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Modelling of Reliability Indicators of a Mining Plant

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Abstract: The evaluation and prediction of reliability and testability of mining machinery and equipment are crucial, as advancements in mining technology have increased the importance of ensuring the safety of both the technological process and human life. This study focuses on developing a reliability model to analyze the controllability of mining equipment. The model, which examines the reliability of a mine cargo-passenger hoist, utilizes statistical methods to assess failures and diagnostic controlled parameters. It is represented as a transition graph and is supported by a system of equations. This model enables the estimation of the reliability of equipment components and the equipment as a whole through a diagnostic system designed for monitoring and controlling mining equipment. A mathematical and logical model is proposed to calculate availability and downtime coefficients for different structures within the mining equipment system. This analysis considers the probability of failure-free operation of the lifting unit based on the structural scheme, with additional redundancy for elements with lower reliability. The availability factor of the equipment for monitoring and controlling the mine hoisting plant is studied for various placements of diagnostic systems. Additionally, a logistic concept is introduced for organizing preventive maintenance systems and reducing equipment recovery time by optimizing spare parts, integrating them into strategies aimed at enhancing the reliability of mine hoisting plants.

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

MSC: 90B25

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1. Introduction

The challenges you have highlighted regarding the increasing depth of mineral resource development, productivity of hoisting plants, and unstable loads emphasize the critical importance of enhancing the reliability and durability of mining equipment. The complexity of functioning mine hoisting plants in deep shafts and large mining enterprises underscores the need for robust and reliable systems to ensure safe and efficient operations [1,2]. The escalating loads on hoisting plants, coupled with the intensified work requirements in multi-level mining operations, contribute to higher failure rates and accelerated wear of components. Addressing these challenges requires a comprehensive approach to improving the reliability of mine hoisting plants [3,4].

By utilizing advanced modeling techniques, such as the mathematical modeling approach discussed earlier, mining companies can forecast and optimize the technical reliability of equipment components. This proactive strategy allows for the identification of potential failure points, optimization of maintenance schedules, and implementation of preventive measures to mitigate risks and enhance equipment performance [5–7]. Furthermore, investing in quality parameters for hoisting complex elements, incorporating redundancy where necessary, and implementing effective monitoring and diagnostic systems can significantly improve the overall reliability and durability of mine hoisting plants. By prioritizing reliability enhancement initiatives and leveraging innovative technologies, mining companies can minimize downtime, reduce maintenance costs, and ensure the safety and efficiency of their operations in challenging mining environments [8].

At the same time, the issues of improving the reliability and continuity in the operation of mine hoisting systems to ensure safety, regulated by rules and regulations, are put forward to the forefront. Of great importance is the problem of determining the reliability of mine hoisting plants and the development of effective ways to improve the operational reliability of the hoisting plant [9,10].

The complexity and criticality of mine hoisting plants underscore the necessity of automating technical diagnostics, function checks, and fault finding procedures to ensure plant uptime and operational efficiency. Given their status as recoverable systems, the reliability of mine hoisting plants can be significantly enhanced by reducing the time required for defect identification and elimination [11]. Adapting these systems to advanced technical diagnostics tools is essential for optimizing their performance and minimizing downtime. By implementing automated diagnostic processes, mining companies can streamline maintenance activities, enhance system reliability, and improve overall operational effectiveness. In addition to mine hoisting plants, stationary machines and installations play a pivotal role in the reliability, safety, and efficiency of mining enterprises. These systems often feature complex designs and consume a significant amount of energy, with up to 70% of total energy consumption at a mining enterprise attributed to stationary equipment. Given their importance, it is crucial for mining companies to prioritize the maintenance and optimization of stationary machines and installations. By investing in advanced monitoring technologies, predictive maintenance strategies, and energy-efficient solutions, mining enterprises can improve the reliability and performance of these critical components, ultimately enhancing the overall productivity and sustainability of their operations [12,13].

The stability of mines is largely determined by the reliable operation of underground transport and lifting systems of vertical shafts, through which minerals and rock are brought to the surface. Lifting plants are designed to deliver mined coal and rock to the surface, to quickly and safely lower and lift people, and to transport fasteners and mining equipment [14–16]. A number of the largest companies and enterprises were engaged in research of reliability and improvement and development of mine hoists: AEG, "Siemens-Schuckert" (Germany), "General Electric" (England), ASEA (Sweden), "CKD-Prague" (Czechoslovakia) and others [17].

One of the promising options for increasing durability and failure-free operation is the creation of an automated system for controlling the reliability of a mine hoist unit (MHP). The subsystem assumes diagnosable (non-disassembling) control of the main electrical and mechanical elements of the MHP, collection and primary processing of information, visualization and control of reliability indicators of the MHP [18,19].

The development of algorithms and mathematical models for assessing the reliability of mine hoisting plants is indeed a crucial aspect of ensuring their optimal performance. By leveraging the theory of random pulse flows to describe the functioning of these systems, researchers can gain valuable insights into the factors influencing reliability and identify potential areas for improvement [20,21].

The use of random pulse flows theory can help in analyzing the stochastic nature of events within mine hoisting plants, such as equipment failures, maintenance needs, and operational disruptions [22]. By modeling these random events, researchers can develop algorithms that predict system behavior, identify potential failure modes, and optimize maintenance schedules to enhance reliability [23].

Practical implementation of a diagnostic device for mine hoisting plants based on these algorithms and mathematical models can provide real-time monitoring and analysis of system performance. This device can enable operators to proactively address issues before they escalate, reduce downtime, and improve overall plant reliability. By justifying ways and means of improving the reliability of operation through the application of random pulse flows theory, researchers can contribute to the development of more robust and efficient mine hoisting plants. This approach can lead to cost savings, increased productivity, and enhanced safety in mining operations [24–26].

The outlined tasks provide a comprehensive roadmap for researching and developing a system of diagnostics and reliability management for mine hoisting plants. By addressing each task systematically, researchers can achieve the overarching goal of enhancing the reliability and controllability of these critical systems. Here is a breakdown of how each task contributes to the overall objective:

- Creation of Effective Algorithms: Developing algorithms to assess the reliability of mine hoisting installations is essential for understanding the factors influencing their performance. These algorithms can help in identifying vulnerabilities, predicting potential failures, and optimizing maintenance strategies to improve overall reliability and controllability;
- Development of Mathematical Model: Creating a mathematical model of a mine hoisting plant allows for a detailed analysis of its reliability as a complex technical system. By considering the different levels of diagnostics for plant elements, researchers can gain insights into the interdependencies within the system and identify critical components that impact overall reliability;
- Calculation of Reliability: By calculating the reliability of the mine hoisting plant based on its structural scheme, researchers can determine the probability of failure-free operation for individual elements and the plant as a whole. This quantitative analysis provides valuable information for decision-making and prioritizing maintenance efforts;
- Development of Generalized Reliability Model: Building a generalized model of reliability for mine hoisting plants involves analyzing the cause-and-effect relationships among system components. By understanding these relationships through mathematical analysis, researchers can develop effective strategies to enhance plant reliability and optimize operational performance;
- Reliability Assessment with Statistical Information: Leveraging statistical data on failures and utilizing technical diagnostics systems enable researchers to assess and manage the reliability of mine hoisting plants effectively. By incorporating real-world data into reliability assessments, operators can make informed decisions to prevent downtime, reduce costs, and ensure safe operation.

By systematically addressing these tasks, we can advance the field of mine hoisting plant diagnostics and reliability management, leading to improved performance, enhanced safety, and increased efficiency in mining operations [27].

The purpose of this work is to develop a comprehensive model for assessing the reliability of mining equipment, namely, a cargo-passenger mine hoist, using both statistical methods to analyze failures and diagnostic controlled parameters. The developed model is presented in the form of a graph of equipment state transitions and a system of equations and allows to estimate the reliability of equipment elements and the whole system on the basis of the system of diagnostics, monitoring, and control of mining equipment. The mathematical and logical model allows to determine the availability factors and downtime of various elements in the system of mining equipment, taking into account the probability of failure-free operation and structural redundancy of elements with the lowest reliability.

2. Research Methods

The research on mine hoisting plant reliability delved into theoretical concepts, employing set theory and graph theory to analyze the system's dependability [28]. Additionally, general probability theory and diverse mathematical modeling methods were utilized. The developed mathematical models were practically implemented and validated using the MATLAB 2022a software package [29].

When calculating maintainability indicators, the study assumed that they are based on representing repair and equipment maintenance as sets of individual tasks, each characterized by performance goals and probabilities determined by the equipment's durability. The investigation of a mine hoisting plant's operation was a focal point of the study [30].

The duration, labor intensity, and cost of each task were found to directly hinge on the plant's design adaptability for maintenance and repair. This is attributed to how design features impact the complexity and time required for various repair and maintenance tasks. Various factors were taken into account when determining maintainability characteristics, including personnel qualifications and diagnostic experience, equipment design complexity, availability of repair facilities, maintenance and repair strategies, and the operating conditions of the equipment [31,32]. The efficient allocation of resources such as time, labor, and cost in the repair and maintenance of a mine hoisting plant is crucial for optimizing operations, reducing costs, and enhancing productivity. Forecasting plays a key role in this process by considering the probability of each repair job and the time required to complete it. By utilizing methods such as failure trees analysis and cost allocation techniques, manufacturers can effectively plan and allocate resources for unscheduled and emergency repairs [33,34].

