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DEFINING A RATIONAL LOCOMOTIVE MAINTENANCE SYSTEM CONSIDERING A COST-BASED RISK ACCEPTABILITY THRESHOLD

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This study examines a locomotive technical maintenance system, represented as a set of interconnected nodes with a predefined structure of dependent failures.

The task addressed is to determine a rational locomotive maintenance system in which the total costs for planned and unplanned repairs are minimal provided that the risk of failures does not exceed the limit level set by the "value at risk" criterion. A risk-oriented mathematical model for the construction of a rational maintenance system has been proposed, in which dependent failures are taken into account by "waves" of failures. An optimization problem has been stated to minimize the total costs for planned and unplanned repairs provided that the risk level is not exceeded.

To model dependent failures, a structure of node connections was constructed, which makes it possible to assess the risk of failure of nodes and the system as a whole, taking into account economic consequences.

Based on the results from modeling a set of maintenance strategies, a nonlinear nature of change in total costs with an increase in the permissible level of risk was revealed; a ranking of elements by the frequency of the need for repair impact was obtained. This is explained by the redistribution between planned and unplanned repairs when changing the adopted risk threshold. It is shown that taking into account dependent failures increases the cost estimate for the maintenance system compared to the independent failure model by 18–47% depending on the adopted risk threshold. A distinctive feature of the approach is the combination of the "value at risk" criterion with the consideration of dependent failures within a single strategy selection procedure, which provides a comparison of strategies on the "risk-cost" scale.

The results of the study could be used when planning the volume and frequency of maintenance and repair of a locomotive fleet. The practical application is to establish the correspondence between the accepted acceptable risk level and a technical maintenance and repair (TM&R) strategy

Keywords: locomotive, risk-oriented maintenance strategy, dependent failures, value at risk

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1. Introduction

Improvement of approaches and principles to the construction of locomotive maintenance systems occurs simultaneously with the evolution of locomotive engineering, the development of new methods and means of technical diagnostics, the introduction of information and measuring systems, as well as artificial intelligence and optimization methods.

The goal of improving rolling stock maintenance systems is to reduce costs for the maintenance system, while simultaneously ensuring both the specified level of reliability and safety indicators, as well as operational and environmental indicators. When improving maintenance systems, it is necessary to consider improving both the maintenance system of a single locomotive and the improvement of the maintenance system of the locomotive owner's fleet as a whole. Improving the maintenance system is a cyclical process that involves a combination of such factors as development and implementation of new methods and approaches to building a maintenance system, implementation of information systems for data collection and analysis, training personnel in the use of improved methods.

Therefore, research into the construction of risk-oriented models of locomotive maintenance, taking into account dependent failures and the economic consequences of failures, is relevant.

2. Literature review and problem statement

The traditional basis for organizing locomotive maintenance in world practice has long been the planned and preventive repair strategy (PRS), in which the frequency and volume of repair impacts are set by regulations and operating experience. Further development of approaches to TM&R was due to the increasing complexity of traction rolling stock, increasing requirements for safety and availability. The accumulation of statistical data on rolling stock failures also contributed to the transition to condition-based maintenance (CBM) and reliability-based maintenance (RCM). Within the framework of these approaches, decisions on repair impacts are formed taking into account the technical condition, reliability indicators, and consequences of failures; technical maintenance is considered as an element of life cycle management. The current stage of development is associated with the implementation of risk-based maintenance (RBM) within the RAMS (Reliability, Availability, Maintainability, Safety) concept [1, 2], where the key is the assessment of the risk of failures and economic consequences for substantiating the TM&R strategy. At the same time, the practical implementation of such approaches requires taking into account not only individual failures of elements but also dependent failures that change the structure of repair impacts and affect costs throughout the locomotive life cycle.

In [1], the application of FMEA/FMECA (Failure Mode and Effects Analysis / Failure Mode, Effects, and Criticality Analysis) methodologies for analyzing failures of diesel locomotive equipment and determining critical elements based on the consequences of failures is demonstrated. However, the expert-oriented nature of the assessment limits the reproducibility of the results and requires supplementation with a quantitative cost model and a mechanism for taking into account dependent failures for selecting TM&R parameters.

RBM-oriented approaches in TM&R tasks are based on quantitative assessment of failure risk as a combination of failure probability and severity of its consequences, which makes it possible to rank maintenance objects and justifying priorities of repair impacts. In [3], the interpretation of the concept of "risk" in technical and economic tasks is systematized; however, the described approaches are of a general nature and require adaptation to the specifics of locomotives and the cost structure throughout the life cycle.

In [4], examples of the application of risk management methodology in railroad transport are given, in particular, risk matrices and failure criticality analysis. At the same time, such tools mostly provide procedural support for decision-making, but do not set a formalized economic criterion for choosing a TM&R strategy and comparing alternatives by cost.

An example of using the FMEA methodology to identify failure causes and rank risks is given in [5], which is useful for forming a list of priority nodes. However, the results of FMEA in this formulation do not provide a direct link to economic consequences and do not set the risk acceptance thresholds necessary for choosing a maintenance and repair strategy.

Despite the practical usefulness of FMEA/FMECA for analyzing the causes of failures and assessing their criticality, the application of these methodologies in TM&R tasks is mostly limited to the stage of identifying and ranking risks. This is not enough to build a locomotive maintenance system because without taking into account dependent failures of nodes and without establishing an economic acceptance threshold, it is impossible to correctly assess unplanned costs and justify the choice of maintenance strategy [6, 7].

The approach to risk management in locomotive operation proposed in [8] using an electronic passport and the "flight capability" indicator is useful as a tool for operational decisions "to release/not release" a locomotive on a route. At the same time, the proposed indicator does not take into account cost implications, so it is difficult to directly use it for economic comparison of TM&R strategies and formation of a risk acceptance threshold.

