

ЕКСПЛУАТАЦІЯ ТА РЕМОНТ ЗАСОБІВ ТРАНСПОРТУ

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CHOOSING THE SYSTEM OF LOCOMOTIVE MAINTENANCE IN VIEW OF THE EFFECT OF DEPENDENT FAILURES

Purpose. Improving the efficiency of the use of locomotives by choosing a rational maintenance system that takes into account the assessment of the effect of dependent failures on the cost of their life cycle is the main purpose of this paper. **Methodology.** The relevance of introducing LCC (Life Cycle Cost) approaches in locomotive facilities is explained by the introduction of new locomotives with on-board control and diagnostic systems, as well as the development of the theory of traction rolling stock maintenance systems. The cost of a locomotive as a traction unit ceases to be the determining factor. This is because the locomotive maintenance and repair cost for the entire period of its operation is much higher than the initial cost of the locomotive. The paper analyses the existing approaches to managing the cost of the life cycle of locomotives at the stages of selecting, updating, upgrading and operating the traction rolling stock. The necessity of improving the methods for assessing the degree of influence of reliability indicators of locomotive assemblies on the choice of the maintenance system and the cost of the locomotive life cycle is substantiated. **Findings.** It is proposed to use the concept of «the effect of dependent failures» when calculating the cost of locomotive renewal after unscheduled repairs and its life cycle cost. We improved the methods for determining the cost of unscheduled repairs, taking into account dependent failures and the coefficient of assessment of the effect of dependent node failure on the locomotive maintenance system. The proposed coefficient will determine the nodes, the failure of which affects the renewal cost more than their nominal value. It will also help to take into account the probable losses due to node failure during the development and adjustment of the locomotive maintenance system. **Originality.** For the first time, it is proposed to use the concept of the effect of dependent failures to calculate the locomotive renewal cost when performing unscheduled repairs, as well as the locomotive life cycle cost. **Practical value.** The improved calculation method for determining the cost of unplanned repairs with account taken of dependent failures can be used to compare and evaluate different variants of the locomotive maintenance system and to develop the locomotive diagnostic systems.

Key words: life cycle cost; maintenance system; locomotive; dependent failures; renewal costs; unscheduled maintenance

Introduction

The task of minimizing total costs at all stages of the lifecycle of vehicles, improving the reliability and safety of equipment is common to both locomotive developers and operating transport com-

panies. For the rail industry, minimizing such costs increases the competitiveness of products and, consequently, stimulates the expansion of the market and increase in profits. For operating companies, thus, the economic efficiency of using rolling stock rises [10].

When substantiating the choice of the most advantageous offer for the supply of traction rolling stock, transport companies, along with comparison of technical characteristics, are increasingly using the LCC (Life Cycle Cost) indicator. Величина капітальних затрат на придбання нового тягового рухомого складу поступово починає замінюватись величиною витрат на всіх етапах життєвого циклу локомотива. The amount of capital costs for the acquisition of a new traction rolling stock gradually begins to be replaced by the cost of all stages of the locomotive life cycle [14, 17, 18].

Actuality of LCC approaches in locomotive services is explained by the introduction of new locomotives with onboard control and diagnostic systems, as well as the development of the theory of traction rolling stock maintenance systems. The cost of a locomotive as a traction unit ceases to be the determining factor. This is due to the fact that maintenance and repair costs for the entire life cycle of a locomotive considerably exceed its initial cost.

The works [3, 5, 9, 11-13, 15, 16, 21] are devoted to the introduction of LCC approaches at the stages of selecting, updating, modernizing and operating the traction rolling stock. Despite a significant number of research results on the use of LCC indicators, the issue of assessing the degree of influence of reliability indicators of locomotive assemblies on the choice of the maintenance system and the cost of the locomotive life cycle remains unsolved.