Several methods are commonly used for cost allocation in the repair of mining equipment, including:

1. Method of rationing: This method involves establishing time, labor, and cost standards for specific repair works, which are then used to allocate resources accordingly;
2. Regression models: Regression equations are developed to establish relationships between repair costs and various parameters such as task complexity, equipment characteristics, and other relevant factors. This method helps in predicting and optimizing repair costs based on specific variables;
3. Expert judgment method: This approach relies on the insights and expertise of experienced specialists in the field of mine hoisting plant repair to make informed calculations and decisions regarding resource allocation.

By allocating costs to individual repair tasks and identifying the most time-consuming and costly operations, manufacturers can prioritize critical areas for optimization. This targeted approach allows for efficient resource utilization, minimizes downtime, and enhances the overall operational efficiency of the mine hoisting plant. Ultimately, the effective allocation of time, labor, and cost in repairing a mine hoisting plant contributes to its smooth and safe operation, reduces downtime, and improves overall productivity in the mining industry [35,36].

This paper presents a complex mathematical model for assessing the reliability of mining equipment by analyzing reliability indicators using the developed diagnostic complex. The model focuses on studying the probability of failure-free operation of a mine hoisting plant based on a structural scheme that incorporates redundancy for the most failure-prone elements of the system [37].

Furthermore, the study includes modeling the increase in reliability while considering economic expenses for maintenance and repairs, including the procurement of spare parts and their stock. The approach involves utilizing the method of stratification of random sampling, which enables the selection of a significant number of tasks from the initial list obtained in the first stage of analysis [38,39]. By incorporating redundancy strategies and considering the economic implications of maintenance and repair activities, the model aims to enhance the overall reliability and operational efficiency of the mine hoisting plant. The utilization of advanced diagnostic tools and strategic allocation of resources can help optimize maintenance practices, minimize downtime, and improve the long-term performance of the mining equipment [40,41].

Experimental studies were conducted and techno-economic information was obtained during the operation of the Butovskaya coal mine in Kemerovo region, Russia. The coal production volume for 2023 was 2.8 million tons of coal per year. In the collection of statistics on equipment failures, 52 objects of the surface technological complex—freight and passenger mine hoists—were involved, and the length of mining capital and preparation workings amounted to 22 km. The industrial site of the mine includes an administrative and welfare complex, repair shop of mining equipment, mine water treatment facilities, an open coal storage area with a capacity of 40,000 tons, a conveyor gallery from the above-mine building to the coal storage area, etc. The mine is the first in Russia to be drilled in a ventilated ventilation system. For the first time in Russia, a 3.6 m diameter ventilation well was drilled here to discharge the outgoing air jet from the mine. The transportation system for delivery of mining equipment and miners is represented by diesel locomotives.

3. Mathematical Model of Reliability of Mining Equipment

3.1. Investigation of Reliability Indicators

A diagnostic complex based on a computer and a digital measuring device is a universal tool that can be successfully used both in production and in research laboratories. Such a measuring system has advantages in terms of processing diagnostic information: it combines fast measurements and high accuracy of calculations [42]. The possibility of computer programming makes the system flexible in terms of application of various algorithms of data processing of the mine hoist system [43].

The developed measuring unit was applied for the purposes of technical diagnostics by measuring parameters in control points. In the test points, it is necessary to have sensors of measured quantities and converters that convert these quantities into voltage. The magnitude of this voltage must correspond to the range measured by the analog-to-digital converter [44,45]. The working version of the electronic block was used for diagnostics of the control system of the mine hoisting plant [46].

The development of a measurement system consists of the following steps:

(a) Development of the electronic unit. The electronic unit interfaces with an IBM PC type computer and shall:

- at the command of the controlling computer, convert voltage in the range from −2.5 to +2.5 V at the input into 12-bit binary code at the output, by eight or more channels;
- store the measurement result in the buffer RAM;
- transfer the measurement results to the controlling computer.

(b) Development of a program package. The program package consists of:

- a firmware to control the operation of the electronic unit;
- subroutines for organizing communication between the control computer and the measuring unit.

The system is a hardware and software complex based on an IBM PC type computer. As a non-standard peripheral device, a unit (hereinafter referred to as a measuring electronic unit) shall be connected to the computer, which converts input measured parameters into a digital code, stores and transmits it to the computer. To the measuring block, in turn, the sources of measuring information are connected. These can be electronic circuits, sensors or other sources, the information at the output of which is a voltage varying in magnitude. The block diagram of the whole system is shown in Figure 1.

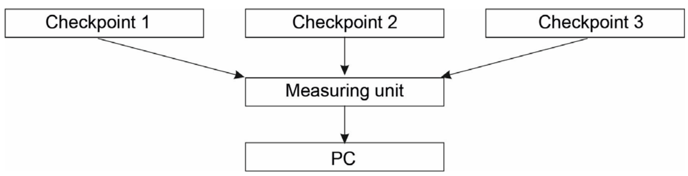

Figure 1. Generalized block diagram of the measuring system of the diagnostic complex.

One of the main advantages of this structure is that the measuring electronic unit can be located near the control panel, far enough away from the operator console, i.e., from the main PC. This is the most efficient solution, as the interaction with sensors is improved by reducing the length of signal wires.

In addition, with this solution, one computer is sufficient to monitor a large number of control points. Several variants can be used to connect peripheral devices to an IBM PC AT type computer [47]. Let's consider their advantages and disadvantages.

To interface the measuring unit with a computer, the option using a serial data transfer port was chosen. The decisive factors were: ease of installation, programming, and connection [48]. The serial data transmission interface is called RS-232. The RS-232-C interface was developed by the Electronic Industries Association as a standard for connecting computers and serial peripherals. The computer does not fully support the RS-232-C interface: the connector labelled on the computer case as a serial data port contains some of the RS-232-C interface signals with voltage levels that conform to this standard [49].

Serial data transmission means that data is transmitted over a single line. In this case, the data bits are transmitted one by one using a single wire. For synchronization, a group of data bits is usually preceded by a special start bit, followed by a parity check bit and one or two stop bits. Sometimes the parity check bit may not be present [50].

The parity bit has a value such that the total number of ones (or zeros) in the bit packet is even or odd, depending on the setting of the port registers. The bit is used to detect errors that occur during data transmission due to line noise [51]. The receiving device recalculates the parity of the data and compares the result with the received parity bit. If there is a parity mismatch, the data is considered to have been transmitted with an error. Of course, this algorithm does not provide a full guarantee of error detection. For example, if an even number of bits is changed during data transmission, the parity is preserved and no error will be detected [52,53].

The diagnostic equipment of the Butovskaya mine is connected to the dispatch center via serial port. The serial port is connected to external devices through a special connector. There are two standards of RS-232-C interface connectors—DB25 and DB9. When transmitting data over long distances without specialized equipment, errors may occur due to interference caused by electromagnetic fields. This leads to a limitation on the length of the connection cable. The official length limit of the RS-232-C connection cable is 15.24 m. However, in practice, this distance can be much longer [54]. As it has been determined, it directly depends on the baud rate. The values given in Table 1 were determined experimentally.

Table 1. Dependence of the maximum length of the connection cable on the baud rate.

Baud Rate, Baud	Maximum Length of Shielded Cable, m	Maximum Length of Unshielded Cable, m
100	1524	914.4
300	1524	914.4
1200	914.4	914.4
2400	304.8	152.4
4800	304.8	76.2
9600	76.2	76.2

Connecting cables were used to connect the measuring diagnostic unit based on a single-chip microcomputer (Figure 2) for collecting diagnostic information of the mining plant equipment to the computer. The connecting cables were an important element of the systems for collecting diagnostic information from the mining plant. They provided reliable data transmission between the measuring diagnostic unit and the equipment, which made it possible to promptly obtain information on the status and parameters of the plant operation. The longest cables were used to connect the diagnostic system to the computer, and shorter cables were used to connect the diagnostic units (Figure 2) to each other.

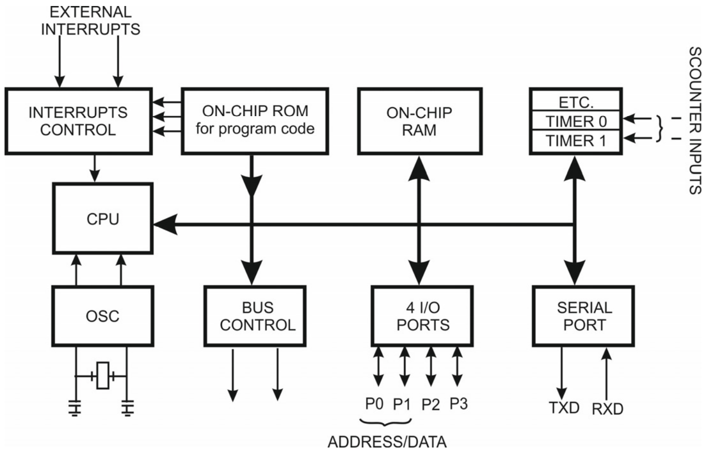

Figure 2. Structural diagram of the measuring unit. The measuring unit is based on a single-chip Intel 8051 microcomputer controlled by the firmware stored in the ROM chip.

