Optimal Planning of the Mobile Cargo Ropeway Repair Strategy

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Optimal planning of the mobile cargo ropeway repair strategy

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Abstract. The focus of this research is to increase the reliability of mobile cargo ropeways formed by autonomous self-propelled transport units. The article deals with the development of a method for forming an effective technical and economic strategy for the restoration during planned repairs of those structural elements of transport units that can lead to critical failures of the ropeway. The method involves predicting the kinetics of the probability of failure-free operation of the ropeway during the entire life of its operation on the basis of predicting the failure-free operation of key elements of the transport units, the failure of which leads to an emergency disruption of the ropeway. In the process of integrating the system of Chapman-Kolmogorov differential equations, its periodic reformation is performed at the time of planned repairs, which allows us to take into account the need for a discrete change in the probability of failure-free operation of the restored structural elements. As a criterion for the optimality of the repairs strategy, the condition for obtaining the minimum total cost of repairs is used, while ensuring the average probability of failure-free operation. The formation of such an optimal strategy includes planning the schedules, number, time points, volume and cost of restoration work. The effectiveness of the repair strategy is determined by the total number of planned repairs and the minimum permissible probability of critical failure of structural elements. Conditions have been established under which further improvement of the level of ropeway reliability becomes an economically unprofitable task.

Key words: Mobile ropeway, Failure kinetics, Repair strategy, Cost of repairs, Optimization

Declarations

Availability of data and material

The datasets used and analysed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Alexander V. Lagerev. The first draft of the manuscript was written by Igor A. Lagerev and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript. Funding for the research was received by Igor A. Lagerev.

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Ethics approval

All the authors of this article approve of the ethical principles of scientific publications adopted in the journal.

Consent to participate

All authors confirm that they have given their consent to be included in the number of authors of this article

Consent for publication

All authors confirm that they have given their consent to the publication of this article

1. Introduction

1.1. Background

Currently, overground rope transport systems in the form of stationary aerial or towed ropeways of various structural designs are widely used for organizing the transportation of passengers and goods [1, 2].

Mobile ropeways formed on the basis of self-propelled wheeled or tracked chassis are a promising direction for the development of fast-mounted transport and reloading equipment for difficult operating conditions [3, 4]. The high mobility and autonomy of moving to the location of the ropeway, which are characteristic of this type of cargo rope transport systems, is due to their placement on special self-propelled multi-axle chassis of high load capacity and cross-country ability of wheeled and tracked multi-purpose vehicles [4]. The scope of effective application of mobile rope systems is quite wide and diverse. It is advisable to use them when performing construction and mounting work at autonomous remote facilities, eliminating the consequences of natural or man-made emergencies [4], mining and extractive industries [5, 6], performing forestry work in mountainous or hard-to-reach areas [7, 8], performing loading and unloading operations [9], etc.

The stationary ropeways currently in operation have high operational characteristics, including reliability, safety and maintainability indicators [10, 11]. This is due to the fact that aerial ropeways are technical devices of increased danger and therefore a wide range of equipment maintenance works is performed during their operation. The necessity and timing of specific works are based on the proactive prediction of the occurrence of critical failures of potentially dangerous structural elements of ropeway equipment using appropriate reliability models (for example, by analyzing failure trees [12] or simulation models [13]) or by the results of continuous monitoring of the current functional state of potentially dangerous structural elements (for example, by direct measurement of characteristic diagnostic parameters using various physical phenomena [14, 15] or approaches based on fuzzy logic [16]). As a rule, there is a specialized repair infrastructure near stationary ropeways with qualified personnel, the necessary technological equipment and the volume of spare parts. This circumstance greatly facilitates the restoration work even in case of sudden emergency stops of ropeways and ensures high efficiency of maintenance.

On the contrary, mobile ropeways are intended for preferential operation in places that are significantly remote from the location of the profile repair infrastructure. This objectively complicates the necessary maintenance of equipment in unprepared field conditions. The quality of maintenance is reduced in comparison with carrying out repairs by specialized operational and repair services in stationary conditions [17]. Obviously, an effective strategy for carrying out repair and restoration works of mobile ropeways during the entire service life is an expedient way out of this situation. The formation of such a strategy is an urgent engineering task that has a technical and economic character [3].

1.2. Setting a research task

The experience of operation of transport and reloading equipment of various types shows that despite the planned repairs, during operation, accidental failures of individual structural elements are observed, leading to the impossibility of further operation of the equipment as a whole [18].

In relation to the studied mobile ropeways, such failures should be considered as critical failures, and such structural elements - as key structural elements that determine the accident-free operation of the ropeway. The failure of these elements requires their immediate unplanned repair or replacement. Unplanned repairs during the operation of a mobile ropeway is a costly event both due to the need to carry out repairs away from the stationary repair infrastructure, and due to a sudden interruption in carrying out transport and reloading operations and a lack of time (for example, during emergency rescue operations). Critical failures of random structural elements of a mobile ropeway are random events, and the time moments of their occurrence are random variables with corresponding distribution laws [19].

Earlier, in the studies of the authors [20], it was shown that an effective approach to maintaining the working condition of a ropeway in the event of a possible accidental occurrence of critical failures is the proactive replacement of key structural elements at the time of planned repairs of a mobile ropeway. The criterion for the need to restore or replace the m-th key element at the time of i-th repair $\tau_{r,i}$ is the achievement of the minimum permissible value by the probability of failure of this structural element $P_m(\tau_{r,i})$:

$$P_m(\tau_{r,i}) \geq [P_m], \tag{1}$$

where $[P_m]$, the minimum permissible value of the probability of a critical failure of the m-th key element.

The values $[P_m]$ are individual for each structural element. Their large values should correspond to the most responsible and expensive elements. Critical failure of such elements can lead to greater damage both due to increased duration and due to increased repair costs. Setting high values $[P_m]$ will lead to the need for more frequent repairs of structural elements and, thus, to increased labor and material and financial costs. However, the amount of technical risk for a mobile ropeway will be low. Otherwise, when assigning lower values $[P_m]$, the cost of repair work will decrease, but the amount of technical risk will increase. Thus, a reasonable assignment of marginal probabilities $[P_m]$ is an important technical task and requires an assessment based on technical and economic optimization.

Within the framework of this study, a method of technical and economic optimal planning at the design stage of mobile ropeways of schedules, the number, volume and cost of planned repair and restoration operations has been developed.

2. Technical objects under study

2.1. Construction and operation of a mobile ropeway

The general view of the studied mobile cable car of the pendulum type is shown in Fig. 1. It consists of two terminal self-propelled transport units 1 (*A* and *B*) installed at the end points of the cable car route [4]. As self-propelled chassis of transport units, multi-axle wheeled chassis are used for high-cross-country and load-carrying tractors. Such wheeled tractors, which have the necessary technical characteristics for placing the technological equipment of mobile ropeways, are produced by a number of automobile companies in Russia, Belarus, Germany, the USA, China, Sweden, etc. [21, 22]. Rope pulleys 3 with traction and tension mechanisms are installed on the heads of the end supports 2. When operating a ropeway, only one of these mechanisms works, and the other is disabled. Thus, one of the transport units provides the movement of the carrying-traction rope 4 with the transported cargo 5 fixed on it by means of a suspension, and the second unit provides the necessary tension of the carrying-traction rope.