Purpose

The main purpose of the work is to increase the efficiency of the use of locomotives by choosing a rational maintenance system that takes into account the assessment of the effect of dependent failures on the cost of their life cycle. To achieve this purpose, it is necessary to analyze the existing approaches for managing the locomotive life cycle cost, as well as to develop a method for assessing the degree of influence of reliability indicators of

locomotive nodes on the choice of the maintenance system and the cost of the locomotive life cycle.

Methodology

The most commonly used approach in developing life-cycle cost management systems is the RAMS (Reliability, Availability, Maintainability, Safety).

Let us consider its embodiment in the railway standards of Europe, Russia and Ukraine.

The main characteristics, definitions and terms relating to RAMS and LCC of rail transport facilities are given in European Standard NF EN 50126-1-2000 [20]. An example of the practical use of the RAMS approach for assessing the safety status of locomotive facilities using an integral indicator is described in [19].

The basic provisions of the RAMS can be used to assess the locomotive operation and maintenance system in terms of reliability, availability, maintainability and safety during their interaction. The proposed approach defines the process based on the life cycle of the whole system, and the tasks in it; allows to effectively monitor and control the interaction between the elements.

Standard EN 50126 [20] presents the system (locomotive) life cycle that is a sequence of phases, each of which solves the corresponding tasks, which cover the entire system service life from the original concept to decommissioning.

The life cycle provides a framework for planning, managing, controlling and monitoring all aspects of the system, including RAMS. Fig. 1 shows the life cycle stages according to this standard.

At each stage of the life cycle, there are certain, related to this stage, tasks: general, tasks of reliability, performance, repairability, as well as also safety-related tasks.

The issues concerning calculations of the system life cycle cost are considered in the second stage, while forming the profile of the system purpose.

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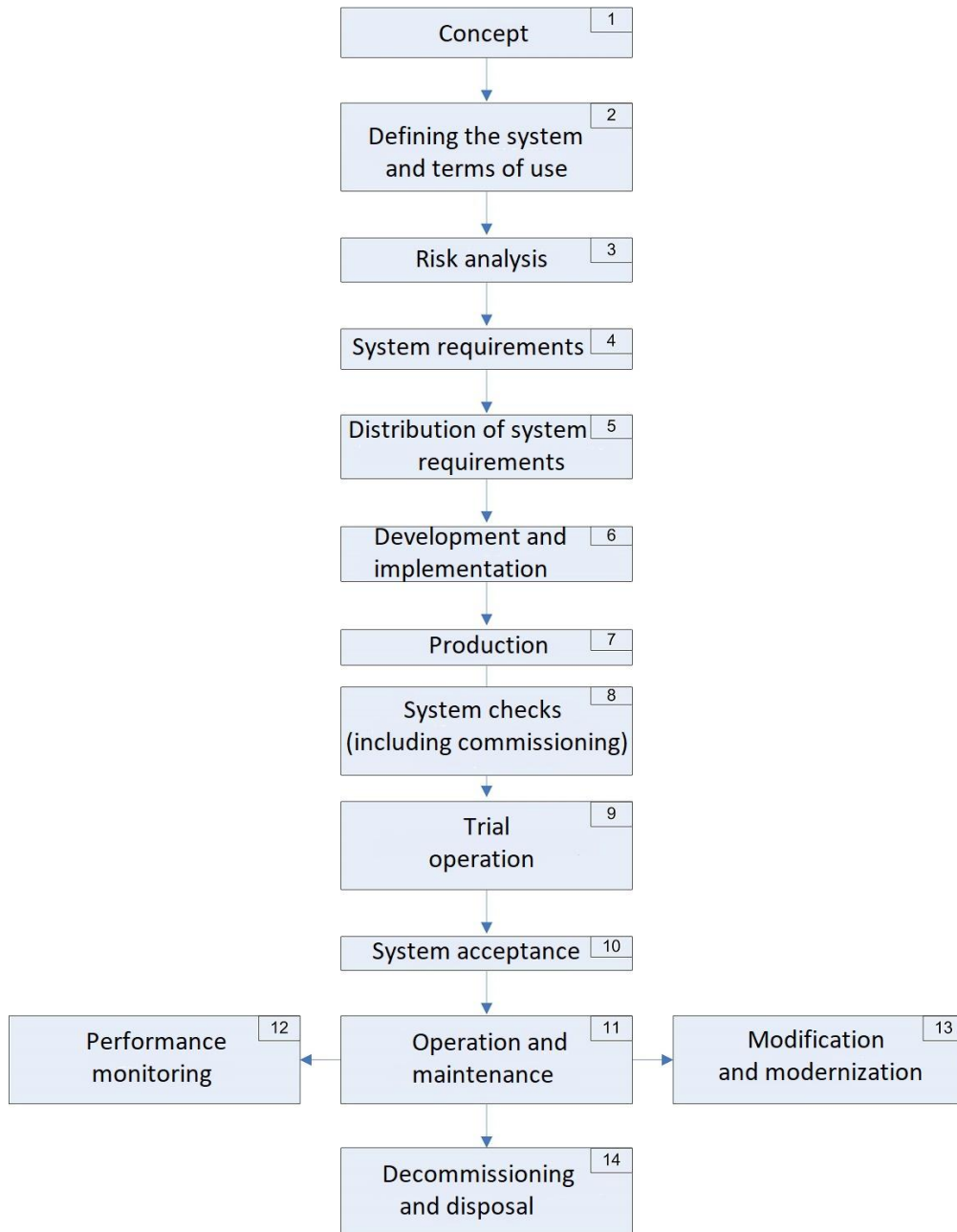