The voltage levels on the connector lines are −15–−3 V for logic zero and 3–15 V for logic one. The interval from −3 to +3 V corresponds to an undefined value. It is this high voltage, compared to the TTL level of 5 V, that gives increased noise immunity over longer distances [55]. If data transmission over long distances is required, the RS485 interface can be used. To use it, an adapter from RS232 to RS485 is used. The latter has greater noise immunity and allows data transmission over distances greater than 1000 m. Interfaces RS232 and RS485 differ in physical implementation and are fully compatible in terms of logical protocol. Another advantage of RS485 is that it can be implemented as a fully isolated twisted pair cable [56].

The measuring unit performs the following functions:

- converts the input voltage (from −2.5 to +2.5 V) into a 12-bit binary code at the command of the controlling computer;
- saves the received code in the buffer RAM with the capacity of 2048 bytes;
- transmits the measurement result to the controlling computer;
- supports RS-232-C serial data transmission interface for interaction with the controlling computer.

In order to improve the performance of the measurement unit and expand the scope of its application, it is necessary for the unit to perform the following additional functions:

- make a series (1024) of measurements at small (hundreds of microseconds) fixed time intervals;
- have as many analog inputs as possible to connect measurement data sources and switch them by signal from the controlling computer;
- each analog input must be equipped with an amplifier with adjustable gain.

According to the described requirements, a measuring unit was developed, the structural diagram of which is shown in Figure 2.

However, the processing of an interrupt (i.e., reception of conversion data from the ADC) takes place only when the interrupt is enabled. This interrupt is enabled only after the measuring unit has received a command to start measurement from the controlling computer [57].

The results of this work were used in the development of the diagnostic system of the «ZK4500» mine hoisting rig designed for operation in the mode of a cargo-laden hoisting rig.

Figure 3 shows a block diagram of the diagnostic system designed for monitoring and control in the form of a graph. The vertices of the graph are the individual functional devices and the branches indicate the connections between them. In this block diagram the following designations of blocks and devices of the system are introduced:

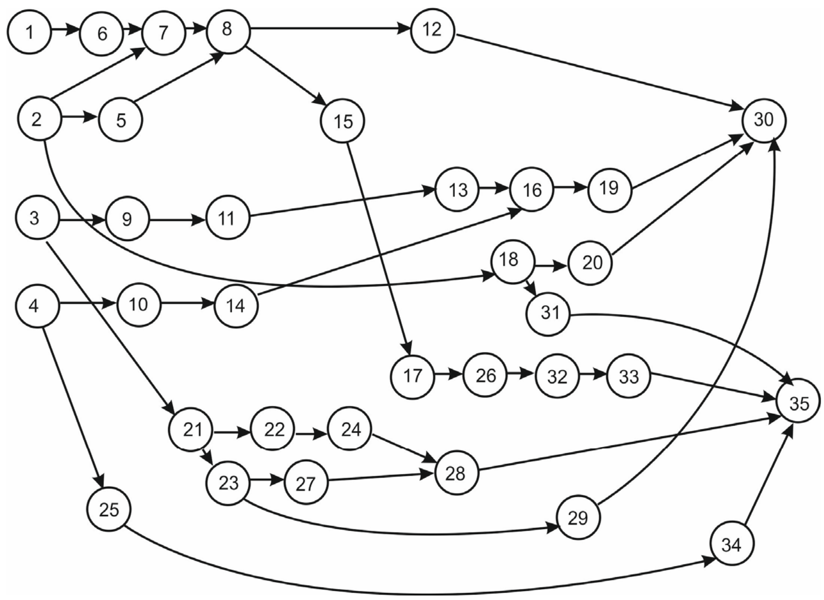

Figure 3. Graph of the mine hoisting machine monitoring and control installation.

1, 2, 3, 4—four groups of sensors installed in the control cabinet;
5, 6, 9, 10—normalization blocks matching signal levels for sensor groups;
7—components of the logical information processing device;
8—relay multifunctional cell designed for realization of logic functions from input variables;
12, 17—cells of time delays formation;
14—control unit of the ULOI power supply source;
13, 21, 26—memory cells, intended for storing values of logical variables;
16, 25—diode cells for performing logic functions;
19—components of the output relay block, actuator control;
18—high level signal switch;
20—indirect measurement unit (determination of brake system pressure);
22—device A511;
23—device A501;
24, 33—components of the digital measurement unit;
27—time block;
28—block of numeric-letter registration;
29—indication of the lifting vessel location;
30—information presentation unit;
31—time block;
32—block of logical control stages;
34—program setting board (voltage shaper according to a certain law);
35—event registration unit.

Table 2 shows the verification matrix for the given graph. Table 2 contains 5 columns with defect diagnostics by the following parameters: 1—current strength, 2—voltage value, 3—current frequency, 4—temperature, 5—ambient air humidity.

Table 2. Verification matrix showing the act of diagnosing an equipment element (1–35) according to the corresponding diagnostic parameter (1—current strength, 2—voltage value, 3—current frequency, 4—temperature, 5—ambient air humidity).

	1	**2**	**3**	**4**	**5**
35					+
34					

Table 2. *Cont.*

	1	2	3	4	5
33					+
32					+
31					
30	+	+		+	
29			+		
28					
27					
26					+
25		+			
24					
23		+			
22					
21			+		
20		+			
19				+	
18		+			
17					+
16			+	+	
15					
14				+	
13					
12	+	+			
11			+		
10				+	
9			+	+	
8	+	+			
7	+	+		+	
6	+				
5		+			
4				+	
3			+		
2		+			
1	+				

By selecting the matching columns of the inspection matrix corresponding to equivalent defects of a certain multiplicity, it is possible to calculate the diagnostic depth:

$$F = 1/35(1{\cdot}6 + 2{\cdot}10 + 3{\cdot}6 + 4{\cdot}8 + 5{\cdot}5) = 2.88$$

This calculated value of the diagnostic depth can be used in further calculations of reliability parameters as the initial diagnostic depth FQ. If the maximum of the coefficient is at $F > F_Q$, the number of test points can be reduced, if at $F < F_Q$, the number of test points should be increased.

Readiness factors were calculated for all four SR placement structures [58]. The calculations showed that the variant with the highest reliability for a given system is the one with the sensors and switches of the diagnostic system in the technical system. It's shown in Figure 4 (K_g15). In this case, the microprocessor unit acts as a switch that switches signals from sensors and transmits them to the PC for processing [59]. For this variant, the dependence of the readiness factor on the diagnostic depth is presented in Figure 4. From the analysis of this dependence, we can conclude that the maximum value of the readiness factor is achieved at $F < F_0$ ($F_0 = 2.88$); thus, it is necessary to increase the number of control points. The best result can be achieved by placing additional control points (Figure 3) between blocks 21, 22, 24 and 26, 32, 33. This solves the problems with defect equivalence [60].

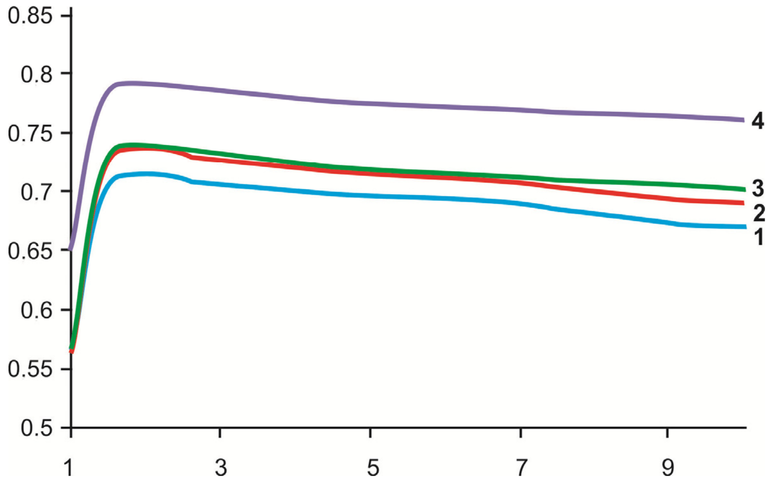

Figure 4. Dependence of the availability factor for monitoring and control of the mine hoisting plant for different ways of diagnostics systems placement: 1—Kg9(F); 2—Kg15(F); 3—Kg12(F); 4—Kg6(F).

Next in terms of availability factor is the inbuilt diagnostics system. This variant can be realized using the proposed microprocessor unit. In this case, it is necessary to supplement it with a logic processing function and an indication function [61,62].

3.2. Modelling the Probability of Failure-Free Operation of a Mine Hoisting Plant

The mine hoisting plant (MHP) is represented by 15 main assemblies and subsystems, the reliability of which is assessed in operation. Among them 1—apparatus for controlling the stroke and protection of the mine hoisting unit; 2—controller of the control panel of the mine hoisting unit; 3—control panel of the mine hoisting plant; 4—encoder unit; 5—electric power wiring; 6—mine shaft signaling; 7—cabinet of auxiliary drives; 8—cabinet of sensors and power supply units; 9—hoist cage; 10—stabilized power supply; 11—voltage stabilizer for 380 V; 12—brake panel; 13—DC drive; 14—electric motor drive control system; 15—mechanical brake of the hoist.

The structural reliability diagram of the mine hoisting plant is shown in Figure 5.