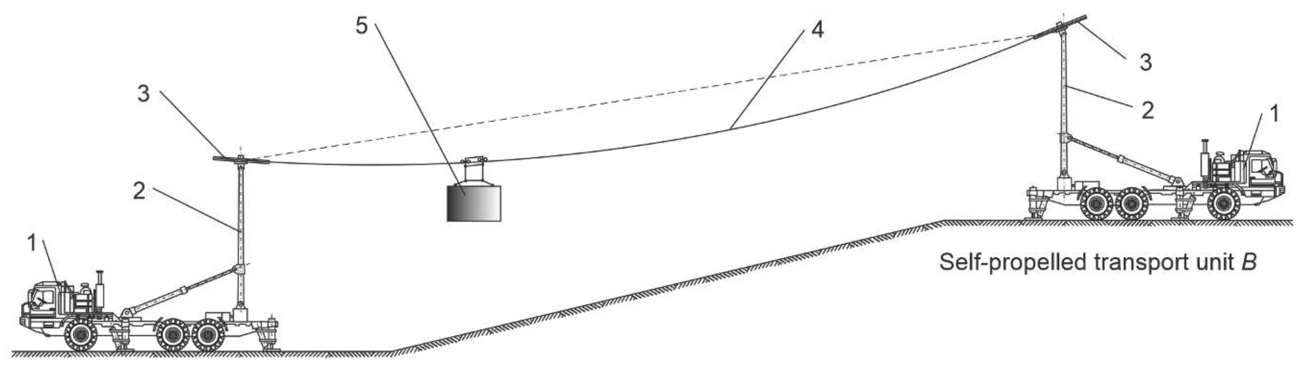

Fig. 1 Mobile ropeway formed by two terminal self-propelled transport units: *A*, *B* – self-propelled transport units, 1 – transport unit, 2 – end tower, 3 – rope pulley, 4 – carrying-traction rope, 5 – cargo

2.2. Construction and operation of a self-propelled transport unit

The design of the transport unit under study, intended for the formation of a mobile cargo ropeway, is shown in Fig. 2. It is protected by the patent RU 200827 [23] and corresponds to a structural modification of the unit with the location of the end tower in the terminal part of the load-bearing frame. Directly on the load-bearing frame 2 of the wheeled chassis 1, the components and elements of the hydraulic mechanism of installing and fixing of the end tower in the working position are mounted. It includes an end tower 3, a lifting hydraulic cylinder 4 and an external braking device to protect the tower from self-overturning when it is lifted into the working position. The end tower is a supporting structure for the hydraulic carrying-traction rope movement mechanism 7, including the rope pulley 5. The end tower and the lifting hydraulic cylinder are kinematically connected to each other and the load-bearing frame by cylindrical hinges *A*, *B* and *C*.

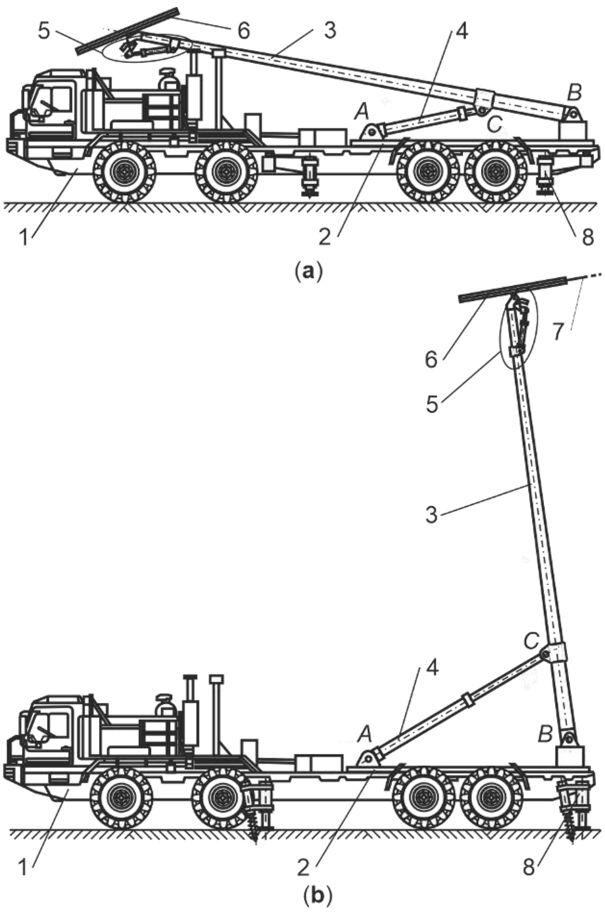

Fig. 2 Self-propelled transport unit: **a** transport position **b** working position (1 – wheel chassis; 2 – load-bearing frame; 3 – end tower; 4 – lifting hydraulic cylinder; 5 – rope pulley; 6 – rope pulley orientation mechanism; 7 – carrying-traction rope; 8 – anchor outrigger)

The transport unit moves independently to the place of deployment of the mobile ropeway, and the end tower is in the transport position (Fig. 2a). At the location, each unit is oriented in such a way that its longitudinal axis coincides with the longitudinal axis of the ropeway. To ensure overall stability under the conditions of significant horizontal overturning loads from the tension force of the carrying-traction rope and the transported cargo, the wheeled chassis is installed on outriggers 8. They are fixed to the ground with the help of additional anchoring devices. When the rod of the lifting hydraulic cylinder is extended, the end tower rotates in a vertical plane relative to the cylindrical hinge *B* and occupies the required working position (Fig. 2b). To coordinate the mutual inclination of the rope pulleys of the conjugate transport units, which is caused by the natural sagging of the carrying-traction rope and the location of the units at different heights [24], a hydraulic rope pulley orientation mechanism is used.

2.3. *Structure and reliability analysis of the technological equipment*

The general structural diagram of the mobile ropeway is shown in Fig. 3. It includes structural diagrams of mechanisms and systems of the main technological equipment of self-propelled transport units (the pumping station, the mechanism of installing and fixing of the end tower in the working position, the carrying-traction rope movement mechanism, rope pulley orientation mechanism, the control system), as well as a single rope system.