Fig. 1. Life cycle phases of the locomotive

The scheme of the system life cycle costs according to EN 50126 [8, 20] is shown in Fig. 2

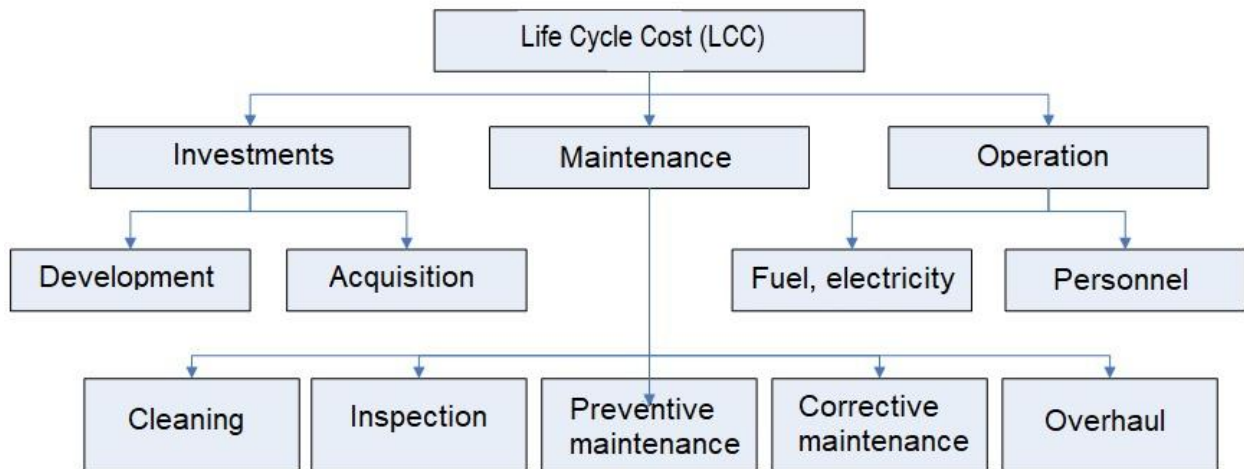


Fig. 2. Scheme of locomotive life cycle costs

The costs incurred during the design phase of the system, as well as those planned during the formation of the requirements for operation and maintenance, constitute a significant part of the locomotive life cycle cost.