When creating the model of probability of failure-free operation of the mine hoisting plant according to the structural scheme (Figure 5), the main and very important numerical parameter of equipment reliability was used, namely the failure rate, which is the ratio of the number of failed objects (samples of equipment, products, parts, mechanisms, devices, units, etc.) per unit of time to the average number of objects working properly in a given period of time, provided that the failed objects are not restored and not replaced by serviceable ones.

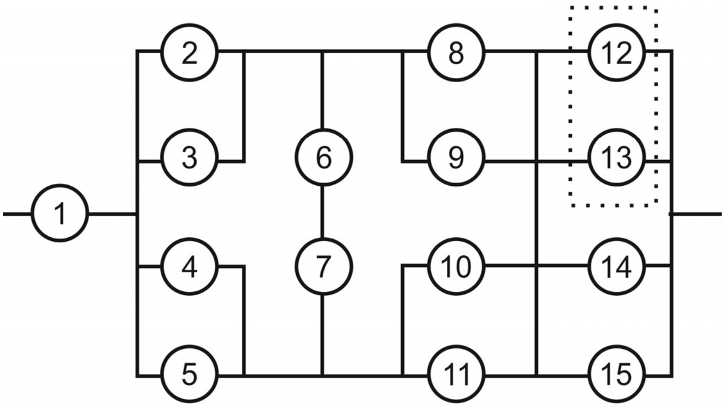

Figure 5. Initial scheme of the mine hoisting plant (MHP) system.

Thus, the failure rate is numerically equal to the number of failures per unit of time attributed to the number of nodes that have worked without failure up to that time. The dimensionality of failure rate is the inverse of time, usually measured in 1/hour. Failure rate is able to determine the reliability of subsystems, units, and individual parts of the equipment as a function of time and allows you to visually establish characteristic areas of the system, where reliability decreases.

Failure rate indicators were obtained during the collection of statistical information on failures of the mining plant for 2022–2023 for each of the 15 elements presented in Figure 5. Element failure rates are given in 10^{-6} 1/h.

$\lambda_1 = 0.001$; $\lambda_2 = \lambda_3 = \lambda_4 = \lambda_5 = 0.1$; $\lambda_6 = \lambda_7 = 0.01$; $\lambda_8 = \lambda_9 = \lambda_{10} = \lambda_{11} = 0.2$; $\lambda_{12} = \lambda_{13} = \lambda_{14} = \lambda_{15} = 0.5$; $\gamma = 50\%$.

In the original circuit, elements 2 and 3 form a parallel connection.

We replace them by a quasielement A. Given that $p_2 = p_3$, we obtain

$$p_A = 1 - q_2 q_3 = 1 - q_2^2 = 1 - (1 - p_2)^2.$$

Elements 4 and 5 also form a parallel connection, replacing it by element B and considering that $p_4 = p_5 = p_2$, we obtain

$$p_B = 1 - q_4 q_5 = 1 - q_2^2 = p_A$$

Elements 6 and 7 in the original circuit are connected in series. We replace them with element C, for which at

$$p_C = p_6 p_7 = p_6^2$$

Elements 8 and 9 form a parallel connection. We replace them by element D, for which at $p_8 = p_9$, we obtain

$$p_D = 1 - q_8 q_9 = 1 - q_8^2 = 1 - (1 - p_8)^2.$$

Elements 10 and 11 with parallel connection are replaced by element E, and since $p_{10} = p_{11} = p_8$, then

$$p_E = 1 - q_{10} q_{11} = 1 - q_{10}^2 = 1 - (1 - p_{10})^2 = p_D.$$

Elements 12, 13, 14, and 15 form a "2 out of 4" connection, which we replace by element F. Since $p_{12} = p_{13} = p_{14} = p_{15}$, we can use the combinatorial method [63] to determine the probability of failure-free operation of the element F:

$$p_F = \sum_{k=2}^{4} p_k = \sum_{k=2}^{4} C_4^k p_{12}^k (1 - p_{12})^{4-k} = \frac{4!}{2!2!} p_{12}^2 (1 - p_{12})^2 + \frac{4!}{3!1!} p_{12}^3 (1 - p_{12}) + \frac{4!}{4!0!} p_{12}^4 =$$
$$6p_{12}^2 (1 - p_{12})^2 + 4p_{12}^3 (1 - p_{12}) + p^4 = 6p_{12}^2 - 8p_{12}^3 + 3p_{12}^4.$$

The transformed circuit is shown in Figure 6.

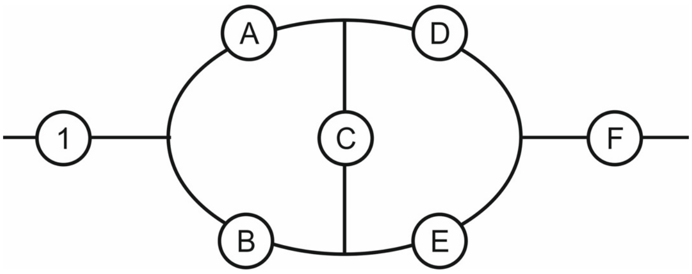

Figure 6. Transformed scheme.

Elements A, B, C, D and E form (Figure 6) a bridging system, which can be replaced by a quasi-element G. To calculate the probability of failure-free operation, we use the method of decomposition with respect to a special element, as which we choose element C [64].

$$p_G = p_C p_G(p_C = 1) + q_C p_G(p_C = 0),$$

where P_G (P_C = 1) is the probability of failure-free operation of the bridging circuit when element C is absolutely reliable (Figure 7a); P_G (P_C = 0) is the probability of failure-free operation of the bridging circuit when element C fails (Figure 7b).

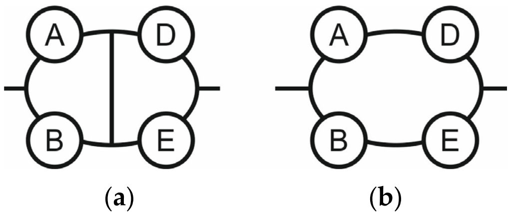

Figure 7. Transformations of the bridge circuit: (**a**)—with absolutely reliable element C, (**b**)—failed element C.

Taking into account that $P_B = P_A$, we obtain

$$\begin{aligned} P_G &= p_C[1-(1-p_A)(1-p_B)]\cdot[1-(1-p_D)(1-p_E)] \\ &\quad +(1-p_C)[1-(1-p_Ap_B)(1-p_Dp_E)] \\ &= p_C\left[1-(1-p_A)^2\right]\cdot\left[1-(1-p_D)^2\right]+(1-p_C)\left[1-(1-p_A^2)(1-p_D^2)\right] \\ &= p_C(2p_A-p_A^2)(2p_D-p_D^2)+(1-p_C)(p_A^2+p_D^2-p_A^2p_D^2) \\ &= p_Ap_Cp_{D(}(2-p_A)(2-p_D)+(1-p_C)(p_A^2+p_D^2-p_A^2p_D^2). \end{aligned}$$

In the converted circuit, elements 1, G and F form a series connection.
Then the probability of failure-free operation of the whole system

$$P = p_1 p_G p_F.$$

Since by convention all elements of the system operate in the period of normal operation, the probability of failure-free operation of elements 1 to 15 (Figure 5) obey the exponential law:

$$p_i = \exp(-\lambda_i t).$$

The results of calculations of probabilities of failure-free operation of elements 1–15 of the initial scheme for operating time up to 3×10^6 h are presented in Table 3.

Table 3. Calculation of probability of failure-free operation of the shaft hoist system.

Element	λ_i, 10^{-6} h^{-1}	Operating Time t, 10^6 h							
		0.5	1.0	1.5	2.0	2.5	3.0	1.9	2.85
1	0.001	0.9995	0.9990	0.9985	0.9980	0.9975	0.9970	0.9981	0.9972
2–5	0.1	0.9512	0.9048	0.8607	0.8187	0.7788	0.7408	0.8270	0.7520
6, 7	0.01	0.9950	0.9900	0.9851	0.9802	0.9753	0.9704	0.9812	0.9719
8–11	0.2	0.9048	0.8187	0.7408	0.6703	0.6065	0.5488	0.6839	0.5655
12–15	0.5	0.7788	0.6065	0.4724	0.3679	0.3865	0.2231	0.3867	0.2405
A, B	-	0.9986	0.9911	0.9822	0.9995	0.9612	0.9412	0.9815	0.9402
C	-	0.9896	0.9912	0.9801	0.9805	0.9688	0.9511	0.9704	0.9458
D, E	-	0.9899	0.9589	0.9304	0.8724	0.8512	0.8001	0.8992	0.8987
F	-	0.9701	0.8304	0.7501	0.4801	0.3314	0.3112	0.4006	0.2259
G	-	0.9931	0.9906	0.9912	0.9995	0.9802	0.9604	0.9906	0.9324
P	-	0.9602	0.8213	0.6352	0.4607	0.3172	0.2233	0.5112	0.2697
$12'$–$15'$	0.322	0.8602	0.7162	0.6169	0.5368	0.5501	0.4102	0.5566	0.4005
F'	-	0.9909	0.9304	0.8397	0.7325	0.6112	0.5004	0.7288	0.4999
P'	-	0.9832	0.9204	0.8270	0.7112	0.6001	0.4514	0.7488	0.5172
16–18	0.5	0.7788	0.6065	0.4724	0.3679	0.2865	0.2231	0.3867	0.2405
F''	-	0.9993	0.9828	0.9173	0.7954	0.6423	0.4858	0.8233	0.5311
P''	-	0.9912	0.9708	0.9034	0.7795	0.6226	0.4641	0.8079	0.5081

The results of calculating the failure probabilities of quasi-elements A, B, C, D, E, F and G are also presented in Table 3.