In Fig. 3 structural elements of the general scheme of the mobile ropeway have the following designations:

- the pumping station (P – hydraulic pump; DV1 – gate directional control valve; GV – gate valve; CV1, CV2 – check valves; SV – pressure safety valve; HR – hydraulic reservoir; F – filter; AF – air intake filter; FD – filling device);
- the carrying-traction rope movement mechanism, including the rope system (HM – hydraulic motor; DV2 – directional control valve; PV1 – pilot operated check valve for fixing the rope pulley; TV1, TV2 – throttle valves; C1, C2, C3 – couplings; B – brake; SR – speed reducer; B1 – axial radial spherical roller bearing; B2 – radial spherical ball bearing; RP – rope pulley; BR – carrying-traction rope; LF – load handling fixture; RC – rope end connector);
- the mechanism of installing and fixing of the end tower in the working position (HC1 – lifting hydraulic cylinder; PV2 – pilot operated check valve; DV3 – directional control valve; TV3 –throttle valve);
- the rope pulley orientation mechanism (HC2 – hydraulic cylinder for the rope pulley orientation; DV4 – directional control valve; TV4 – throttle valve);
- the control system (M – microprocessor; CP – control panel for rope system operation; IP – information panel on the current state of the rope system; DiS – end tower angle transmitter; DS1 – pump volumetric flow transmitter; DS2 – hydraulic motor volumetric flow transmitter; LI – hydraulic reservoir liquid level transmitter; LS1 – limit switch for the lowest position of the tower; LS2 – limit switch for the upper end position of the tower; LS3 – limit switch for the lowest position of the rope pulley; LS4 – limit switch for the upper end position of the rope pulley; PS1 – pump outlet pressure transmitter; PS2, PS3 – pressure transmitters in the hydraulic lines of the hydraulic motor; PS4, PS5 – pressure transmitter at the inlet of the hydraulic cylinder; RS1 – rotational velocity transmitter of the pump shaft; RS2 – rotational velocity transmitter of the hydraulic motor shaft; RS3 – rotational velocity transmitter of the rope pulley; TeS – hydraulic reservoir fluid temperature transmitter; TiS – transmitter for counting the time of the carrying-traction rope movement; TS1 – tension transmitter of the carrying-traction rope; TS2 – weight transmitter of transported cargo; VE1 – gate directional control valve solenoid; VE2, VE3, VE4 – directional control valve solenoids).

Obviously, not all of the listed structural elements are the key elements that lead to a critical failure and shutdown of the mobile ropeway. In general, they include elements such as P, HM, HC1, HC2, HR, SV, F, DV1 - DV4, PV1, PV2, RP, SR, B, C1 – C3, B1, B2, BR, LF, RC, M, CP, IP, VE1 – VE4, RS1, RS3, TS1, TS2, TiS. Additionally, among the key structural elements, a part of the responsible metal and flexible pipelines of the hydraulic system and the transmission shafts of the carrying-traction rope movement mechanism should be considered. With a good level of maintainability of the control system, the control system sensors (RS1, RS3, TS1, TS2, TiS) can be excluded from the number of key elements due to the low labor intensity of their replacement during operation.

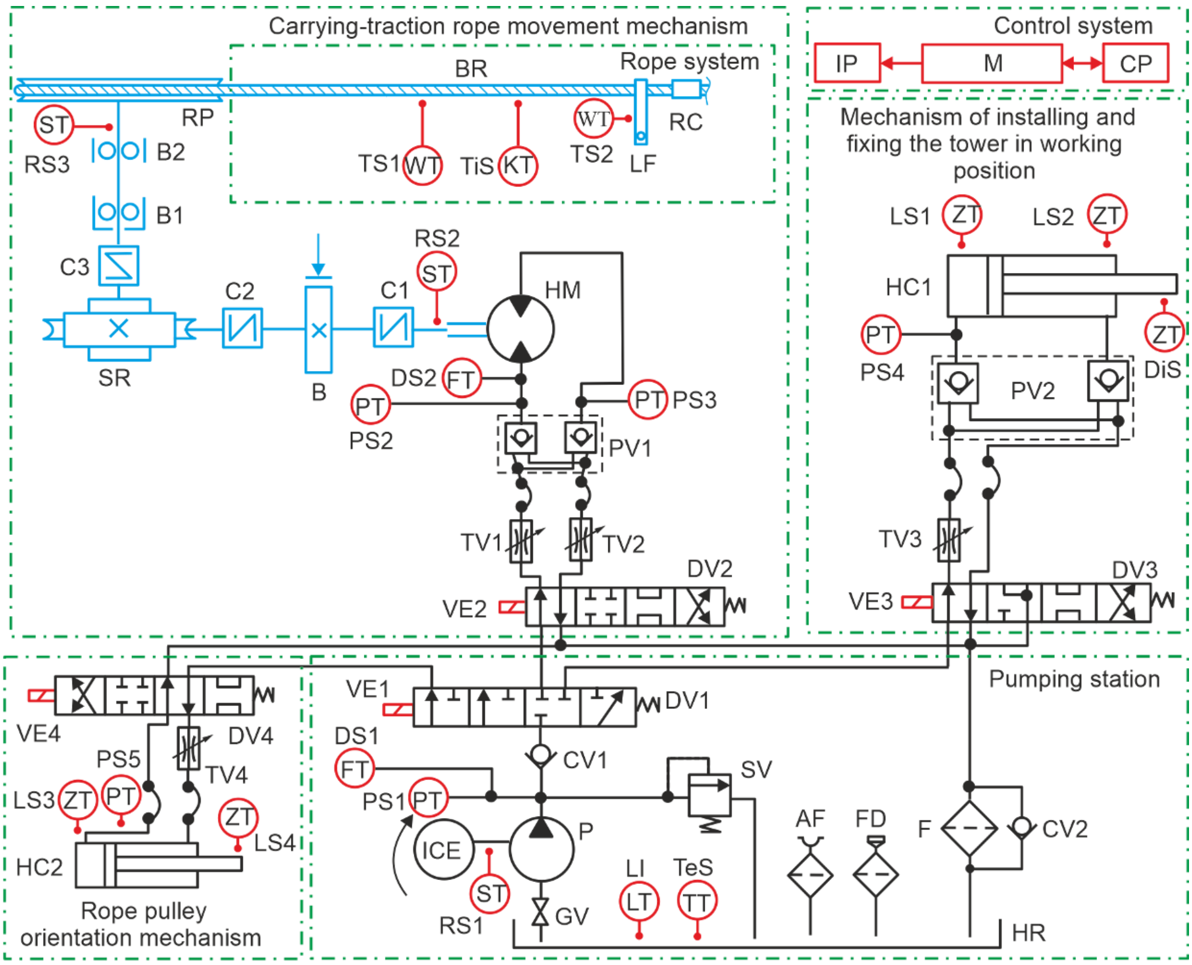

Fig. 3 General scheme of the mobile cargo ropeway

3. Mathematical models

As a basis for the development of a mathematical model for the formation of an optimal schedule of planned repairs of a mobile cargo ropeway, ensuring optimization (minimization) of the cost of its operation, it is advisable to use the method of probabilistic forecasting of the reliability kinetics of lifting and transport equipment [17, 20]. It is based on the use of the Chapman-Kolmogorov equation [19].

3.1. A model for probability predicting the kinetics of failure-free operation

When predicting the kinetics of the probability of accidence-free operation of a mobile ropeway, it should be taken into account that at any time of operation it can be in one of the following possible states:

- in one operable state S_0 (it is characterized by finding all the key structural elements in operable state and therefore it determines the normal accident-free operation of the ropeway);

- in one of several inoperable states $S_1, S_2, \ldots, S_m, \ldots, S_N$ (each state is characterized by finding one corresponding m-th key element in an inoperable state with the operable state of all other N-1 elements, and therefore it determines the occurrence of an emergency mode of the ropeway operation).