The "concept of acceptable risk" approach defines the interpretation of risk as a combination of probabilistic and cost factors (in the form of losses per unit of time), which is important for the transition from purely technical reliability indicators to economically justified solutions in TM&R. At the same time, the above considerations are of a general nature and require adaptation to the task of choosing the repair intervals and repair volumes for locomotives and to the task of taking into account dependent failures of units [9]. At the level of the organization of the operation of the locomotive fleet, a complex indicator of technical operation can be used, which makes it possible to assess the efficiency of the system in an integral form. However, such an indicator does not specify the mechanism for forming repair impacts for specific units and does not establish a direct connection with the risk of failures and costs for scheduled/unscheduled repairs [10]. For tasks of predicting the technical condition of individual units, it is effective to use the "safety factor" for individual prediction of the residual resource of electrical equipment, taking into account operating conditions and probabilistic voltage characteristics. However, the approach focuses on the reliability of individual equipment and requires expansion to the level of the TM&R system (set of nodes) with explicit consideration of economic consequences and dependent failures, as represented in [11].

A similar logic of the transition to making decisions on the performance of TM&R work based on the actual condition of the equipment is demonstrated by the use of the technical condition coefficient of a shunting locomotive as an index for choosing a rational maintenance system. However, for a risk-based strategy selection, it is necessary to additionally formalize the acceptance threshold in economic terms and take into account the interdependence of node failures in order to avoid underestimating unplanned costs [12].

To analyze the state of traffic safety and performance indicators of the locomotive fleet, papers [13, 14] proposed methods for determining the traffic safety index [13] and the specific integral index of operational traffic safety [14]. The difference between the considered indices is the use of dimensionality reduction methods when determining the contribution to the total value of the index of absolute or relative analyzed indicators [13]. The use of such indices in the tasks of improving TM&R requires a transition from the assessment "as a whole" to the level of locomotive units and the rules for forming repair impacts, as well as coordination with the economic consequences of failures.

In [15], a methodology for calculating the technical condition index of locomotives and its units based on monitoring system data is proposed. The methodology is based on the formation of latent diagnostic parameters using the principal component method and the subsequent calculation of weight coefficients of these parameters using the analysis of hierarchies. A feature of the methodology is that the weight coefficients are calculated using the analysis of hierarchies without the need to involve experts [15]. However, for the application of the technical condition index in the risk-oriented choice of the TM&R strategy, it is advisable to combine it with risk acceptability criteria in economic terms and taking into account the interdependence of node failures.

At the level of locomotive fleet management, work [16] proposes improving the technical operation strategy using risk management principles, which is useful for decision-making under conditions of limited resources and different criticality of failures. However, for locomotive maintenance tasks, such a problem statement requires detailing to the level of nodes and a clear connection between the estimated risk and the rule for assigning repair impact, as well as a quantitative acceptance limit in economic terms.

The theoretical foundations of building a rational system of technical maintenance of traction rolling stock, focused on minimizing the total costs of planned and unplanned repairs, are given in [17]. However, to use this statement for locomotives, it is necessary to separately take into account the dependence of node failures because it changes the structure of unplanned costs and affects the choice of inter-repair intervals.

A further step towards formalizing the choice of a locomotive maintenance system was taken through a mathematical model of a rational maintenance system for railroad transport technical facilities, which makes it possible to justify TM&R parameters based on costs [18]. However, for a risk-based strategy choice, it is advisable to introduce an explicit acceptance threshold (in particular, cost threshold) and a mechanism that describes how dependent failures propagate between nodes.

The practical significance of taking into account dependent failures was confirmed in [19], which considered the choice of a locomotive maintenance system taking into account dependent failures. However, to compare alternative strategies on a single cost scale, these dependences should be related to a quantitative risk acceptance criterion (i.e., with a given acceptable level of losses). It has also been shown that taking into account dependent failures significantly affects the assessment of the locomotive life cycle costs and that the assumption of independence of failures of locomotive units can underestimate unplanned costs [20]. Therefore, for the tasks of selecting a TM&R strategy, a procedure is required that converts such estimates into a decision rule for performing repair actions and into an economically interpreted risk acceptance threshold.

Based on our review, it can be concluded that the methods and criteria of risk management theory are appropriate for improving strategies for managing the operation and technical maintenance of locomotives. This approach makes it possible to assess the consequences of decisions made to change the strategy, taking into account economic, technical, and safety factors. Within the proposed logic, it is advisable to use the VaR criterion ("value at risk") as a quantitative threshold for loss acceptability. The adopted threshold value should not be exceeded during a given period of operation, and it is advisable to determine the VaR for groups of locomotive components taking into account the probability of dependent failures.

Analysis of the literature [1, 2, 8, 17–19] also revealed that existing approaches to locomotive TM&R are mainly focused on assessing the technical condition or optimizing costs. The risk-oriented choice of TM&R strategy, taking into account dependent failures and the cost threshold for risk acceptability, remains insufficiently studied. This complicates the correct assessment of unplanned costs and the comparison of alternative strategies in the "risk-cost" scale.

The above allows us to state that it is advisable to conduct a study aimed at constructing a risk-oriented model of locomotive maintenance. Therefore, further considerations in our work aim to formalize a risk-oriented model of locomotive maintenance, in which the acceptance threshold is set through VaR while dependent failures are taken into account when forming repair impacts and estimating costs.

3. The aim and objectives of the study

The purpose of our study is to build a risk-oriented model for constructing a rational locomotive TM&R system taking into account dependent failures and the threshold value of the risk of failure. This will make it possible to provide a mechanism for selecting a TM&R strategy based on the criteria of "costs – risk level" for planning the volume and periodicity of repair impacts.

To achieve this goal, the following research tasks were defined:

– to model a test technical object with a predefined structure of connections among elements, based on the costs of element restoration, reliability parameters, and probabilities of dependent failures;

– to develop an algorithm for forming a maintenance and repair strategy that takes into account the threshold value of the risk of failure; to form an appropriate set of strategies that differ in risk acceptance thresholds, and to build a rational maintenance system for each of the strategies;

– to determine the total costs of the maintenance system and the number of planned repair impacts for each of the strategies for two options: without taking into account and with taking into account dependent failures;

– to analyze the structure of repair impacts and costs depending on the chosen strategy, in particular the frequency of element repairs, the volume of repairs, as well as the distribution of planned and unplanned recoveries.