From the graph (Figure 8, P curve) we find for γ = 50% ($P\gamma$ = 0.5) γ—percent system runtime $T = 1.9 \times 10^6$ h.

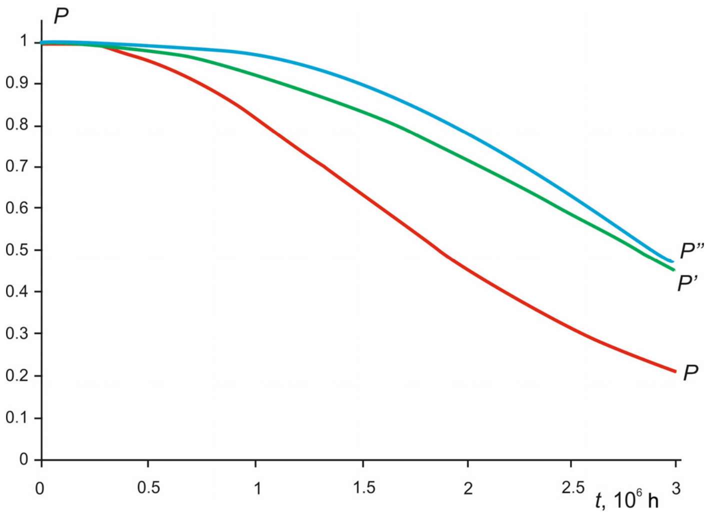

Figure 8. Variation of probability of failure-free operation of a mine hoisting unit: P—probability of failure-free operation of the initial scheme; P'—probability of failure-free operation of the scheme with increasing reliability of individual elements; P''—probability of failure-free operation of the scheme with application of structural redundancy.

A verification calculation at $t = 1.9 \times 10^6$ h shows (Table 3) that $P\gamma = 0.4923 \approx 0.5$.

Under the terms of the job, the increased γ—percentage system operating time $T'\gamma = 1.5 \times T\gamma = 1.5 \times 1.9 \times 10^6 = 2.85 \times 10^6$ h

The calculation shows (Table 3) that at $t = 2.85 \times 10^6$ h for the elements of the transformed scheme $p_1 = 0.9972$, $p_G = 0.9594$ and $p_F = 0.2458$. Consequently, of the three elements connected in series, the minimum value of probability of failure-free operation has element F (system "2 out of 4" in the original scheme (Figure 5)) and it is the increase in its reliability will give the maximum increase in the reliability of the system as a whole.

In order that at $T'\gamma$ = 2.85 × 10^6 h the system as a whole has a probability of failure-free operation of $P\gamma$ = 0.5, it is necessary that element F has a probability of

$$p_F = \frac{p_\gamma}{p_1 p_G} = \frac{0.5}{0.9972 \cdot 0.9594} = 0.5256.$$

At this value, element F will remain the most unreliable element in the circuit.

Obviously, the obtained value p_F is the minimum value for fulfilment of the condition of increase of operating time not less than 1.5 times; at higher values, p_F the increase in system reliability will be greater.

To determine the minimum required probability of failure-free operation of elements 12–15 (Figure 4), it is necessary to solve the equation with respect to p_{12} at p_F = 0.5226. However, since the analytical expression of this equation is associated with certain difficulties, it is more appropriate to use the graph-analytical method. For this purpose, using the data in Table 3, we plot the graph of the relationship $p_F = f(p_{12})$. The graph is presented in Figure 9.

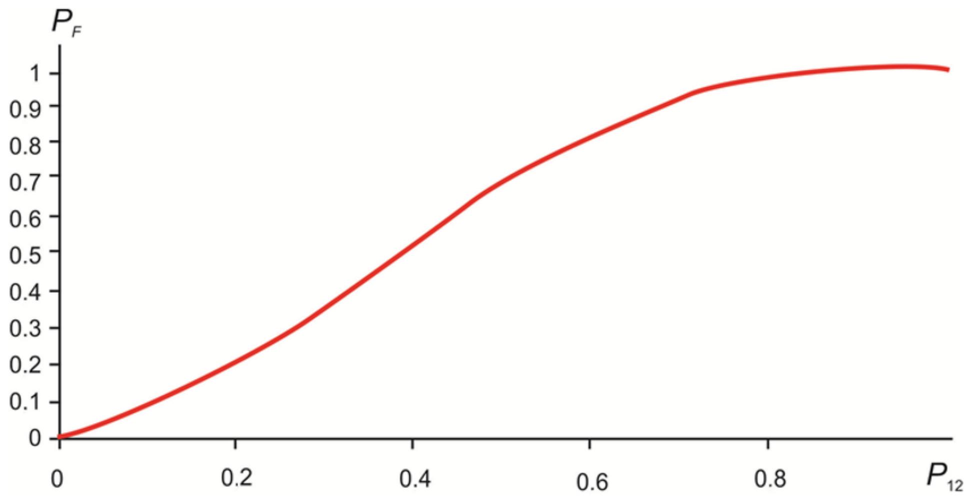

Figure 9. Dependence of the probability of failure-free operation of the "2 out of 4" system on the probability of failure-free operation of its elements.

From the graph when p_F = 0.5226, we find $p_{12} \approx 0.4$.

Since, under the conditions of the task, all elements operate in the period of normal operation and obey the exponential law, then for elements 12–15 at t = 2.85 × 10^6, we find

$$\lambda'_{12} = \lambda'_{13} = \lambda'_{14} = \lambda'_{15} = -\frac{\ln p_{12}}{t} - \frac{\ln 0.4}{2.85 \cdot 10^6} = 0.322 \cdot 10^6 \ \text{h}^{-1}.$$

Thus, to increase γ—the percent system lifetime, it is necessary to increase the reliability of elements 12, 13, 14 and 15 and reduce their failure rate from 0.5 to 0.322 × 10^{-6} h^{-1}, i.e., by a factor of 1.55.

The results of calculations for the system with increased reliability of elements 12, 13, 14 and 15 are given in Table 3. The calculated values of probability of failure-free operation of the "2 out of 4" F' system and the system as a whole P' are also given there. At t = 2.85 × 10^6 h, the probability of failure-free operation of the system P' = 0.5011 ≈ 0.5.

For the second method of increasing the probability of failure-free operation of the system—structural redundancy—by the same considerations we also choose the element F, the probability of failure-free operation of which after redundancy should be not lower than p_F'' = 0.5226.

For element F—the "2 out of 4" system—redundancy means an increase in the total number of elements. It is impossible to determine analytically the minimum required number of elements because the number of elements must be integer and the function $p_F = f(n)$ is discrete [65].

To increase the reliability of the "2 in 4" system, we add to it elements identical in reliability to the original elements 12–15 until the probability of failure-free operation of the quasi-element F reaches a given value.

For the calculation we will use the combinatorial method:

- add element 16, we get the "2 out of 5" system:

$$\begin{aligned} q_F = \sum_{k=0}^{1} C_5^k p_{12}^k (1-p_{12})^{5-k} &= C_6^0 (1-p_{12})^5 + C_5^1 p_{12} (1-p_{12})^4 \\ &= (1-p_{12})^5 + 5p_{12}(1-p_{12})^4 = 0.6528, \\ p_F &= 1 - q_F = 0.3472 < 0.5226; \end{aligned}$$

- add element 17, we get the "2 out of 6" system:

$$\begin{aligned} q_F = \sum_{k=0}^{1} C_6^k p_{12}^k (1-p_{12})^{6-k} &= C_6^0 (1-p_{12})^6 + C_6^1 p_{12} (1-p_{12})^5 \\ &= (1-p_{12})^6 + 6p_{12}(1-p_{12})^5 = 0.5566, \\ p_F &= 1 - q_F = 0.4434 < 0.5226; \end{aligned}$$

- add element 18, we get the "2 out of 7" system:

$$\begin{aligned} q_F = \sum_{k=0}^{1} C_7^k p_{12}^k (1-p_{12})^{7-k} &+ C_7^0 (1-p_{12})^7 + C_7^1 p_{12} (1-p_{12})^6 \\ &= (1-p_{12})^7 + 7p_{12}(1-p_{12})^6 = 0.4689, \\ p_F &= 1 - q_F = 0.5311 > 0.5226; \end{aligned}$$

Thus, to improve reliability to the required level, it is necessary to complete the "2 of 4" system in the original scheme (Figure 4) with elements 16, 17, and 18 to the "2 of 7" system (Figure 10).