Fig. 4 shows the corresponding graph of possible states and their connecting transitions during the operation of a mobile ropeway. A quantitative measure of the transition of a ropeway from an operable state S_0 to an inoperable state S_m caused by the failure of the m-th structural element is the failure rate of this element λ_m. A quantitative measure of the reverse transition from an inoperable state S_m to an operable state S_0 caused by the restoration or replacement of the m-th structural element is the restoration rate of this element μ_m.

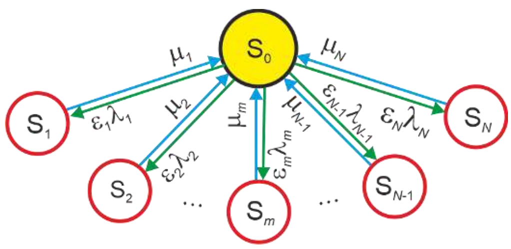

Fig. 4 Graph of possible states and transitions for a mobile ropeway

The probabilities $P_0, P_1, \ldots, P_m, \ldots, P_N$ of finding a mobile ropeway at an arbitrary time of operation τ in all possible states $S_0, S_1, \ldots, S_m, \ldots, S_N$ can be determined by step-by-step integration in time of a system of linear differential equations of the first order of the form

$$\{\dot{\mathbf{P}}\}=[\mathbf{A}]\{\mathbf{P}\}\,, \tag{2}$$

where $\{\mathbf{P}\}$, a vector containing the probabilities of finding a mobile ropeway at a time τ in all possible states $S_0, S_1, \ldots, S_m, \ldots, S_N$; $[\mathbf{A}]$, a square matrix containing the coefficients of the Chapman-Kolmogorov system of linear differential equations.

For a mobile ropeway formed from two identical transport units *A* and *B* (Fig. 1) with a common rope system, the number of key elements leading to critical failure will be determined taking into account the distribution of functions of these units during the mobile ropeway operation. For a drive transport unit that ensures the operation of the cable system, it is necessary to take into account all the key structural elements listed in subsection 2.3. For a non-drive transport unit, only a part of the key structural elements of the carrying-traction rope movement mechanism (namely B1, B2, RP) is used. This is due to the fact that in a non-drive unit, the carrying-traction rope movement mechanism does not work during the ropeway operation, the drive of the rope pulley is disabled, and the rope pulley itself rotates freely due to contact interaction with the carrying-traction rope.

Thus, for a mobile ropeway, the total number of elements leading to a critical failure is $N = 60$ (or if the control system sensors specified in subsection 2.3 are not taken into account, $N = 55$).

In relation to the considered structural scheme of a mobile ropeway (Fig. 3) and the graph of possible states and transitions (Fig. 4), the system of Eqs. (2) has the following form:

$$\begin{Bmatrix} \dot{P}_0 \\ \dot{P}_1 \\ \ldots \\ \dot{P}_m \\ \ldots \\ \dot{P}_N \end{Bmatrix} = \begin{bmatrix} -\Lambda_\Sigma & \{\mathbf{M}\} \\ \{\mathbf{\Lambda}\} & [\mathbf{\Omega}] \end{bmatrix} \begin{Bmatrix} P_0 \\ P_1 \\ \ldots \\ P_m \\ \ldots \\ P_N \end{Bmatrix}, \tag{3}$$

where Λ_Σ, the coefficient determined by the dependence

$$\Lambda_\Sigma = \sum_{m=1}^{m=N} \varepsilon_m \lambda_m ; \tag{4}$$

ε_m, the number of m-th structural elements working in the ropeway operation; $\{\mathbf{M}\}$ is a vector-string of size $1\times(N+1)$ whose structure has the following form:

$$\{\mathbf{M}\} = \{\varepsilon_1\mu_1 \;\; \varepsilon_2\mu_2 \;\; \ldots \;\; \varepsilon_m\mu_m \;\; \ldots \;\; \varepsilon_{N-1}\mu_{N-1} \;\; \varepsilon_N\mu_N\} ; \tag{5}$$

$\{\mathbf{\Lambda}\}'$, a vector-column of size $(N+1)\times 1$ whose structure has the following form:

$$\{\mathbf{\Lambda}\}' = \{\varepsilon_1\lambda_1 \;\; \varepsilon_2\lambda_2 \;\; \ldots \;\; \varepsilon_m\lambda_m \;\; \ldots \;\; \varepsilon_{N-1}\lambda_{N-1} \;\; \varepsilon_N\lambda_N\} ; \tag{6}$$

$\{\ldots\}'$, vector transpose operation; $[\mathbf{\Omega}]$ is square diagonal matrix of size $N\times N$ whose structure has the following form:

$$\mathrm{diag}\{\mathbf{\Omega}\} = [-\varepsilon_1\mu_1\ \ -\varepsilon_2\mu_2\ \ \ldots\ \ -\varepsilon_m\mu_m\ \ \ldots\ \ -\varepsilon_{N-1}\mu_{N-1}\ \ -\varepsilon_N\mu_N]\ . \tag{7}$$

The initial conditions for solving the system of differential Eqs. (3) include a set of probability values P_0, P_1, …, P_m, …, P_N at the time of commissioning of the mobile ropeway (at $\tau = \tau_0 = 0$) and are expressed by a vector of initial conditions of the form:

$$\{\mathbf{P}\}_{\tau=0} = \{P_0(0)\ \ P_1(0)\ \ \ldots\ \ P_m(0)\ \ \ldots\ \ P_N(0)\}'_{\tau=0} = \{1\ \ 0\ \ \ldots\ \ 0\ \ \ldots\ \ 0\}'\ . \tag{8}$$

The solution of the system of differential Eqs. (3) under the initial conditions (8) adequately characterizes the change in time of the probability of accident-free operation of the mobile ropeway until the first planned repair $\tau_{r,1}$. At the moment of time $\tau_{r,1}$, one or more key structural elements that meet the condition (1) are replaced or restored. Therefore, the probability of finding an m-th arbitrary element in an inoperable state decreases abruptly from the value $P_m(\tau_{r,1}-0) = P_m(\tau_{r,1})$ to the value $P_m(\tau_{r,1}+0) = 0$.

The probability of finding a ropeway in an operable state increases abruptly from $P_0(\tau_{r,1}-0) = P_0(\tau_{r,1})$ by the amount of the sum of the probabilities of the restored elements $P_m(\tau_{r,1})$. Therefore, from the moment of time, the integration of the system of differential Eqs. (3) must be performed with a new vector of initial conditions:

$$P_0(\tau_{r,1}+0) = P_0(\tau_{r,1}) + \sum_{m=1}^{m=n_{r,1}} P_m(\tau_{r,1})\,; \tag{9}$$

$$P_m = 0,\quad m \in [1;\,N]\ , \tag{10}$$

where $n_{r,1}$, the number of key structural elements that were planned restored or replaced during planned repairs at a time $\tau_{r,1}$.