4. The aim and objectives of the study

The object of our study is the locomotive maintenance system, represented as a set of interconnected nodes (elements) with a predefined structure of dependent failures.

The principal hypothesis assumes that the adopted risk threshold value provides a comparison of alternative maintenance and repair strategies and makes it possible to choose an economically feasible strategy.

The following assumptions are adopted in the study. The locomotive is considered as a set of nodes with a predefined structure of connections, while dependent failures are possible only between nodes connected by these connections. For each node, the cost of restoration and reliability parameters are given; these parameters are considered constant over the considered modeling interval.

Dependent failures are taken into account probabilistically; for each pair of connected nodes, the probability of dependent failure is given, which is used when calculating risk and costs. Failure risk is interpreted as expected losses from failures, and the acceptability of the strategy is determined by the threshold risk level. The maintenance strategy is formed as a sequence of planned repair actions, which are assigned upon reaching a threshold value of the growth rate of the average number of failures. The comparison of alternative strategies is carried out based on the total costs of planned and unplanned restorations for the period under consideration.

The following simplifications are accepted in the study. The work adopts an aggregate repair method: a node requiring repair is removed and replaced with a previously restored (or new) one. In this regard, the cost of a planned repair impact is assumed to be constant throughout the life cycle.

The work considers a risk-oriented approach to the formation of a TM&R system, in which a technical object is represented as a set of elements with a known structure of dependent relationships. The input data of the model are the cost of restoring elements C_i, reliability characteristics $h(t)$, probability of dependent failures p_k and the limit level of acceptable risk VaR. The result of applying the model is a formed TM&R strategy in the form of a sequence of planned repair impacts and the corresponding total costs for planned and unplanned repairs.

The cost of the maintenance system (costs for the maintenance system) includes the costs of performing repairs and eliminating the consequences of failures. Over the entire life cycle of a locomotive, or over the period of operation between certain types of repairs, the costs of the maintenance system can be defined as the sum of the costs of performing TM&R work and the costs of eliminating the consequences of failures.

$$F_{LCC}=\sum_{j=1}^{n}F_j+\sum_{i=1}^{e}F_i^*, \tag{1}$$

where $\sum_{j=1}^{n}F_j$ – amount of costs for scheduled repairs; n – number of scheduled repairs during the operation period; $\sum_{i=1}^{e}F_i^*$ – amount of costs for eliminating the consequences of failures, taking into account dependent failures; e – number of unscheduled repairs during the operation period.

The optimization problem of determining a rational locomotive maintenance system is formulated as minimizing the total costs for scheduled and unscheduled repairs in the presence of restrictions on the total time spent in repair and the maximum risk level

$$\begin{pmatrix}\sum_{j=1}^{n}F_j\\ \sum_{i=1}^{e}F_i^*\end{pmatrix}\to\min,\ R<VaR, \tag{2}$$

where R is the risk level; VaR is the marginal risk level; j is the counter, the number of the planned repair impact.

The planned repair impact is defined as the set of repair actions aimed at restoring the locomotive during its life cycle. The amount of expected costs for each j-th repair impact is defined as

$$F_j=C_{fix}+\sum_{i=1}^{N}p_i\cdot C_i, \tag{3}$$

where C_{fix} – fixed costs (diagnostics, disassembly/assembly, overhead); N – number of locomotive units; p_i – probability of failure of the i-th unit; C_i – costs of repair of the i-th unit.

It should be noted that the probability of failure of the i-th unit p_i depends on its operating time, i.e.

$$p_i=f_i(t). \tag{4}$$

In [17], the failure probability function is given as

$$f(t)=1-e^{-h(t)}, \tag{5}$$

where $h(t)$ is the h-characteristic (function of the growth rate of the average number of failures over time)

$$h(t)=\int_0^t\lambda(x)\mathrm{d}x. \tag{6}$$

In the following, the work uses $h(t)$ – a characteristic as a basic indicator for the formation of repair impacts.

The list of repair operations in each repair impact may vary depending on the need to perform a specific operation. The need to perform a repair operation is determined by the condition:

$$\sigma(t)=\begin{cases}0,\text{ if } h(t)<h(VaR),\\ 1,\text{ if } h(t)\geq h(VaR),\end{cases} \tag{7}$$

where $h(VaR)$ is the marginal growth rate of the average number of failures for the selected risk level.

Then the formula for calculating the expected costs for each jth repair impact will take the form

$$F_j=C_{fix}+\sum_{i=1}^{N}\sigma_i(t)\cdot C_i. \tag{8}$$

The repair effect for the corresponding node of the locomotive occurs when its h-characteristic reaches the limit value (Fig. 1).

To take into account the risks of dependent failures when estimating the costs of failures (unscheduled repairs), for each i-th element, a set of elements that can be damaged as a result of its failure (the so-called "first wave" of failures) is determined

$$V_i(1)=\left\{\langle p_k,c_k\rangle,k=1,\bar{m}\right\}, \tag{9}$$

where $\bar{m}$ is the number of elements that are directly related to the i-th element and that its failure may affect.

Thus, each element of a technical object is assigned a vector of pairs of values: the probability of dependent failures of other elements p_k and the cost of their restoration c_k.

