2023**, *16*, 4907. https://doi.org/10.3390/en16134907.
44. Malozyomov, B.V.; Martyushev, N.V.; Voitovich, E.V.; Kononenko Designing the Optimal Configuration of a Small Power System for Autonomous Power Supply of Weather Station Equipment. *Energies* **2023**, *16*, 5046. https://doi.org/10.3390/en16135046.
45. Malozyomov, B.V.; Martyushev, N.V.; Konyukhov, V.Y.; Oparina, T.A.; Zagorodnii, N.A.; Efremenkov, E.A.; Qi, M. Mathematical Analysis of the Reliability of Modern Trolleybuses and Electric Buses. *Mathematics* **2023**, *11*, 3260. https://doi.org/10.3390/math11153260.
46. Efremenkov, E.A.; Valuev, D.V.; Qi, M. Review Models and Methods for Determining and Predicting the Reliability of Technical Systems and Transport. *Mathematics* **2023**, *11*, 3317. https://doi.org/10.3390/math11153317.
47. Zuo, X.; Yu, X.R.; Yue, Y.L.; Yin, F.; Zhu, C.L. Reliability Study of Parameter Uncertainty Based on Time-Varying Failure Rates with an Application to Subsea Oil and Gas Production Emergency Shutdown Systems. *Processes* **2021**, *9*, 2214.
48. Kumar, N.S.; Choudhary, R.P.; Murthy, C. Reliability based analysis of probability density function and failure rate of the shovel-dumper system in a surface coal mine. *Model. Earth Syst. Environ.* **2020**, *7*, 1727–1738.
49. Balaraju, J.; Raj, M.G.; Murthy, C. Estimation of reliability-based maintenance time intervals of Load-Haul Dumper in an underground coal mine. *J. Min. Environ.* **2018**, *9*, 761–771.
50. Bala, R.J.; Govinda, R.; Murthy, C. Reliability analysis and failure rate evaluation of load haul dump machines using Weibull. *Math. Model. Eng. Probl.* **2018**, *5*, 116–122.
51. Waghmode, L.Y.; Patil, R.B. Reliability analysis and life cycle cost optimisation: A case study from Indian industry. *Int. J. Qual. Reliab. Manag.* **2016**, *33*, 414–429.
52. Barabady, J.; Kumar, U. Reliability analysis of mining equipment: A case study of a crushing plant at Jajarm Bauxite Mine in Iran. *Reliab. Eng. Syst. Saf.* **2008**, *93*, 647–653.
53. Taherı, M.; Bazzazı, A.A. Reliability Analysis of Loader Equipment: A Case Study of a Galcheshmeh. *J. Undergr. Resour.* **2016**, 37–46. Available online: https://dergipark.org.tr/en/pub/mtb/issue/32053/354893 (accessed on 3 March 2022).
54. Hoseinie, S.H.; Ataei, M.; Khalokakaie, R.; Ghodrati, B.; Kumar, U. Reliability analysis of the cable system of drum shearer using the power law process model. *Int. J. Min. Reclam. Environ.* **2012**, *26*, 309–323.
55. Mouli, C.; Chamarthi, S.; Chandra, G.; Kumar, V. Reliability Modeling and Performance Analysis of Dumper Systems in Mining by KME Method. *Int. J. Curr. Eng. Technol.* **2014**, 2, 255–258. http://dx.doi.org/10.14741/ijcet/spl.2.2014.46
56. Roche-Carrier, N.L.; Ngoma, G.D.; Kocaefe, Y.; Erchiqui, F. Reliability analysis of underground rock bolters using the renewal process, the non-homogeneous Poisson process and the Bayesian approach. *Int. J. Qual. Reliab. Manag.* **2019**, *37*, 223–242.
57. Sorokova, S.N.; Efremenkov, E.A.; Valuev, D.V.; Qi, M. Stochastic Models and Processing Probabilistic Data for Solving the Problem of Improving the Electric Freight Transport Reliability. *Mathematics* **2023**, *11*, 4836. https://doi.org/10.3390/math11234836.