It is impossible to determine the exact costs for the entire life cycle. They can be evaluated only with different degree of confidence.

Initial data for the analysis and calculation of the life cycle cost of the traction rolling stock are:

1. During the reliability, availability, maintainability and safety analysis (RAMS analysis):

- Service life;
- Average annual mileage of the locomotive;
- Average time of locomotive operation per year;
- Other quantitative and qualitative indicators of the use of locomotives.

2. When determining the life cycle cost (LCC analysis):

- Specifications / technical manuals from the component or subsystem provider (for example, FIT rate, MTBF rate)
- Identification, collection and use of statistical data (for example, failure rates, repair costs, part

$$CY_{MP} = \sum_{i=1}^X N_{MP_i} \times QT_i \times (CM_{MP_i} + MH_{MP_i} \times CMH)$$

where X – total number of elementary technological operations; N_{MP_i} – number of i -th elementary technological operations, which must be performed throughout the life cycle; QT_i – total number of elements requiring the use of the i -th elementary

replacement statistics, part wear dynamics, etc.);

- Models for forecasting changes in the technical condition of the locomotive and its subsystems;

Databases and statistical reports on the reliability and operation of locomotives.

The [20] presents two methods for calculation of costs for the life cycle components:

- Calculation of costs for preventive maintenance (analogue of planned preventive repair system);

- Calculation of costs for corrective maintenance (after failures) (analogue of the current state maintenance system).

Let us consider these methods in more detail.

Calculation of costs for preventive maintenance. Preventive maintenance, in accordance with European Standard EN 13306 (2001) [8], is maintenance performed at specified intervals or according to the proposed criteria. It is intended to reduce the likelihood of a failure or deterioration of the functioning of the technical unit.

Calculation of costs CY_{MP} for preventive maintenance during a life cycle is carried out by the formula:

technological operation; CM_{MP_i} – average cost of materials to be used during the use of the i -th elementary technological operation; MH_{MP_i} – number of working hours required for the imple-

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mentation of the i -th elementary technological operation; CMH – cost of 1 working hour.

This method does not take into account the following time expenditures:

- for organizational, administrative and logistic processes;
- for purchase / delivery of consumables;
- for emptying of wastewater reservoirs;
- in anticipation of service;
- for utilization duration;

– for external and internal cleaning of the vehicle.

Calculation of costs for corrective maintenance. Corrective (unscheduled) service according to [20] is the maintenance performed after the fault recognition. It is designed to restore a locomotive to a technical state in which it can perform the necessary functions.

Calculation of costs for corrective maintenance CY_MC during the life cycle is performed according to the formula:

$$QT = IN_FAI_i \times OT$$

$$CY_MP = \sum_{i=1}^X N_MC_i \times QT_i \times (CM_MC_i + MH_MC_i \times CMH),$$

where QT – number of elements to be restored for the entire life cycle; IN_FAI_i – failure rate of the i -th element; OT – operating time or run-time (depends on failure rate); N_MC_i – number of i -th elementary technological operations to be performed throughout the life cycle; QT_i – number of elements that require the use of the i -th elementary technological operation for renewal; CM_MC_i – average cost of materials for the implementation of the i -th elementary technological operation; MH_MC_i – number of working hours for the implementation of the i -th elementary technological operation; CMH – cost of a working hour.

Basic rules for determining the cost of life cycle of rolling stock and complex technical systems of rail transport on the Russian railways are given in [11]. This method contains the main provisions and formulas for calculating such indicators of the efficiency of rolling stock and complex technical systems of rail transport, as the life cycle cost, the useful economic effect and the limit price of machinery.

The life cycle cost indicator is used in this methodology to evaluate the effectiveness of innovative measures, including those at rail transport.

The term «Life cycle cost» (LCC) of the technical equipment in [11] is defined as the total consumer's cost for the purchase and use of the equipment for the duration of its service.