Dependent failures, as a rule, are chain in nature, that is, the failure of a dependent element may, in turn, cause dependent failures of other elements. Therefore, the second wave of dependent failures is determined depending on the set of elements that were included in the "first wave"

$$V_i(2)=\bigcup_{j\in V_i(1)}V_j(1). \tag{10}$$

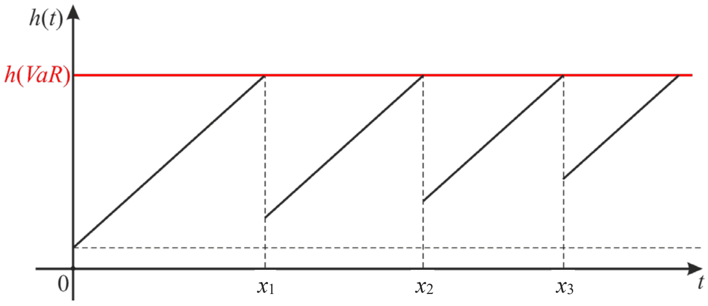


Fig. 1. Dependence graph of the h-characteristic of a restoration technical object on the operating time/working time t

In general, the *n*-th generation of failures for the *i*-th element is given by the expression

$$V_i(n) = \bigcup_{j \in V_i(n-1)} V_j(1), \tag{11}$$

where *j* is the index of the element from the previous generation of failures.

The last wave of failures *n* is recorded when the set of pairs (9) becomes an empty set, i.e., there are no elements that could be affected by the failure of the elements of the previous wave.

Taking into account the dependent elements, the failure risk for the *i*-th element is determined from the following formula

$$\bar{R}_i = \sum_{j=1}^{m(i)} p_i^j C_i + \sum_{k=1}^{n(i)} v_i(w), \tag{12}$$

where *j* is the counter of the failure causes of the *i*-th element; *m*(*i*) is the number of failure causes for the *i*-th element; *k* is the counter for the failure waves of the *i*-th element; *n*(*i*) is the number of failure waves for the *i*-th element; p_i^j is the probability of failure of the *i*-th element due to the *j*-th cause; C_i is the cost of restoring the *i*-th element.

Then, the failure risk for the *i*-th element, taking into account dependent failures

$$\bar{R}_i = \sum_{j=1}^{m} p_i^j C_i + \sum_{k=1}^{n(i)} \bigcup_{a \in v_i(k)} p_a C_a, \tag{13}$$

where *a* is an element from the set of dependent elements for the *i*-th element; p_a is the probability of failure of element *a*; C_a is the cost of restoring element *a*.

The total risk level *R* is found as the sum of risks for all elements

$$\bar{R} = \sum_{i=1}^{N} R_i = \sum_{i=1}^{N} \left(\sum_{j=1}^{m} p_i^j C_i + \sum_{k=1}^{n(i)} \bigcup_{a \in v_i(k)} p_a C_a \right), \tag{14}$$

where *N* is the total number of elements of the system.

To simplify further calculations, only the first wave of dependent failures (one generation) is taken into account, i.e. $(n(i) = 1)$. The probability of failure of the *i*-th element is considered in terms of the total probability for all causes $\left(p_i = \sum_{j=1}^{m} p_i^j \right)$

$$\bar{R} = \sum_{i=1}^{N} \left(p_i C_i + \bigcup_{a \in v_i(k)} p_a C_a \right). \tag{15}$$

In this case, the overall risk level depends on the operating time and the cost of replacing the elements. If the impact of dependent failures on the reliability of the locomotive is taken into account, the risk level is calculated from the following formula

$$\bar{R} = \sum_{i=1}^{N} \left(f(t_i) C_i + \bigcup_{a \in v_i(k)} p_a C_a \right), \tag{16}$$

where *N* is the number of system nodes.

For the case where only independent failures of locomotive nodes are considered, the risk level is defined as

$$R = \sum_{i=1}^{N} f_i(t) C_i, \tag{17}$$

or

$$R = \sum_{i=1}^{N} \left(1 - e^{-h_i(t)} \right) C_i. \tag{18}$$

Thus, the risk level is determined by the operating life of the locomotive components and the costs of their restoration.

The resulting relations (14) to (18) allow us to calculate the total risk level of the system both for the case with dependent failures and for the case of independent failures of the components. Subsequently, the calculated risk value *R* is used as an acceptability limit in the statement of problem (2) $R \le VaR$ and for the formation of repair impacts according to rule (7). This provides the possibility of constructing and comparing alternative TM&R strategies for different *VaR* values for total costs and risk level.

5. Results of modeling a risk-oriented system of locomotive maintenance and repair

5. 1. Modeling a technical object taking into account dependent failures

The maintenance system was modeled for a test technical object consisting of six elements with a predefined structure of connections among elements (Fig. 2).

For each element, the cost of restoration C_i is given (taken as a constant), the reliability characteristics are given by the function of the average failure rate growth $h_i(t)$, p_i (probabilities of dependent failures of elements). The $h_i(t)$ value for each element is taken as a quadratic dependence (19), where a_1, a_2, a_3 are the model coefficients, and *T* is the time of the start of operation. The $h_i(t)$ dependences reflect the individual nature of the change in the technical condition of each of the elements.

The probabilities of dependent failures p_i [0, 0.1, 0.2, 0.15, 0.07, 0.05] are given for pairs of directly connected elements according to the structure of connections (Fig. 2) and are used in the formation of waves of dependent failures according to (9) to (11).

The dependent failure probabilities $p_{21} = 0.1$, $p_{31} = 0.2$, $p_{51} = 0.07$, $p_{61} = 0.05$, $p_{42} = 0.15$, $p_{52} = 0.07$, $p_{62} = 0.05$, $p_{23} = 0.1$, $p_{53} = 0.07$, $p_{63} = 0.05$, $p_{24} = 0.1$, $p_{54} = 0.07$, $p_{64} = 0.05$, $p_{65} = 0.05$ are given for pairs of directly connected elements according to the structure of connections (Fig. 2) and are used in the formation of dependent failure waves according to (9) to (11).

The input data for simulation (the cost of restoring elements C_i, parameters of the functions $h_i(t)$ and the structure of elements' connections) were taken in accordance with the calculation example given in [2].

Based on the set of initial assumptions, the cost of the maintenance system was estimated for alternative TM&R approaches. This ensures comparability of the results and makes it possible to assess the impact of the proposed methodology without distortion associated with changing the initial data.

The initial parameters for simulation are given in Table 1.