The vectors of the initial conditions (8) change similarly for other time points $\tau_{r,i}$. Thus, the process of predicting changes in the probabilities of finding a ropeway in an operable or inoperable state over time is reduced to the alternate integration of a system of differential Eqs. (3) within sequentially arranged time intervals $\tau_{r,i} \le \tau \le \tau_{r,i+1}$. The vectors of the initial conditions (8) at the starting point of each such interval $\tau_{r,i}$ are subject to periodic reformulation according to Eqs. (9) and (10).

As an example of using the considered mathematical model, Fig. 5 shows graphs of changes in the probability of accident-free operation of the ropeway $P_0(\tau)$ during the service life T_{op} = 40,000 hours, depending on the accepted value of the minimum permissible probability of critical failure $[P_m]$ and the number of repairs N_{pr}. When performing calculations, it was assumed that during the service life T_{op}, the time points of planned repairs $\tau_{r,i}$ are distributed evenly with frequency $\Delta T_{op} = T_{op}/N_{pr}$ and all key structural elements have the same value $[P_m] = [P] = const$. The calculations were carried out in relation to a mobile ropeway with a length of 200 m with hydraulic frequency-throttle control of the speed of cargo movement [25] weighing up to 100 kN, formed by two self-propelled rope units with a height of the end tower of 12 m, with a standard service life of 40,000 hours. The values of the failure rate λ_m of key structural elements of transport units and the rope system were adopted on the basis of experimental and reference data [26-28].

4.2 A model for calculating the indicators of the schedule of planned repairs

The primary task that needs to be solved when forming an effective strategy for maintaining a mobile ropeway during operation in an accident-free state is the mutual linking of both the technical aspect of this task (ensuring an acceptably high level of reliability and technical risk) and its economic aspect (ensuring an acceptably low level of the total cost and number of repairs during the entire specified period of ropeway operation).

The analysis of the graphs in Fig. 5 allows us to draw the following conclusion: the main factors determining the effectiveness of the ropeway repair strategy are the total number of planned repairs N_{rp} during a given service life T_{op} and the minimum permissible value of the probability of critical failure $[P]$. These graphs also indicate that the probability of accident-free operation of a mobile ropeway $P_0(\tau)$ changes significantly during operation. Kinetic curves $P_0(\tau)$ have a sawtooth shape with sharp jumps at the time of planned repairs.

Therefore, it is advisable to use the following technical and economic indicators as the studied factors that quantitatively characterize the effectiveness of the mobile ropeway repair strategy:

- the minimum value of the probability of failure-free operation during the entire life of the ropeway

$$(P_0)_{\min} = \min_{0 \le \tau \le T_{op}} [P_0(\tau)]; \tag{11}$$

- the average value of the probability of failure-free operation during the entire life of the ropeway

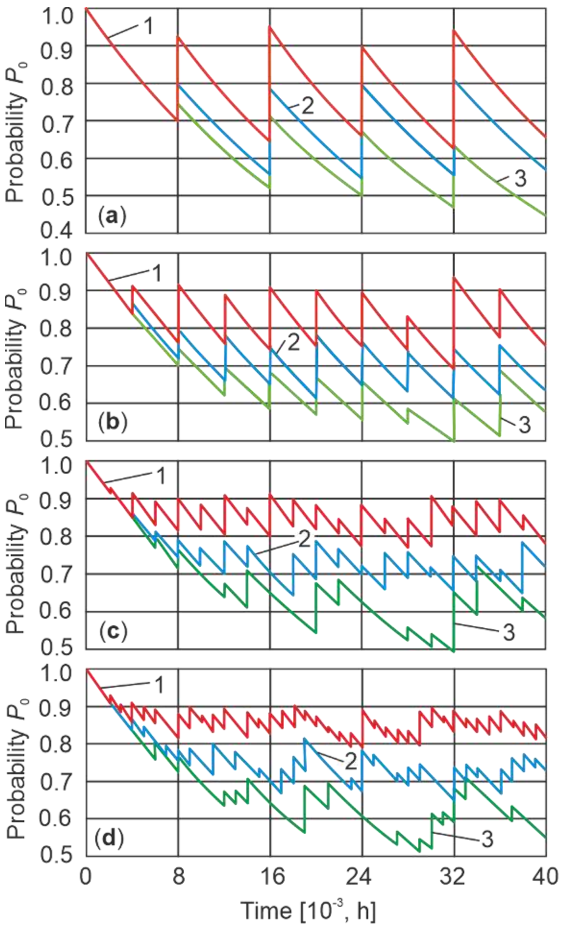

Fig. 5 Change in the probability of failure-free operation of a mobile ropeway with different repair intervals: **a** 8000 h **b** 4000 h **c** 2000 h **d** 1000 h (1 – [*P*]=0.99, 2 – [*P*]=0.98, 3 – [*P*]=0.97)

$$(P_0)_{av} = T_{op}^{-1} \int_0^{T_{op}} P_0(\tau) d\tau \,; \tag{12}$$

- the total cost of repairs of the ropeway during the entire life of its operation

$$C_{rp} = \sum_{i=1}^{i=N_{rp}} c_{rp,i} \,; \tag{13}$$

- the relative total cost of repairs of the ropeway during the entire life of its operation

$$C_{rp,rel} = C_{rp}/C_{1set} \,, \tag{14}$$

where $\min_{\Delta B}(A)$, the operation of searching for the minimum value of the parameter A on the interval ΔB; $c_{rp,I}$, the cost of the i-th repair; C_{1set} , the cost of one set of key structural elements.

The assessment of economic indicators C_{rp} and $C_{rp,rel}$ can be performed both in absolute and relative (conditional) units of the cost. However, it is important to assign the correct ratio between the costs of individual structural elements.

Fig. 6 and Fig. 7 give an idea of the influence of the minimum permissible probability [P] and the number of repairs N_{rp} on the studied parameters of various strategies for repairing a mobile ropeway. There is a clear tendency to decrease the quantitative values of the studied parameters with increasing probability [P]. However, the schedules corresponding to different numbers of repairs N_{rp} may overlap. The graphs $(P_0)_{\min}$ and $(P)_{av}$ (Fig. 7a, b) corresponding to the value [P] = 1.0 have no practical significance, since they provide for the complete replacement of all key structural elements during each planned repair. This strategy is the most expensive and unrealistic. However, these graphs serve as a guideline for what maximum values of the minimum $(P_0)_{\min}$ and average $(P)_{av}$ probability of accident-free operation can theoretically be obtained with a different number of repairs of the ropeway. With an increase in the number of repairs, there is a certain increase in the values of $(P_0)_{\min}$ and $(P)_{av}$. However, their constant growth is typical for small values [P] ≤ 0.98. At large values, almost equal values $(P_0)_{\min}$ and $(P)_{av}$ are observed and with the number of repairs N_{rp} ≥ 4…8.