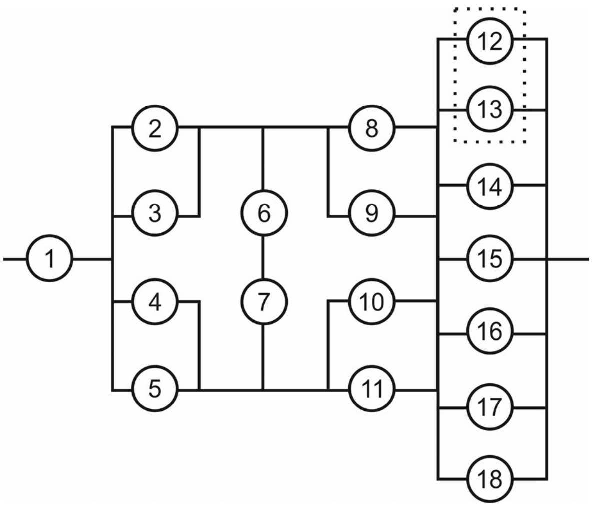

Figure 10. Structural diagram of the system after structural redundancy.

The results of calculating the probabilities of failure-free operation of the "2 in 7" system F'' and the system as a whole P'' are presented in Table 3.

Figure 8 shows the curves of dependence of the system uptime probability after reliability improvement of elements 12–15 (curve P') and after structural redundancy (curve P'').

The following conclusions can be drawn.

1. Figure 8 shows the dependence of the probability of failure-free operation of the system (curve P). The graph shows that 50%—operating time of the original system is 1.9×10^6 h.
2. To increase the reliability and increase the 50%—running time of the system by 1.5 times (up to 2.85×10^6 h), two methods are proposed:
   (a) Improved reliability of elements 12, 13, 14 and 15 and reduction in their failures from 0.5 to 0.322×10^{-6} h^{-1};
   (b) loaded redundancy of main elements 12, 13, 14 and 15 with identical redundant elements 16, 17 and 18 (Figure 11).
3. The analysis of the dependences of the probability of failure-free operation of the system on time (operating time) shows that the second way of increasing the reliability of the system (structural redundancy) is preferable to the first one because, in the period of operating time up to 2.85×10^6 h, the probability of failure-free operation of the system at structural redundancy (curve P'') is higher than at increasing the reliability of elements (curve P'').

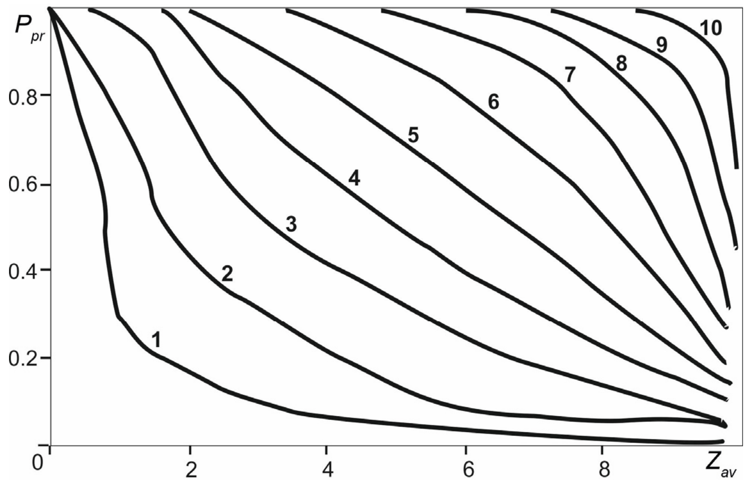

Figure 11. Graph of dependence of the guaranteed probability of ensuring the stock of lifting elements on the parameter z_{av} at different values of N_{spe}. The numbers above curves 1,2,....10 denote the values of the parameter N_{spe} used to plot these curves.

3.3. Improving the Reliability of Lifting Systems

Increasing the reliability of the mine hoisting plant is possible due to the implementation of a number of technological measures [66,67]. To maintain the necessary level of constant readiness of the lifting unit for use by the reliability factor, a set of requirements and measures must be fulfilled, the main of which are compliance with the operating instructions and organization of a rational system, maintenance, and repair of lifting units [68,69]. The main result of compliance with the operating instructions should be the avoidance of incorrect actions of operators, which can lead to failures, called "faults", and the selection and observance of operating modes of the hoist system that exclude the possibility of significant or long-lasting overloads of the system components [70,71].

Maintenance and repair of the hoisting plant is a system of measures for technical care, maintenance and restoration of the plant's serviceability [72]. Properly organized maintenance and repair allow: increasing the reliability of plant operation and preventing rapid wear of elements; preparing for repair works in time and carrying them out qualitatively in due time; ensuring productive and safe operation of machinery; reducing operating costs by reducing the number of emergency failures and losses due to their occurrence [73]. The essence of preventive maintenance consists in the planned performance, in accordance with the structure of the repair cycle, of the established types of maintenance and scheduled repairs, the volumes of which are determined by the actual technical condition of assemblies and equipment as a whole [74,75].

Scheduled current repairs include: monthly repair maintenance performed by repair electricians of the mine's power and mechanical service, equipment operators, production process workers, and specialized teams of repair electricians; the first and second current repairs T_1 and T_2, with a frequency of 3 and 6 months, respectively, are performed by the same forces as the repair maintenance, as well as by specialized repair adjusting and installation enterprises of production associations and production companies.

Repairs T_1 and T_2 are the main types of current repairs. If there are elements with service life exceeding 6 months but less than the periodicity of major repairs, the manufacturer of the equipment can assign additional types of current repairs with the periodicity of 9, 12, . . . months. Execution of additional types of current repairs is carried out by the same forces as the main types of repairs. For complex equipment of lifting installations, scheduled current repairs are assigned, combined with the revision, adjustment, and adjustment of parts and assemblies of equipment: quarterly, semi-annual, annual, and biennial. Scheduled current repairs should be carried out by specialized adjustment and installation departments [76].

Scheduled overhaul is performed by specialized repair companies at intervals established by regulatory and technical documentation. The duration of all types of scheduled maintenance and repair is established by industry repair standards. Volumes of maintenance and repair for specific operating conditions of cleaning and tunnelling equipment systems are developed by the power engineering service of associations and mines on the basis of instructions for maintenance, equipment adjustment manuals, and other regulatory documents, which provide the composition of the necessary work and the technology of their performance [77,78].

Factory instructions when assigning the frequency of maintenance and repairs operate with average data on the durability of assemblies and parts and cannot take into account the conditions and modes of operation of the mine hoisting plant in each specific case. Therefore, in practice, "basic" replacement of elements is still widespread enough, i.e., replacement of elements after their failures. The new element, replacing the failed one, works again until it fails.

If the first element had a mean time between failures (MTBF—it's a technical parameter characterizing the reliability of the technical system being restored) t_1, the second element had a MTBF t_2, and the last element had a MTBF t_n, the total MTBF will be equal to the sum of the MTBFs.

Total costs of unscheduled repairs

$$(t_p) = nc_0,$$

where n is the number of failures for working time t_p; c_0 is the average cost of element replacement after failure, including losses due to equipment downtime.

Specific costs $c_{sp.u}$ for unscheduled repairs are as follows

$$c_{sp.u} = \frac{nc_0}{t_p} = \frac{nc_0}{\sum_{i=1}^{n} t_i} = \frac{c_0}{T_1},$$

where T_1 is the average operating time of the element before failure, h.

Basic replacement of elements can be justified only in case of sudden-type failures and a large value of depressed operating time of elements before failure [79].

Regulated replacement consists in obligatory replacement of all elements of the given type at intervals of time, which have been recently delivered to replace the failed ones. This method is convenient for replacement of elements whose failures are gradual, as well as when it is difficult for the service personnel to keep records of the time until failure of each element out of many elements available in the equipment (hydraulic valves, etc., elements).

The main task is to find such a period of group replacement of similar elements for which the losses due to the need to eliminate emergency failures of elements with actual resources or service life $t_{av} < t$, as well as due to underutilization of the resource of elements for which $t_{av} > t$, will be minimal.

The total costs of possible replacements of elements after failures occur and for regulated replacements at the operating time equal to t are determined from the expression

$$c(t) = m(t)c_0 N + c_p N,$$

where c_0 and c_p are the average costs of unscheduled and regulated replacement of one element, respectively; $m(t)$ is the mathematical expectation of the number of failures of an element installed at the same place (recovery function); N is the number of similar elements.

Specific costs c_{sp} per unit of operating time

$$c_{sp} = \frac{m(t)}{t} c_0 N + \frac{c_p}{t} N.$$

To find the replacement interval according to this formula, it is necessary to set the value of the cost parameters c_p and c_0, and the value of the mathematical expectation of the number of failures $m(t)$ during the various possible intervals t; take the value t, at which $c_{sp} = \min$.

The optimum value t_i should be less than the average operating time of the element before failure. In this case, for engineering calculations, it can be assumed that the mathematical expectation of the number of failures $m(t)$ for the period (0; t) is numerically equal to the probability of element failure $q(t)$ for the same period. Costs of planned (regulated) replacement of an element

$$c_p = \frac{s_{\mathrm{n.e}} + n_r s_r}{n_r + 1} + c_{\mathrm{repl.ex}} + c_{\mathrm{trans.ex}} + c_{\mathrm{und.ex}},$$

where $s_{\mathrm{n.e}}$—cost of a new element; n_r—average number of possible restorations of the element when carrying out regulated replacements with the period t; s_r—average cost of element restoration; $c_{\mathrm{repl.ex}}$—average cost of works on element replacement according to the plan, including the cost of delivery within the mine; $c_{\mathrm{trans.ex}}$—average cost of transport expenses on delivery to the repair plant and back; $c_{\mathrm{und.ex}}$—value of losses from underutilization of fixed assets for the period of regulated replacement.