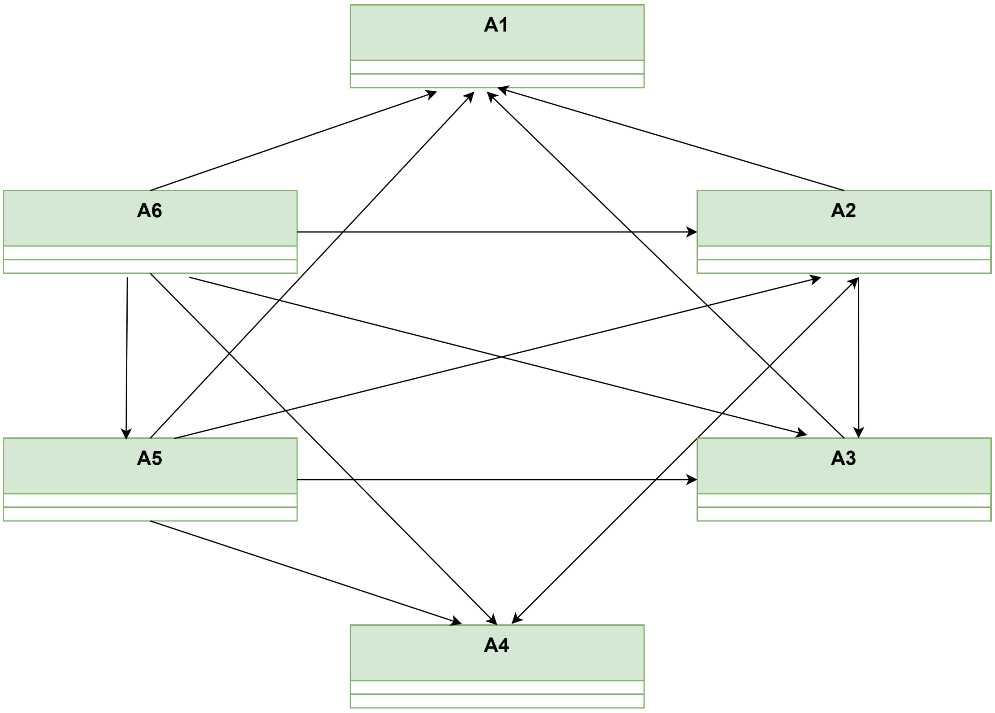


Fig. 2. Graph of connections among elements of a technical object: A1, A2, A3, A4, A5, A6 – elements' IDs

Table 1

Input data for modeling

Element name	Cost of restoration, C_i, arbitrary monetary unit	Function coefficients $h_i(t)$		
		a_1	a_2	a_3
A1	8.62	7.68	–11.5	7.41
A2	6.29	2.71	–7.49	5.48
A3	50.51	1.41	–1.79	1.03
A4	6.59	0.93	–3.00	2.42
A5	36.60	1.29	–3.83	3.37
A6	32.74	0.622	–0.063	0.286

The cost of restoration for each element is fixed. Based on the research reported in [2], the *h*-characteristic for each element of the system is usually calculated using a quadratic model

$$h(t)=a_1+a_2(t-T)+a_3(t-T)^2, \tag{19}$$

where T is the time of the start of operation; a_1, a_2, a_3 are the model coefficients.

5. 2. Formation of maintenance and repair strategies based on risk acceptance thresholds and construction of a rational maintenance system

To form a maintenance and repair strategy that takes into account the threshold value of the risk of failures, the following algorithm of actions has been developed:

1) the limit level of acceptable risk VaR and the corresponding threshold $h(VaR)$ are set, which determines the permissible growth rate of the average number of failures;

2) for each element (node) of a technical object, the $h(t)$ value is determined according to the adopted $h(t)$ dependence and the moments of reaching the threshold $h(VaR)$ are set;

3) according to rule (7), the j-th planned repair impact includes elements for which $h(t)$ reaches the threshold $h(VaR)$;

4) for the formed j-th repair impact, expected costs are calculated from formula (8);

5) for each element, a set of dependent failures ("first wave") is determined according to (9); if necessary, subsequent generations of dependent failures are taken into account, the sets are formed according to (10), (11);

6) the risk level is calculated taking into account dependent failures according to (16); for comparison, the risk level is additionally determined assuming independent failures according to (17), (18);

7) the fulfillment of the risk acceptability restriction $R \leq VaR$ in the statement of problem (2) is checked, after which a sequence of planned repair impacts (TM&R strategy) is formed at a given operating interval;

8) the total costs of the maintenance system are determined from formula (1) for two cases: without taking into account dependent failures and with taking into account dependent failures;

9) the calculations are repeated for a set of VaR values corresponding to the adopted TM&R strategies, after which the strategies are compared by total costs and risk level.

The described algorithm provides a reproducible transition from the input parameters of the model (C_i, $h(t)$, p_k, VaR and the structure of dependent relationships of elements) to the construction of TM&R strategies and obtaining cost/risk indicators.

Calculations were carried out for a set of VaR values corresponding to the adopted TM&R strategies 1–9 (Table 2).

Each maintenance system corresponds to a separate TM&R strategy and is characterized by an accepted threshold level of failure risk and the corresponding level of costs for planned and unplanned restorations.

Based on the initial data, the risk and cost of the maintenance system for TM&R strategies 1–9 (Table 2) was calculated using the adopted VaR and $h(VaR)$ thresholds.

Table 2

Adopted TM&R strategies

Adopted TM&R strategy	The limiting value of the growth rate function of the average number of failures over operating time $h(VaR)$	Marginal cost of VaR recovery, arbitrary monetary units
1	30	700
2	40	950
3	50	1150
4	60	1400
5	70	1650
6	80	1900
7	90	2150
8	100	2400
9	110	2650

5. 3. Total costs and number of planned repair impacts for the specified strategies

A rational maintenance system was formed for two settings: without taking into account dependent failures and with taking into account dependent failures of technical facility elements. The total costs for the life cycle period are given in Table 3.