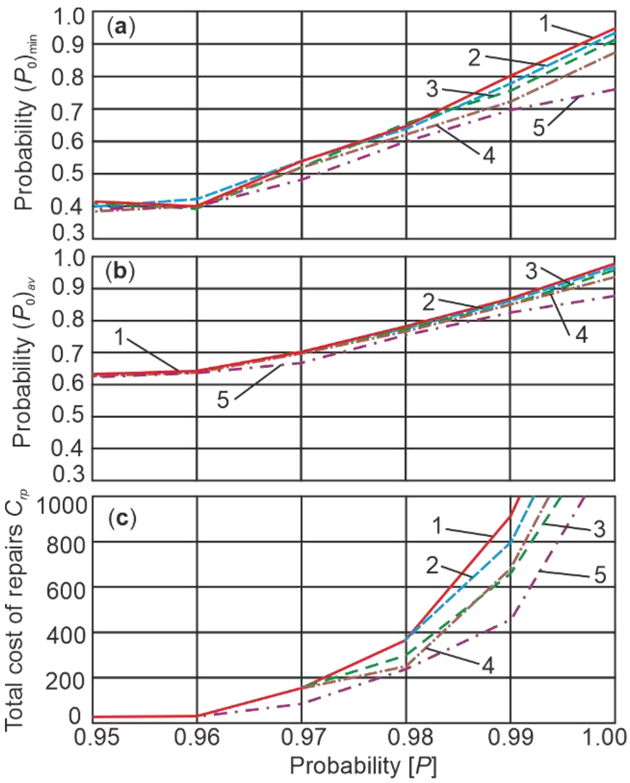

Fig. 6 Indicators of various ropeway repair strategies: **a** minimum probability of failure-free operation for the entire service life **b** the average value of the probability of failure-free operation for the entire service life **c** the total cost of repairs (1 - N_{rp} = 20, 2 - N_{rp} = 16, 3 - N_{rp} = 12, 4 - N_{rp} = 8, 5 - N_{rp} = 4)

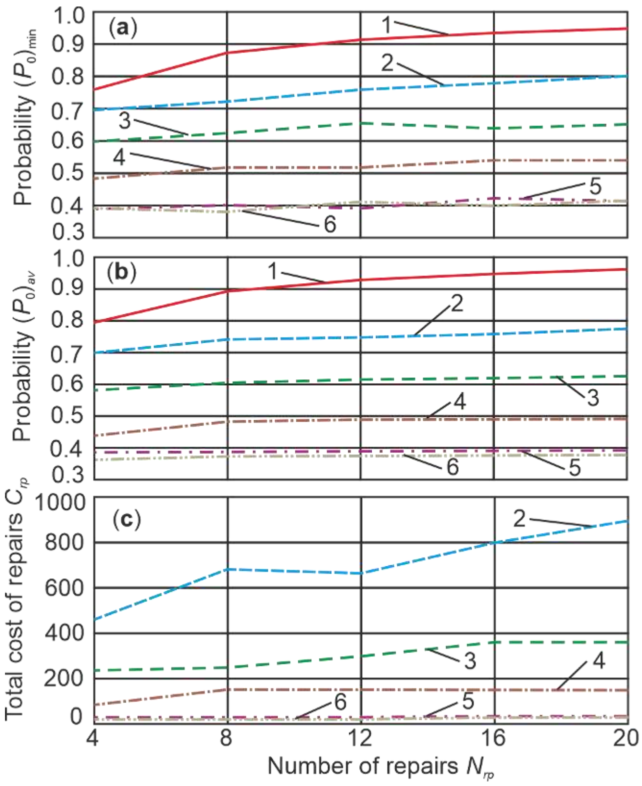

Fig. 7 Indicators of various ropeway repair strategies: **a** minimum probability of failure-free operation for the entire service life **b** the average value of the probability of failure-free operation for the entire service life **c** the total cost of repairs (1 - [*P*]= 1.0, 2 - [*P*]= 0.99, 3 - [*P*]= 0.98, 4 - [*P*]= 0.97, 5 - [*P*]= 0.96, [*P*]= 0.95)

Fig. 8 shows graphs $\tau_{rel} = \tau_{rel}(P_0)$ describing the relative duration of the ropeway operation time $\tau_{rel} = \Delta\tau\,(P_0)/T_{op}$ with a probability of failure-free operation exceeding P_0 (i.e. lying in the range from P_0 to 1.0). The points P_0 satisfying the condition $\tau_{rel}(P_0) = 1$ (i.e. the leftmost points of the graphs) correspond to the minimum values of the probability of failure-free operation during the entire life of the mobile ropeway. It is obvious that the repair strategy, in which the ropeway works most of the time of operation with increased values of the probability of failure-free operation, is more favorable. From this point of view, Graph 2 in Fig. 8, which has a more convex curve shape, is more favorable than Graph 3.

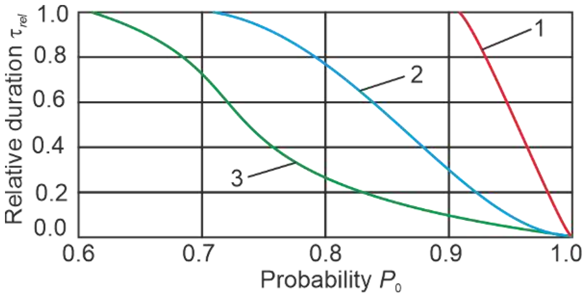

Fig. 8 The relative duration of the operating time with an arbitrary probability of failure-free operation: 1 - $(P)_{av} = 0.95$, 2 - $(P)_{av} = 0.85$, 3 - $(P)_{av} = 0.75$

4. The method of forming the mobile ropeway planned repair strategy

As a technical and economic criterion for the effectiveness of the mobile ropeway planned repair strategy, the following condition was adopted: obtaining the minimum possible total C_{rp} or relative total $C_{rp,rel}$ cost of repairs of a ropeway during the entire life of its operation, while ensuring the average probability of failure-free operation $(P)_{av}$ set in the technical task for design. As factors x that vary when searching for the minimum cost C_{rp} (or $C_{rp,rel}$), and are used $[P]$ and N_{rp}. Thus, the task of optimizing the mobile ropeway planned repair strategy has the following form:

- objective function

$$O(x_1; x_2) = C_{rp}([P]; N_{rp}) \to \min \; ; \tag{15}$$

- restrictions

$$(P_0)_{av} = [P_{av}] \; ; \tag{16}$$

$$[P] - [P]_{\min} \geq 0, \quad 1.0 - [P] \geq 0 \; ; \tag{17}$$

$$(N_{rp})_{\max} - N_{rp} \geq 0 \; , \quad N_{rp} - (N_{rp})_{\min} \geq 0 \; , \tag{18}$$

where $[P]_{\min}$, the minimum possible value of the permissible probability of a critical failure $[P]$; $(N_{rp})_{\min}$, $(N_{rp})_{\max}$, the minimum and maximum possible number of planned repairs N_{rp}.

Setting the required average value of the probability of failure-free operation $(P)_{av}$ is more preferable than rationing the minimum value of the probability of failure-free operation $[P_0]_{\min}$, since in the first case an acceptable level of reliability of the ropeway is provided during the entire service life, and in the second case – only for a local moment of time.

The formation of a mobile ropeway repair strategy based on the accepted efficiency criterion is based on finding the optimal combination of two variable factors $[P]$ and N_{rp}. The process of finding the optimal combination is based on a discrete iteration of several values of the number of repairs N_{rp} from the interval $(N_{rp})_{\min} \le N_{rp} \le (N_{rp})_{\max}$. For each value under consideration N_{rp}, the following calculation steps must be performed.