58. Martyushev, N.V.; Malozyomov, B.V.; Kukartsev, V.V.; Gozbenko, V.E. Determination of the Reliability of Urban Electric Transport Running Autonomously through Diagnostic Parameters. *World Electr. Veh. J.* **2023**, *14*, 334. https://doi.org/10.3390/wevj14120334.
59. Boychuk, I.P.; Grinek, A.V.; Kondratiev, S.I. A Methodological Approach to the Simulation of a Ship's Electric Power System. *Energies* **2023**, *16*, 8101. https://doi.org/10.3390/en16248101.
60. Filina, O.A.; Panfilova, T.A. Increasing the Efficiency of Diagnostics in the Brush-Commutator Assembly of a Direct Current Electric Motor. *Energies* **2024**, *17*, 17. https://doi.org/10.3390/en17010017.
61. Yi, X.J.; Chen, Y.F.; Hou, P. Fault diagnosis of rolling element bearing using Naïve Bayes classifier. *Vibroeng. Procedia* **2017**, *14*, 64–69.

62. Rokach, L.; Maimon, O. *Data Mining With Decision Trees*, 2nd ed.; World Scientific Publishing Co. Pte. Ltd.: Singapore, 2015.
63. Du, C.-J.; Sun, D.-W. (Eds.). Object Classification Methods. In *Computer Vision Technology for Food Quality Evaluation*; Elsevier Inc.: Amsterdam, The Netherlands; Academic Press: Cambridge, MA, USA, 2008; pp. 57–80.
64. Gong, Y.-S.; Li, Y. Motor Fault Diagnosis Based on Decision Tree-Bayesian Network Model. In *Advances in Electronic Commerce, Web Application and Communication*; Jin, D., Lin, S., Eds.; Springer: Warsaw, Poland, 2012; pp. 165–170.
65. Hildreth, J.; Dewitt, S. Logistic Regression for Early Warning of Economic Failure. In Proceedings of the 52nd ASC Annual International Conference Proceedings, Provo, UT, USA, 13–16 April 2016.
66. Bhattacharjee, P.; Dey, V.; Mandal, U.K. Risk assessment by failure mode and effects analysis (FMEA) using an interval number based logistic regression model. *Saf. Sci.* **2020**, *132*, 104967.
67. Ku, J.-H. A Study on Prediction Model of Equipment Failure Through Analysis of Big Data Based on RHadoop. *Wirel. Pers. Commun.* **2018**, *98*, 3163–3176.
68. Efremenkov, E.A.; Valuev, D.V.; Qi, M. Analysis of a Predictive Mathematical Model of Weather Changes Based on Neural Networks. *Mathematics* **2024**, *12*, 480. https://doi.org/10.3390/math12030480.
69. Konyukhov, V.Y.; Oparina, T.A.; Sevryugina, N.S.; Gozbenko, V.E.; Kondratiev, V.V. Determination of the Performance Characteristics of a Traction Battery in an Electric Vehicle. *World Electr. Veh. J.* **2024**, *15*, 64. https://doi.org/10.3390/wevj15020064.
70. Abdelhadi, A. Heuristic Approach to schedule preventive maintenance operations using K-Means methodology. *Int. J. Mech. Eng. Technol.* **2017**, *8*, 300–307.
71. Riantama, R.N.; Prasanto, A.D.; Kurniati, N.; Anggrahini, D. Examining Equipment Condition Monitoring for Predictive Maintenance, A case of typical Process Industry. In Proceedings of the 5th NA International Conference on Industrial Engineering and Operations Management, Detroit, MI, USA, 10–14 August 2020.
72. Valuev, D.V.; Qi, M. Mathematical Modelling of Traction Equipment Parameters of Electric Cargo Trucks. *Mathematics* **2024**, *12*, 577. https://doi.org/10.3390/math12040577.
73. Morenov, V. Advances in Oil and Gas Production: A Viewpoint. *Energies,* **2023**, *16(3),* 1379. https://doi.org/10.3390/en16031379