Fig. 3, 4 show the distribution of repair impacts of a rational maintenance system for strategies 1 and 9 for the entire life cycle of a technical object. The selected strategies reflect two extreme options for the settings of the technical maintenance system and allow us to clearly assess the impact of the adopted risk thresholds on the structure of repair impacts. Strategy 1 corresponds to the most stringent (conservative) risk acceptance thresholds, while strategy 9 – the softest (liberal); therefore, their comparison demonstrates the maximum range of changes in repair schedules and cost structure.

Table 3

Total TM&R costs over the life cycle

Adopted strategy	Additional costs at a given level of risk, VaR, arbitrary monetary units	Costs for planned restoration, arbitrary monetary units	Recovery costs taking into account dependent failures, arbitrary monetary units	Number of planned repair impacts, n
1	700	1660	2010	17
2	950	1450	1940	17
3	1150	1100	1530	16
4	1400	1050	1440	16
5	1650	959	1430	16
6	1900	831	1390	15
7	2150	798	1260	16
8	2400	776	1220	16
9	2650	731	1170	16

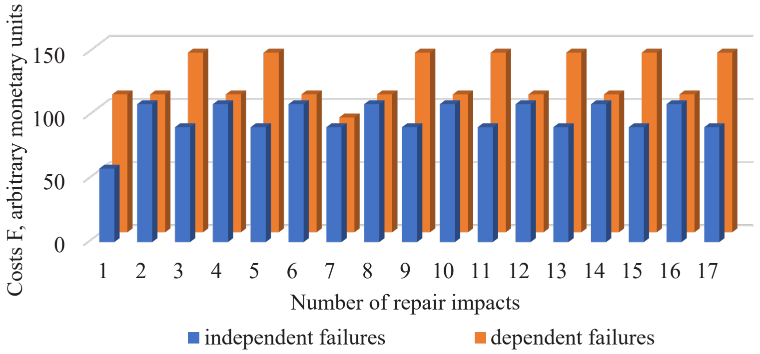


Fig. 3. Distribution of repair impacts of a rational maintenance system for the first adopted strategy over the entire life cycle of a technical object

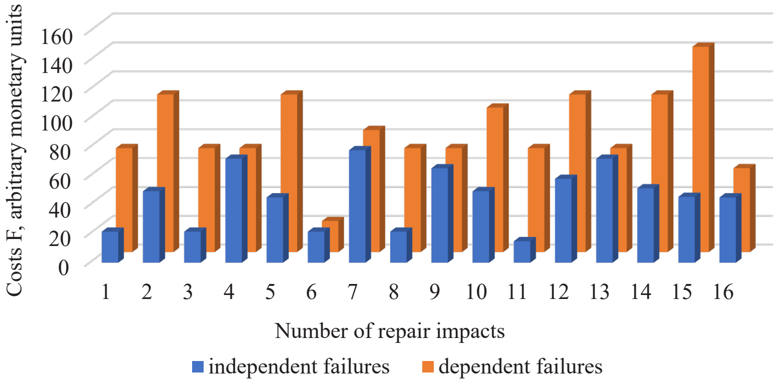


Fig. 4. Distribution of repair impacts of a rational maintenance system for the ninth adopted strategy over the entire life cycle of a technical object

Based on the results of strategy 1 (Fig. 3) and strategy 9 (Fig. 4), the difference is manifested in two aspects: the number of planned repair impacts and the level of costs. For strategy 1, 17 planned repair impacts are formed, while for strategy 9–16, i.e., for strategy 1, repair events are generally more frequent. At the same time, according to Table 4, for strategy 1, the costs of planned restoration are 1660, and taking into account dependent failures – 2010 (for $n = 17$); for strategy 9, respectively, 731 and 1170 (for $n = 16$).

Therefore, strategy 1 provides higher total costs and a more intensive schedule of planned impacts, while strategy 9 is characterized by lower basic planned costs.

5. 4. Analyzing the structure of repair impacts and costs depending on the strategy

The impact of the cost of restoring elements on planned maintenance is illustrated by a heat map (Fig. 5), which shows the frequency of inclusion of each element in planned repair impacts depending on the TM&R strategy.

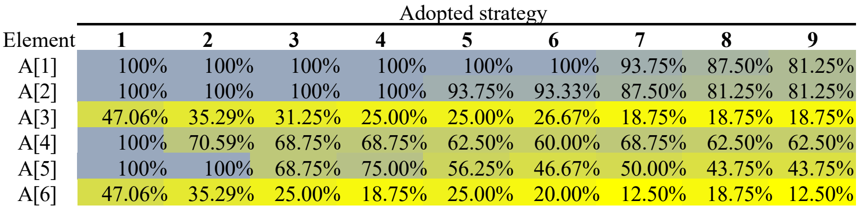
As can be seen from Fig. 5, in the studied technical object, elements A_1 and A_2 are included in the repair impacts practically during each planned repair; elements A_3 and A_6 are characterized by higher reliability indicators. Therefore, with an increase in the accepted level of risk, the frequency of their inclusion in planned repairs decreases to 12–19%. Elements A_4 and A_5 occupy an intermediate position and are characterized by a gradual transition from frequent, almost constant repairs to the implementation of repair impacts in approximately half of the cases.

The number of elements that are simultaneously subjected to repair impacts for each accepted level of risk is shown in Fig. 6.

Fig. 7, 8 show a comparison of the distribution of costs for planned and unplanned repairs for different TM&R strategies without and with dependent failures.

Taking into account dependent failures leads to an increase in the total costs of the maintenance system and changes the ratio between planned and unplanned repairs.

As a result, the dependence of the total costs of the maintenance system on the selected TM&R strategy was constructed for cases without and with dependent failures (Fig. 9).