Individual replacement consists in the fact that an element cannot be replaced if its operating time is less than t, and it is serviceable. But at the same time, if there is a failure of an element at the operating time $t < t_{\mathrm{i}}$, then a new period of scheduled replacement t_{i} is assigned after the elimination of the failure. At this method of replacement it is necessary to keep record of the "age" of each element.

Customized replacement is preferred when replacing expensive machine components.

In the aggregate method of repair, individual component parts or equipment assemblies containing worn parts are replaced with new or pre-repaired parts. Component parts and assemblies containing worn parts are replaced with new or pre-repaired parts. Dismantled parts and assemblies containing worn parts are to be reconditioned, usually by repair facilities. This method ensures high quality of repair.

Costs for individual replacement

$$c = q(t)c_0 + p(t)c_p,$$

where c_0, c_p—average costs of unscheduled (in case of failure) and scheduled replacement of the element, respectively; $q(t)$, $p(t)$—probability of failure and failure-free operation of the element, respectively.

Unit costs

$$c_{un} = \frac{q(t)c_0 + p(t)c_p}{t_{av}},$$

where t_{av} is the average operating time of the element before its scheduled repair.

3.4. Optimizations of Time to Eliminate Failures

The elimination of failures of various structural elements of the lifting unit—a process that cannot be combined with the operation of mechanization means—always causes the need for unscheduled (emergency) repairs during working shifts, and, consequently, leads to a reduction in the time allotted for the lifting unit to perform its main functions.

Reduction in time costs for elimination of failures of the lifting unit is closely related to the possibilities of correct assessment of the technical condition of the elements of the unit and its assemblies, as well as to the development of methods for establishing the optimal frequency of current repairs of equipment [80].

Precise performance of regulated works on daily and daily maintenance allows to prevent or significantly reduce the number of such unauthorized failures (leaks in hydraulic systems of braking devices, burning of contacts of electric starting equipment, etc.).

To correctly determine the technical condition of the lifting unit requires a wide introduction of technical diagnostic tools and diagnostic methods at mining enterprises.

Technical diagnostics in the process of operation of the lifting unit allows, on the basis of determining their technical condition, to reduce downtime due to correctly set resources of elements, assemblies and their timely replacement; to reasonably establish the types and volume of repairs; to fully utilize the inter-repair resources of machines; to reduce the consumption of spare parts; to properly plan the work of repair services; and to improve the system of preventive maintenance [67].

The technical condition of lifting units, their assemblies and elements is characterized by a number of parameters. Diagnostic parameters include: power, temperature, pressure, noise and vibration, insulation resistance of electric motor windings and other factors.

To determine the replacement period of an element that has failed due to wear, such as brake pads, the element failure probability function for a highly agitated wear process can be used:

$$P(u) = 0.5 + \phi(z),$$

where $\phi(z)$—Laplace function (probability integral) $\phi(z) = \frac{1}{\sqrt{2\pi}}\int_0^x e^{-\frac{z^2}{2}}dz$; $z = \frac{\omega-\delta_0-m_\varsigma t}{v_v\sqrt{m_\varsigma(\omega-\delta_0)}}$; δ_0—initial value of the measured parameter; ω—critical value of the measured parameter, when reaching which the element should be replaced; m_ς and v_v—mathematical expectation and coefficient of variation of the wear rate, respectively.

Setting the value of probability of failure-free operation of the element P_u (t), it is possible to find the operating time of the element before replacement by the factor of the onset of its ultimate wear.

As an example of calculation, we set the value P_u $(t) > 0.95$. From the formula we obtain

$$\phi(z) = P_u\ (t)–0.5–0.95–0.5 = 0.45,$$

Let us find that $\phi(z) = 0.45$ at $z = 1.645$. Then at known values of ω, δ_0 and m_ς we obtain

$$t_{\rm r} = \frac{\omega - \delta_0 - 1.645 v_v \sqrt{m_\zeta(\omega - \delta_0)}}{m_\zeta}.$$

The coefficient of variation of the wear rate can be taken $v_v = 0.2–0.3$.

3.5. Modelling the Optimal Number of Spare Parts

Lifting systems are reusable systems that must fulfil a given function over a long period of time or operating time t (e.g., overhaul period). During this time, a random number p may occur in the system due to the unreliability of its individual components [79].

The flow of occurring failures of lifting installations can be considered as the simplest, the average number of failures of a set N of similar elements is defined as follows

$$n_{\text{av}} = \frac{Nt}{T_1},$$

where t is the considered period of operation; T_1 is the time until failure of the considered type of elements.

A failed element is usually not repaired, but replaced by a new one, removed from the stock. Therefore, the number of used up elements z during the time or runtime t will be equal to the number of failures occurring during the same time or runtime (excluding secondary failures). Under these conditions, the probability P_z (t) that exactly z spare elements will be needed to eliminate failures during the operating time t can be determined by the Poisson formula

$$P_z(t) = \frac{(Nt)^z}{T_1^z z!} e^{-\frac{Nt}{T_1}},$$

where z = 0, 1, 2, . . ., i, . . ., ∞.

The average number of spare elements z_{av}, consumed during the inter-repair period t_{irep}, is equal to the average number of failures n_{av}, i.e., according to the above expression

$$z_{\text{av}} = \frac{Nt_{\text{irep}}}{T_1}.$$

Due to the randomness of failures, a greater or lesser number of spare elements than z_{av} may be required. If the stock of elements N_{spe}, equal to the average expected consumption z_{av}, i.e., if the stock factor $K_{spe} = N_{spe}/z_{\text{av}} = 1$, the need for spare elements will be satisfied with a guaranteed probability of 0.5, which is clearly insufficient. Therefore, it is necessary to calculate the number of spare elements with a given guaranteed probability P_{pr} of their availability [81].

The graph of dependence of the stock factor of elements of the lifting unit on the average number of their failures z_{av} for the overhaul period is presented in Figure 12. Curve 1—probability of providing the reserve P_{pr} = 0.95; curve 2—probability of providing the reserve P_{pr} = 0.9.

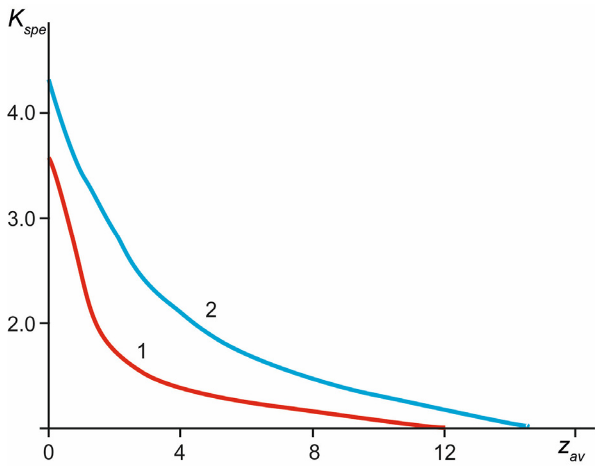

Figure 12. Graph of dependence of the stock factor of the lifting unit elements on the average number of their failures z_{av} for the overhaul period. Curve 1—probability of providing the reserve P_{pr} = 0.95; curve 2—probability of providing the reserve P_{pr} = 0.9.

The probability that no more than N_{spe} spare elements will be required during the overhaul interval t_{irep} can be found from the expression

$$P_{N_{spe}}(t_{\text{irep}}) = e^{-\dfrac{Nt_{\text{irep}}}{T_1}} \sum_{z=0}^{N_{\text{spe}}} \frac{(N_{\text{irep}})^z}{T_1^z z!}.$$

Thus, the developed model of the diagnostics system allows to fully use the information about the current resource of the equipment along with statistical data on its failures.

4. Discussion

The proposed algorithms and methods of increasing the reliability of technical systems with diagnostics allow to increase the operational reliability by 10–15%. The model for calculating the probability of failure-free operation of a lifting unit according to the structural scheme with the subsequent structural redundancy of elements having the lowest reliability is proposed, which allows not only to estimate the reliability of the system, but also to compare the reliability of similar systems among themselves. The concept to improve the reliability of the mine hoisting plant is presented, which consists in the organization of the system of preventive maintenance and reducing the recovery time due to the availability of necessary spare parts.

It can be said that the results of the study can be applied to a wide range of applications covering mining equipment reliability, energy and mining practice, and suggest that the developed reliability model can be adapted for use in other industries. The study involved modeling and reliability assessment of MHP (mining equipment) performance, leading to the determination of optimal parameter values. The development of the reliability model was driven by the integration of a transition graph with a system of equations, enabling the assessment of MHP reliability through a diagnostic system. The authors explored the impact of various parameters on the MHP system, such as troubleshooting time, failure rate, and monitoring intensity of the diagnosis system, revealing causal relationships between MHP elements. This model facilitated the determination of the maximum availability factor and the depth of possible diagnostics for this equipment availability factor. Furthermore, they developed a methodology for equipment reliability assessment using MHP as an example, aiming to reduce the probability of equipment failure and enhance overall operational reliability.