The life cycle costs of the technical equipment include all consumer costs associated with its acquisition and possession, that is, the purchase price, the associated one-time costs, as well as the

operating costs for the entire life and the costs of disposal.

The [11] proposes to limit the number of life cycle stages of technical equipment by the following stages:

- 1) Development of concepts and definitions;
- 2) Research and development works;
- 3) Manufacturing of technical means;
- 4) Putting technical equipment into operation with accompanying measures to train the personnel, upgrade the repair base, etc.;
- 5) Operation and maintenance;
- 6) Retirement (liquidation, disposal).

The general LCC of a product (of all its six stages) is divided into two main parts:

- 1) Costs associated with the acquisition (stages 1-4);

Costs related to operation and disposal (stages 5-6).

Initial LCC analysis is carried out at the acquisition stage – comparisons are made with analogues. Then, during the exploitation phase, the monitoring of economic indicators is carried out in order to confirm the initial life cycle costing.

LCC of rolling stock and complex technical systems of rail transport is defined in [11] by the formula:

$$LCC = P_{acq} + \sum_{t=1}^T (O_t + \Delta K_t - D_t) \cdot \alpha_t$$

where P_{acq} – object acquisition price (initial value). At the stage of new locomotive concept development and R&D works (1-2 stages of the life cycle)

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the equipment acquisition price can be presented as its limit price; O_t – annual operating costs; ΔK_t – accompanying one-time costs associated with putting of machinery into operation; D_t – disposal value of the object; α_t – discount coefficient; t – current year of operation; T – final year of operation, established in accordance with the technical requirements or other documentation (including the accounting policy of the enterprise on whose balance the object is located).

The discount coefficient for the constant discount rate is determined by the expression:

$$\alpha_t = \frac{1}{(1+E)^t}$$

$$LCC_i = \sum_{t=t_{n_i}}^{t_{k_i}} (m_i \cdot P_i^a \cdot \alpha_t) + \sum_{t=t_{a_i}}^{t_{k_i}} (K_i^{cyn} \cdot \alpha_t) + \sum_{t=t_{a_i}}^{t_{k_i}} (m_i \cdot P_i^{OV} \cdot \alpha_t) + \sum_{t=t_{a_i}}^{t_{d_i}} (m_i \cdot P_i^M \cdot \alpha_t) + \sum_{t=t_{n_{ai}}}^{t_{k_i}} (m_i \cdot O_i \cdot \alpha_t) - \sum_{t=t_{n_{ai}}}^{t_{k_i}} (m_i \cdot D_i \cdot \alpha_t),$$

where i – investment variant number; m_i – number of traction rolling stock units by the i -th investment variant purchased in year t of the lifecycle; P_i^a – price of acquisition of the traction rolling stock unit by the i -th investment variant in year t of the life cycle, UAH; K_i^{ass} – one-time associated costs during implementation of the rolling stock by the i -th investment variant in year t of the life cycle, UAH; P_i^{OV} – price of overhaul of the traction rolling stock unit by the i -th investment variant in year t of the life cycle, UAH; P_i^M – price of modernization of the traction rolling stock unit by the i -th investment variant in year t of the life cycle, UAH; O_i – current expenses for operation and maintenance in a technically sound condition of the rolling stock by the i -th investment variant in year t of the life cycle, UAH; D_i – disposal value of the traction rolling stock unit by the i -th investment variant in year t of the life cycle, UAH; α_t – discount factor; t_{a_i} – year of acquisition of the traction rolling stock by the i -th investment va-

where t – step of the calculation period ($t = 0, 1, 2, \dots, T$); T – time horizon (life cycle duration); E – discount rate.