	Adopted strategy								
Element	1	2	3	4	5	6	7	8	9
A[1]	100%	100%	100%	100%	100%	100%	93.75%	87.50%	81.25%
A[2]	100%	100%	100%	100%	93.75%	93.33%	87.50%	81.25%	81.25%
A[3]	47.06%	35.29%	31.25%	25.00%	25.00%	26.67%	18.75%	18.75%	18.75%
A[4]	100%	70.59%	68.75%	68.75%	62.50%	60.00%	68.75%	62.50%	62.50%
A[5]	100%	100%	68.75%	75.00%	56.25%	46.67%	50.00%	43.75%	43.75%
A[6]	47.06%	35.29%	25.00%	18.75%	25.00%	20.00%	12.50%	18.75%	12.50%

Fig. 5. Heat map of system element repairs

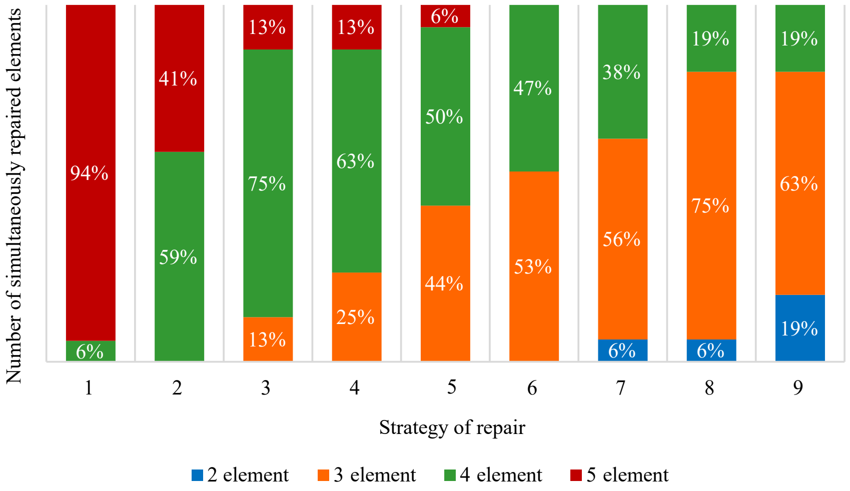


Fig. 6. Repair volumes depending on the level of the adopted strategy

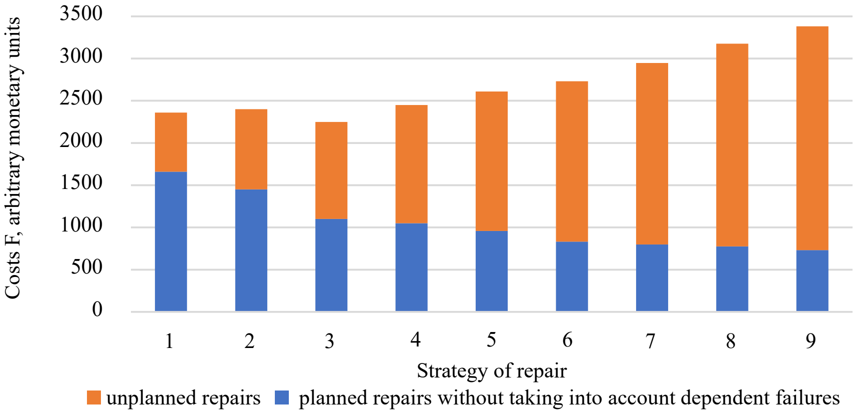


Fig. 7. Distribution of costs for planned and unplanned restorations for each selected strategy without taking into account dependent failures

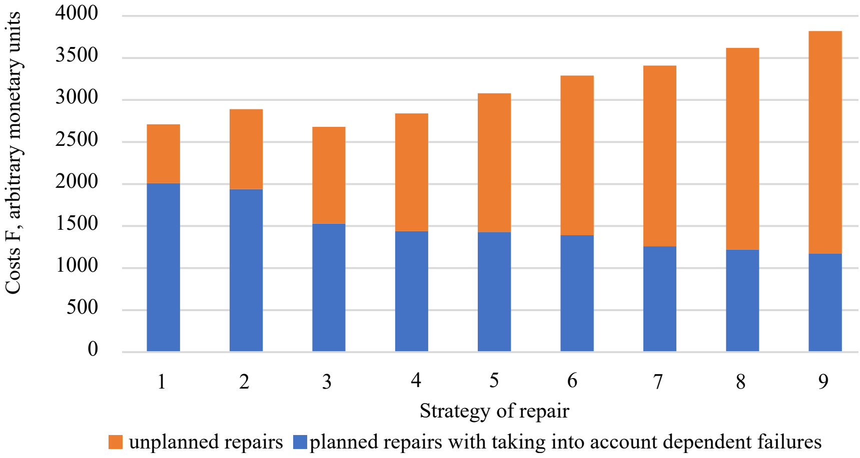


Fig. 8. Distribution of costs for planned and unplanned restorations for each selected strategy, taking into account dependent failures

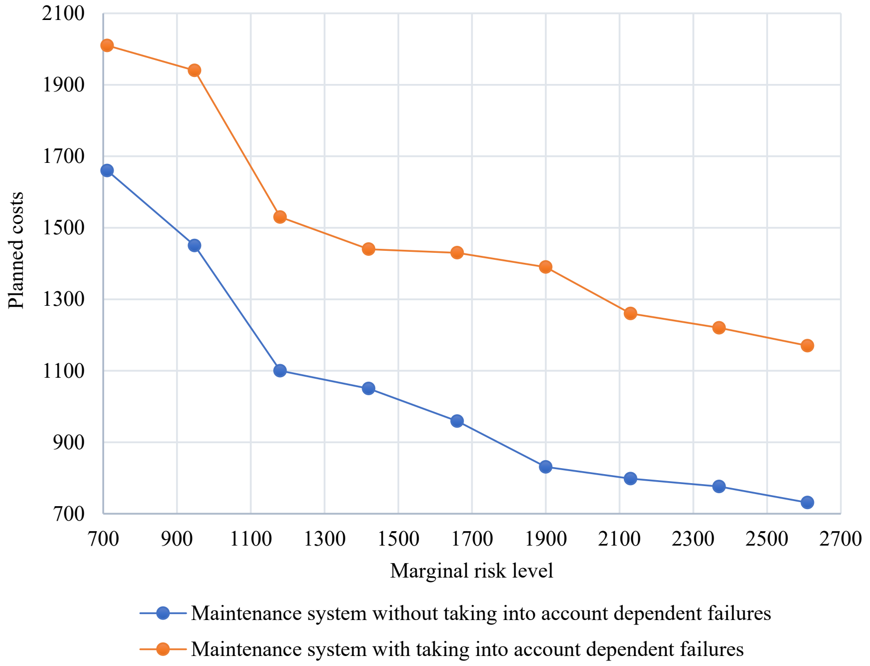


Fig. 9. Dependence of costs on maintenance system depending on the chosen strategy

The resulting dependence of the maintenance system costs on the marginal risk level *VaR* has a pronounced nonlinear character. Taking into account dependent failures causes a shift of the cost curve upwards, which indicates an underestimation of the costs of the maintenance system in models that do not take into account dependent node failures.