Step 1. Determination of the limit (maximum) value $[P]$ at which the condition (16) is met. To do this, it is convenient to use the approach [25]. It is based on determining the average probability of failure-free operation $(P)_{av}$ in a discrete number of points $[P]_1, \ldots, [P]_K$ within the possible change in the limit value $[P] \in [[P]_{\min}; 1.0)$ at $[P]_{\min}$ in the range from 0.93 to 0.96 (Fig. 9). Then the resulting discrete function is approximated using a one-dimensional spline interpolation of the form $(P_0)_{av} = (P_0)_{av}([P])$. One-dimensional spline interpolation allows us to approximate this function on each k-th section between neighboring discrete reference points $[P]_k$ and $[P]_{k+1}$ using a cubic polynomial:

$$(P_0)_{av}([P]) = (P_0)_{av,k} + b_{P,k}([P] - [P]_k) + c_{P,k}([P] - [P]_k)^2 + d_{P,k}([P] - [P]_k)^3 , \tag{19}$$

where $[P]_k$, abscissas of reference points of spline interpolation; $(P_0)_{av,k}$, ordinates of the reference points of the spline interpolation (Fig. 9); $b_{P,k}$, $c_{P,k}$, $d_{P,k}$, spline interpolation coefficients.

The desired limit value $[P]$ is determined by the solution of a nonlinear algebraic equation

$$(P_0)_{av,k} + b_{P,k}([P] - [P]_k) + c_{P,k}([P] - [P]_k)^2 + d_{P,k}([P] - [P]_k)^3 - [P_{av}] = 0 \tag{20}$$

by one of the known methods of numerical analysis [29].

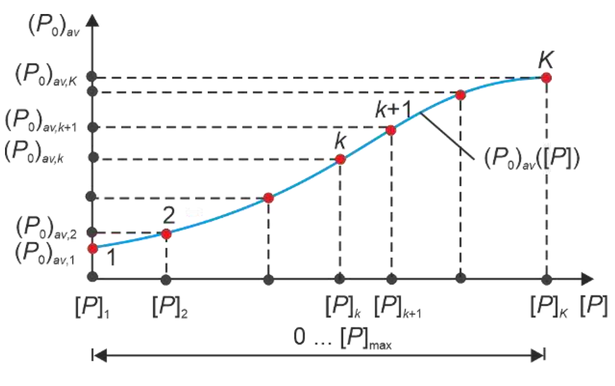

Fig. 9 Spline interpolation of the average probability of uptime

Step 2. Construction of the kinetic curve of the change in the probability of failure-free operation of a mobile ropeway during the entire service life and determination of the total C_{rp} (or relative total $C_{rp,rel}$) the cost of repairs. For this purpose, the mathematical model presented in subsection 4.1 and Eqs. (13) or (14) are used.

Step 3. Comparison of the C_{rp} or $C_{rp,rel}$ indicators corresponding to the kinetic curves $P_0(\tau)$ for a different number of planned repairs, and the choice of the strategy that has the smallest value of C_{rp} or $C_{rp,rel}$. This ropeway repair strategy is the most cost-effective, since it requires minimal financial costs. The combination of variable factors $[P]$ and N_{rp}, which characterizes this strategy, is optimal.

Step 4. Clarifying calculation of the optimal strategy for the planned repair of the ropeway. This is necessary, since the procedure of approximate representation of the function $(P_0)_{av} = (P_0)_{av}([P])$ was used to determine the limit value of $[P]$. The clarifying calculation includes the construction of a kinetic curve of the change in the probability of failure-free operation of the ropeway $P_0(\tau)$ with an optimal combination of variable factors $[P]$ and N_{rp}. At the same time, the time points of planned repairs $\tau_{rp,i}(1 \le i \le N_{rp})$, the minimum $(P_0)_{\min}$ and actual average $(P_0)_{av}$ probability of failure-free operation, the total C_{rp} and relative total $C_{rp,rel}$ cost of all planned repairs and the cost of individual repairs $c_{rp,i}(1 \le i \le N_{rp})$ are determined. Also, for each planned repair, a list of key structural elements to be restored during each planned repair is determined. During these repairs, the relevant elements must be restored or replaced. This allows you to make a list of restored structural elements for each i-th planned repair, estimate the volume and cost of i–th repair, as well as form an application for the need for spare parts. This information allows you to plan the consumption of spare parts during the entire service life of the mobile cargo ropeway.

5 Test analysis and discussion of the results

A test evaluation of the developed method for forming an optimal strategy for planned repairs of a mobile cargo ropeway was carried out with the same initial data as in subsection 3.1. Calculations were carried out for three values of the average probability of failure-free operation $[P_{av}]$: 0.95, 0.85 and 0.75.

Fig. 10 shows the kinetic curves of the probability of failure-free operation of the ropeway with the most effective strategies of planned repairs, depending on the normalized value $[P_{av}]$. In the Table 1 and Fig. 11 show the values of the parameters that characterize these strategies. According to Fig. 11c, up to the normalized value of $[P_{av}]$~ 0.92, there is a linear increase in the total cost of repairs, and then it is replaced by a sharply nonlinear increase. As a result, for the ropeway under study, with the accepted failure rate and the cost of key structural elements, achieving a higher level of reliability is an economically unacceptable task.

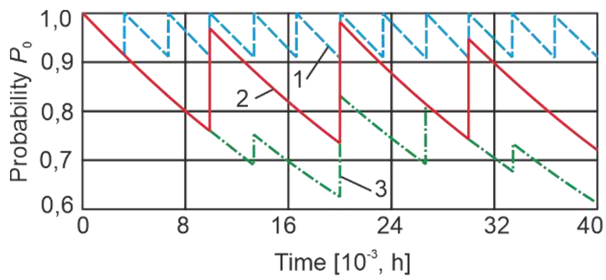

Fig. 10 Changing the probability of failure-free operation of the ropeway with optimal strategies of planned repairs: 1 - $[P_{av}]$= 0.95, 2 - $[P_{av}]$= 0.85, 3 - $[P_{av}]$= 0.75

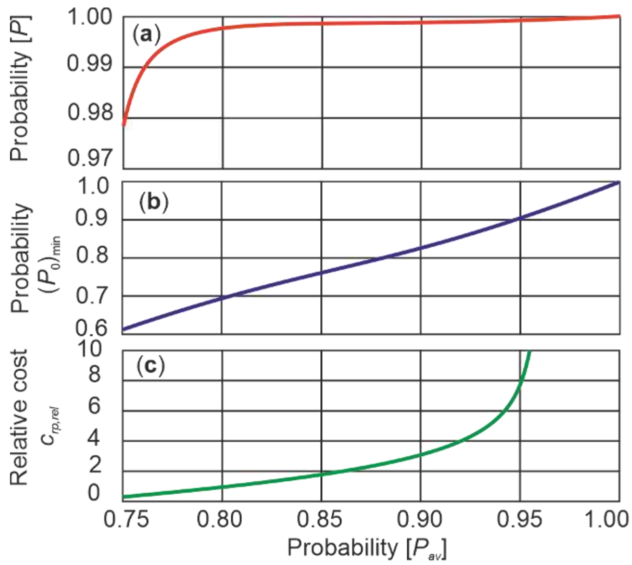

Fig. 11 Indicators of optimal strategies for planned repairs: **a** the minimum permissible probability of critical failure **b** the minimum probability of failure-free operation **c** the relative total cost of repairs