The authors also proposed a mathematical logic model for analyzing the controllability of mining equipment, considering resource and diagnostic parameters, which aligns with established reliability models. They concluded that the testability of equipment is a crucial property that influences its adaptability to control and technical diagnostics. They suggested that solving diagnostic tasks efficiently depends on the testability of an object, emphasizing the need to minimize costs associated with control and technical diagnostics. They put forward an approach to fostering testability in diagnostic objects during the design stage, emphasizing the establishment of interconnectivity and relationships to construct an effective model of the diagnostic object.

5. Conclusions

The authors emphasize the exceptional importance of assessing and predicting the reliability and controllability of mining machinery and equipment to ensure the safety and wellbeing of people working in the mining industry. The paper presents a comprehensive model for assessing the reliability of mining equipment, in particular, a mine hoist of the cargo-passenger type, using statistical methods of failure analysis and diagnostics of controllable parameters. The developed model, represented as a graph of transitions and supported by a system of equations, allows to estimate the reliability of equipment elements and the whole system on the basis of a diagnostic system designed to monitor and control mining equipment. A mathematical and logical model for calculating availability factors and downtime of various structures in the mining equipment system is proposed, taking into account the probability of failure-free operation and structural redundancy of elements with the lowest reliability. It is the elements and units with the lowest reliability that reduce the reliability of the system as a whole to the greatest extent. Additionally, for the first time, the influence of different variants of diagnostics system placement on the availability factor of mining equipment was considered, and the probability of failure-free operation based on structural redundancy strategies is modeled. The presented concept of organization of preventive maintenance systems and spare parts optimization to reduce the time of equipment recovery, allows to reduce the operating costs of equipment repair due to the optimal balance of stored spare parts in the warehouse by 10%. The practical significance of the work lies in the proposed parameter determining the depth of diagnosis, which can be used to find not only the failed subsystem, unit or assembly, but also a separate failed part of the equipment, which significantly reduces the cost of repair of mining equipment.

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References

1. Dhillon, B.S. *Mining Equipment Reliability, Maintainability, and Safety*; Springer: London, UK, 2008.
2. Carlo, F.D. *Reliability and Maintainability in Operations Management*; Massimiliano, S., Ed.; InTech: London, UK, 2013.
3. 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. [CrossRef]
4. 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. [CrossRef]
5. Troy, D. The Importance of Efficient Mining Equipment. Available online: https://industrytoday.com/importance-efficient-mining-equipment/ (accessed on 12 February 2023).
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. [CrossRef]
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-to-predictive-maintenance-for-the-smart-mine/ (accessed on 16 April 2020).
12. Sellathamby, C.; Moore, B.; Slupsky, S. Increased Productivity by Condition-Based Maintenance Using Wireless Strain Measurement System. In Proceedings of the Canadian Institute of Mining (CIM) MEMO Conference, Sudbury, ON, Canada, 24–27 October 2010.
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. [CrossRef]
14. Koteleva, N.; Korolev, N. A Diagnostic Curve for Online Fault Detection in AC Drives. *Energies* **2024**, *17*, 1234. [CrossRef]
15. Vasilyeva, N.; Golyshevskaia, U.; Sniatkova, A. Modeling and Improving the Efficiency of Crushing Equipment. *Symmetry* **2023**, *15*, 1343. [CrossRef]
16. Zakharchenko, A.I.; Leusenko, Y.A. A comprehensive approach to solution of the problem of improving the quality of mine equipment. *Ugol'Ukr (Ukr. SSR)* **1980**, *7*, 16–17.
17. Viray, F.L. *Coal Mine Productivity Assessment as Influenced by Equipment Reliability and Availability*; ProQuest Dissertations Publishing: Ann Arbor, MI, USA, 1982; p. 338.

18. 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. [CrossRef]
19. Zhukovskiy, Y.; Buldysko, A.; Revin, I. Induction Motor Bearing Fault Diagnosis Based on Singular Value Decomposition of the Stator Current. *Energies* **2023**, *16*, 3303. [CrossRef]
20. Stanek, E.; Venkata, S. Mine power system reliability. *IEEE Trans. Ind. Appl.* **1988**, *24*, 827–838. [CrossRef]
21. 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.
22. 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. [CrossRef]
23. 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. [CrossRef]
24. Abdollahpour, P.; Tabatabaee Moradi, S.S.; Leusheva, E.; Morenov, V. A Numerical Study on the Application of Stress Cage Technology. *Energies* **2022**, *15*, 5439. [CrossRef]
25. Coetzee, J.L. The role of NHPP models in the practical analysis of maintenance failure data. *Reliab. Eng. Syst. Saf.* **1997**, *56*, 161–168. [CrossRef]
26. 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. [CrossRef]
27. 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 the 2023 5th International Conference on Control in Technical Systems CTS 2023, Saint Petersburg, Russia, 26–28 September 2023; pp. 79–82. [CrossRef]
28. 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, REEPE 2023, Moscow, Russia, 16–18 March 2023. [CrossRef]
29. 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. [CrossRef]
30. Ascher, H.; Feingold, H. *Repairable Systems Reliability: Modeling, Inference, Misconceptions and Their Causes*; Marcel Dekker, Inc.: New York, NY, USA, 1984.
31. 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. [CrossRef]
32. Rahimdel, M.J.; Ghodrati, B. Reliability analysis of the compressed air supplying system in underground mines. *Sci. Rep.* **2023**, *13*, 6836. [CrossRef]
33. Efremenkov, E.A.; Qi, M. Mathematical Modeling the Performance of an Electric Vehicle Considering Various Driving Cycles. *Mathematics* **2023**, *11*, 2586. [CrossRef]
34. 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. [CrossRef] [PubMed]
35. 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.
36. 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.
37. 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. [CrossRef]
38. Ruijters, E.; Stoelinga, M. Fault Tree Analysis: A survey of the state-of-the-art in modelling, analysis and tools. *Comput. Sci. Rev.* **2015**, *15–16*, 29–62. [CrossRef]
39. Yong, B.; Qiang, B. *Subsea Engineering Handbook*; Gulf Professional Publishing: Oxford, UK, 2018.
40. Singh, R. *Pipeline Integrity Handbook*; Gulf Professional Publishing: Oxford, UK, 2017.
41. 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. [CrossRef]
42. Kang, J.; Sun, L.; Soares, C.G. Fault Tree Analysis of floating offshore wind turbines. *Renew. Energy* **2019**, *133*, 1455–1467. [CrossRef]
43. Tuncay, D.; Nuray, D. Reliability analysis of a dragline using fault tree analysis. *Bilimsel Madencilik Derg.* **2017**, *56*, 55–64. [CrossRef]
44. 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.
45. 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.
46. 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. [CrossRef]
47. 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. [CrossRef]

48. 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 BinaryDecision Diagrams for Explosive Vehicle. *Math. Probl. Eng.* **2021**, *2021*, 5559475. [CrossRef]
49. Kabir, S. An overview of fault tree analysis and its application in model based dependability analysis. *Expert Syst. Appl.* **2017**, *77*, 114–135. [CrossRef]
50. 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. [CrossRef]
51. Malozyomov, B.V.; Martyushev, N.V.; Voitovich, E.V.; Kononenko, R.V.; Konyukhov, V.Y.; Tynchenko, V.; Kukartsev, V.A.; Tynchenko, Y.A. Designing the Optimal Configuration of a Small Power System for Autonomous Power Supply of Weather Station Equipment. *Energies* **2023**, *16*, 5046. [CrossRef]
52. 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. [CrossRef]
53. 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. [CrossRef]
54. 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. [CrossRef]
55. 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. [CrossRef]
56. 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.
57. 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. [CrossRef]
58. 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).
59. 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. [CrossRef]
60. 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. [CrossRef]
61. 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. [CrossRef]
62. 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**, *SP2*, 255–258.
63. 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. [CrossRef]
64. 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. [CrossRef]
65. 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. [CrossRef]
66. 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. [CrossRef]
67. 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. [CrossRef]
68. Yi, X.J.; Chen, Y.F.; Hou, P. Fault diagnosis of rolling element bearing using Naïve Bayes classifier. *Vibroeng. Procedia* **2017**, *14*, 64–69. [CrossRef]
69. Lu, Y. Decision tree methods: Applications for classification and prediction. *Shanghai Arch. Psychiatry* **2015**, *27*, 130.
70. Rokach, L.; Maimon, O. *Data Mining with Decision Trees*, 2nd ed.; World Scientific Publishing Co. Pte. Ltd.: Singapore, 2015.
71. 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.
72. 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.
73. 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.
74. 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. [CrossRef]
75. 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. [CrossRef]
76. 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. [CrossRef]

77. 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. [CrossRef]
78. Abdelhadi, A. Heuristic Approach to schedule preventive maintenance operations using K-Means methodology. *Int. J. Mech. Eng. Technol.* **2017**, *8*, 300–307.
79. 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.
80. Valuev, D.V.; Qi, M. Mathematical Modelling of Traction Equipment Parameters of Electric Cargo Trucks. *Mathematics* **2024**, *12*, 577. [CrossRef]
81. Pryalukhin, A.F.; Filina, O.A.; Konyukhov, V.Y.; Makarov, A.A. Improvement of Operational Reliability of Units and Elements of Dump Trucks Taking into Account the Least Reliable Elements of the System. *World Electr. Veh. J.* **2024**, *15*, 365. [CrossRef]