6. Discussion of results based on investigating the risk-oriented model of technical maintenance

Our results are explained by the fact that in the proposed statement, the TM&R strategy is formed according to the accepted threshold level of risk ("value at risk") and the corresponding threshold value of the growth rate of the average number of failures. Changing the threshold level of the accepted risk determines the compromise between the frequency of planned repair impacts and the proportion of unplanned restorations. At lower risk thresholds, the intensity of planned impacts and planned costs increase. At higher risk thresholds, the planned component decreases, but the contribution of unplanned restorations increases (Fig. 7, 8, Table 3). The nonlinear nature of change in total costs when the risk acceptance threshold changes is confirmed by the dependence in Fig. 9, which reflects the uneven sensitivity of costs to changes in the accepted risk level. This result is consistent with the conclusions from [17–19], which show that a change in the structure of repair impacts significantly affects the total life cycle costs.

In [4, 5], risk-based approaches and FMEA/FMECA methodologies are used mainly for ranking failures by criticality and supporting decision-making on maintenance. However, in those studies there is no mechanism for directly forming repair impacts based on a quantitative risk acceptance threshold and economic comparison of alternative TM&R strategies. In the proposed work, the *VaR* criterion is used not only as an indicator of risk assessment but also as an element of the procedure for building a maintenance strategy, which makes it possible to form sets of repair impacts depending on the acceptable level of risk.

The peculiarity of the proposed approach is to use the cost risk acceptance threshold as the only criterion for comparing alternative strategies. The adopted approach makes it possible to compare decisions on the "cost – risk" scale and justify the choice of strategy for a given level of risk acceptance (Tables 2, 3). Unlike approaches that provide ranking of failures by criticality, in our work the threshold criterion is used to form sets of repair impacts and further comparison of strategies by total costs (Fig. 7–9). Taking into account dependent failures in the model is considered as a refinement of the calculation of risk and costs, which increases the correctness of the economic assessment for interconnected nodes; in practice, this is manifested in the shift of cost estimates compared to the case of independent failures (Fig. 9).

The limitations of our study are related to the conditions for applying the threshold approach. First, it is necessary to set a threshold level of risk acceptability in cost terms and the corresponding reliability parameters for the nodes, otherwise the comparison of strategies loses its practical meaning. Second, the quality of results depends on the adequacy of the cost indicators and reliability parameters because they determine the form of the dependences in Table 3 and Fig. 9. Third, our results were obtained at a test object; when scaling to a real locomotive fleet, the need for reliable operational data increases.

The shortcomings of the study are due to the adopted simplifications of the economic model. In particular, the aggregate repair method and the constant cost of the planned repair impact simplify the cost estimate and do not take into account the possible change in the repair cost over time or the dependence of costs on the depth of restoration. This drawback can be eliminated by introducing alternative repair impacts (repair of different levels/replacement) and differentiated cost models.

Further studies should be directed towards substantiating the choice of the threshold level of acceptable risk in relation to actual operating and downtime limitations. Automation of reliability parameter assessment based on operational and diagnostic data. The main difficulties on this path are related to the completeness and quality of data, the heterogeneity of operating conditions, as well as the need to validate parameters on real samples.

7. Conclusions

1. We have modeled a test technical object with six interconnected elements, for which the restoration costs, parameters of the growth rate functions of the average number of failures, and the probability of dependent failures were given. This ensured the reproducibility of calculations and the

comparability of results. As a result of the simulation, dependences were obtained for estimating the cost of the technical object maintenance system, taking into account dependent failures of its nodes. The resulting dependences were used in the development of maintenance and repair strategies with an accepted limit level of failure risk. This, in turn, allowed the formation of rational maintenance strategies based on two indicators – the accepted limit level of failure risk and taking into account dependent failures of nodes.

2. An algorithm for forming a maintenance and repair strategy that takes into account the threshold value of the risk of failures has been developed. A set of alternative maintenance and repair strategies has been formed, differing in risk acceptance thresholds and the corresponding threshold values of the growth rate function of the average number of failures. For each strategy, a rational maintenance system has been constructed in the form of a sequence of planned repair impacts at a given operating interval. The rationality of each maintenance system was determined by solving an optimization problem with the corresponding threshold risk level.

3. For each formed strategy, the total costs of the maintenance system and the number of planned repair impacts were determined in two variants: without and with dependent failures. It is shown that taking into account dependent failures increases the estimate of maintenance costs by 18–47% depending on the adopted risk threshold.

4. The structure of repair impacts and costs depending on the selected TM&R strategy has been analyzed, in particular the frequency of element repairs, the volume of repairs, and the ratio of planned and unplanned repairs. The nonlinear nature of the change in total costs with the increase in the accepted risk threshold has been established, which is explained by the redistribution between planned and unplanned repairs.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

The data will be provided upon reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

Authors' contributions

Borys Bodnar: Supervision, Writing – Review & Editing, Project administration; **Oleksandr Ochkasov**: Conceptualization, Methodology, Formal analysis, Investigation, Validation, Writing – Original Draft, Writing – Review & Editing; **Tetiana Hryshechkina**: Software, Methodology, Formal analysis, Data curation, Visualization, Writing – Review & Editing; **Oleksandr Zhovnirenko**: Investigation, Resources, Validation, Data curation, Visualization.

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