Table 1 Calculated indicators of optimal strategies for planned repairs of the ropeway

Indicators	The value of the indicator when $[P_{av}]$				
	0.95	0.90	0.85	0.80	0.75
Number of planned repairs N_{rp}	11	11	11	10	5
Minimum permissible probability of critical failure $[P]$	0.9995	0.9995	0.9901	0.9845	0.9786
Actual average probability of failure-free operation $(P_0)_{av}$	0.9524	0.9003	0.8517	0.8050	0.7547
Minimum probability of failure-free operation $(P_0)_{min}$	0.9066	0.8204	0.7588	0.6998	0.6109
Relative total cost of repairs $C_{rp,rel}$	7.62	3.14	1.72	1.08	0.53

When using structural elements that have other values of the failure rate as part of self-propelled transport units, this value of the normalized probability $[P_{av}]$ may shift. Thus, by purposefully using key elements with increased reliability indicators in the design of transport units, it is possible to manage quantitative indicators of the optimal strategy for planned repairs of a mobile cargo ropeway.

Table 2 shows calculated data on the structure and volume of each i-th planned repair for optimal strategies for repairing a mobile ropeway, corresponding to two given values of the average probability of failure-free operation $[P_{av}] = 0.95$ and 0.85. For each m-th key element, the critical failure of which causes the ropeway to stop, it is shown by which points in the time of planned repairs $\tau_{rp,i}$, their probability of being in an inoperable state increases to the value $(P_0)_m(\tau_{rp,i}) \geq 1 - [P_{av}]$. During these repairs, the corresponding structural elements must be restored. For each planned repair, this allows you to determine the structure of the repair (that is, to make a list of restored elements), to estimate the volume and cost of the repair, as well as to form an application for the necessary spare parts. As a result, a joint analysis of the structure and volume of all repairs included in the optimal mobile cargo ropeway repair strategy allows planning the distribution of material and financial resources for carrying out the necessary repairs during the operation of the ropeway at the design stage of self-propelled transport units.

Table 2 Structure and volume of planned repairs

Element	Number of planned repair										
	1	2	3	4	5	6	7	8	9	10	11
P	x/x	x/-	x/x	x/x	x/-	x/x	x/-	x/x	x/-	x/x	x/-
HM	x/-	x/-	x /x	x/-	x/-	x/x	x/-	x/-	x /x	x/-	x/-
HC1	-/-	-/-	-/-	-/-	-/-	-/-	-/-	-/-	-/-	-/-	-/-
HC2	-/-	-/-	-/-	-/-	-/-	-/-	-/-	-/-	-/-	-/-	-/-
HR	x/-	x/-	x/-	x/-	x/-	x/-	x/-	x/x	x/-	x/-	x/-
SV	x/-	x/x	x/-	x/x	x/-	x/x	x/-	x/x	x/-	x/x	x/-
F	-/-	-/-	-/-	-/-	-/-	-/-	-/-	x/-	-/-	-/-	-/-
DV1- 4	x/-	x/-	x /x	x/-	x/-	x/-	x/x	x/-	x/-	x/-	x /x
PV1, 2	x/-	x/-	x/-	x/-	x/-	x/-	x/-	x/-	x/-	x/-	x/-
RP	-/-	-/-	-/-	-/-	-/-	-/-	-/-	-/-	-/-	-/-	-/-
SR	-/-	-/-	-/-	-/-	-/-	-/-	-/-	-/-	-/-	-/-	-/-
B	x/-	x/x	x/-	x/-	x/x	x/-	x/-	x/x	x/-	x/-	x/x
C1- 3	-/-	-/-	x/-	-/-	-/-	x/-	-/-	-/-	x/-	-/-	-/-
B1	-/-	-/-	-/-	-/-	-/-	-/-	-/-	x/-	-/-	-/-	-/-
B2	-/-	-/-	x/-	-/-	-/-	x/-	-/-	-/-	x/-	-/-	-/-
BR	x/-	x/-	x/x	x/-	x/-	x/x	x/-	x/-	x/x	x/-	x/-
LF	x/-	x/-	x/-	x/x	x/-	x/-	x/-	x/x	x/-	x/-	x/-
RC	x/-	x/-	x/x	x/-	x/-	x/x	x/-	x/-	x/x	x/-	x/-
M	x/-	x/-	x/-	x/-	x/-	x/-	x/-	x/-	x/x	x/-	x/-
CP	-/-	-/-	-/-	-/-	-/-	-/-	-/-	x/-	-/-	-/-	-/-
IP	-/-	-/-	-/-	-/-	-/-	-/-	-/-	x/-	-/-	-/-	-/-
VE1	x/-	x/-	x/x	x/-	x/-	x/x	x/-	x/-	x/x	x/-	x/-
VE2- 4	x/-	x/-	x/-	x/-	x/-	x/-	x/-	x/-	x/x	x/-	x/-
$c_{rp,I}/C_{rp}$	0.67/ 0.06	0.70/ 0.02	0.69/ 0.39	0.71/ 0.12	0.67/ 0.01	0.72/ 0.30	0.67/ 0.11	0.74/ 0.15	0.69/ 0.37	0.70/ 0.08	0.70/ 0.12

[a]"x" - the element is subject to restoration during i-th repair, "-" - the element cannot be restored during i-th repair.

[b]In the numerator - the calculation results for a probability of failure-free operation $[P_{av}] = 0.95$, in the denominator - for $[P_{av}] = 0.85$.

Conclusion

The mathematical models presented in this article for predicting the kinetics of reliability and the method for forming an optimal strategy for planned repairs can be recommended for use at the design stage of technological equipment of self-propelled transport units intended for creating mobile cargo ropeways.

The functionality and algorithm of using this method were considered in relation to the structural scheme of a mobile ropeway based on two terminal transport units with a specific set of structural elements. However, this circumstance does not reduce the universality of the method of forming an optimal repair strategy in relation to other currently known structural variants of terminal transport units [4]. Taking into account the features of the design of mechanisms and systems of the technological equipment, as well as the specific structural elements used, only leads to a change in the dimension of the problem being solved, but does not change the algorithm of the researcher's actions.

The proposed approach makes it possible to maintain the reliability level initially set during the design of both self-propelled transport units themselves and the mobile ropeways formed by them. The approach is implemented by preemptively restoring or replacing during planned repairs in stationary conditions those of its structural elements whose probability of loss of operable state reaches by the time of repair the minimum permissible value of the probability of critical failure specified in the technical task for design. At the same time, a two-pronged technical and economic task is solved: ensuring an acceptably high level of reliability and technical risk while simultaneously ensuring the minimum possible total cost and number of repairs during the entire specified service life of a mobile cargo ropeway. This approach is a promising direction for improving the operational performance of this transport equipment.

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