In [13] it was noted that despite the significant number of research results regarding the use of the LCC economic indicator as one of the main criteria for evaluating and approving investment decisions in the long run, the issue of adaptation of this indicator to the operational features of Ukrainian railways needs further development. The paper proposes to calculate the rolling stock life cycle cost for alternate investment variants in its renewal as follows:

riant; t_{d_i} – year of disposal of the rolling stock by the i -th investment variant.

Findings

The conducted analysis of the life cycle costing approaches allows us to conclude that none of the considered methods takes into account the effect of failure of one node on the failure of other connected nodes (dependent failures of system elements) of the locomotive. According to researches [4, 6], quite a significant part of failures (and, as a consequence, of unscheduled repairs) occurs due to the dependent failures of elements. Thus, when calculating LCC and costs for all types of maintenance, it is necessary to take into account the effect of dependent locomotive failures.

One of the LCC components is the locomotive maintenance cost. The amount of these costs depends on the reliability indicators and the accepted technical maintenance system. Methods for assessing the economic efficiency of a locomotive maintenance system are given in [2, 3, 7]. In order to improve the methodology for calculating the locomotive maintenance system cost, the authors

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suggest taking into account the dependent failures of nodes.

According to [3], the cost of unscheduled repairs in a rational system without taking into account dependent failures can be defined as follows:

$$C = C_{\text{unsch}} \cdot H_p$$

where C_{unsch} – average cost of unscheduled repair of the locomotive node; H_p – average number of failures during an hour of the locomotive life cycle.

The average cost of one unscheduled repair C_{unsch} is determined by the expression:

$$C_{\text{unsch}} = C_{\text{sch}} + C_{\text{lh}}(t_{\text{tr}} + t_{\text{dt}}),$$

where C_{sch} – cost of one scheduled repair; C_{lh} – cost of one locomotive-hour; t_{tr} – time of locomotive transportation to the place of repair; t_{dt} – locomotive repair downtime.

In order to calculate the renewal costs during unscheduled repairs, it is necessary to take into account dependent failures of the elements. To cal-

culate the life cycle cost of a locomotive with account taken of the dependent failures of its elements, it is necessary to determine the probabilistic dependencies between the failures of its main nodes, that is, with what probability the failure of each node will affect the failure of other locomotive nodes.

The average cost of one unscheduled repair C_3 , taking into account the dependent failures, is determined by the expression:

$$C_3 = C_{\text{sch}} + \sum_{i \in V} p_i C_{\text{sch}}^i + C_{\text{lh}}(t_{\text{tr}} + t_{\text{dt}})$$

where C_{sch}^i – cost of one scheduled repair of the i -th dependent element; p_i – probability of dependent failure of the i -th element; V – set of dependent elements.

Calculation of the probability of dependent failures can be performed using expert research methods [1], methods of fuzzy logic and neural networks [22]. In general, the probability of occurrence of dependent failures is presented in the Table 1.

Table 1

Probabilities of occurrence of dependent failures

Locomotive equipment	Node 1	Node 2	...	Node i	...	Node N
Node 1		p_{12}		p_{1i}		p_{1N}
Node 2	p_{21}			p_{2i}		p_{2N}
...						
Node i	p_{i1}	p_{i2}				p_{iN}
...						
Node N	p_{N1}	p_{N2}		p_{Ni}		

Table 1 in the columns indicates the names of nodes with primary failures, and in rows – the names of nodes with dependent failures. The elements of this matrix (tables) are filled by experts, which indicate the probability of dependent failures for each node of the locomotive.

For example: p_{12} is the probability that a dependent failure of Node 1 will occur in the event of Node 2 failure. In general:

p_{iN} – probability that a dependent failure of the Node i will occur in the event of the Node N failure.

It is obvious that the probabilities of the type are always equal to one.

To estimate the influence of dependent failures on the locomotive maintenance system and life cycle cost, we propose to use a coefficient P_{df} .

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This indicator of the dependent failure effect on the after-failure renewal cost is calculated as follows:

$$P_{df} = \frac{C_3}{C_{unsch}} \cdot 100\%$$

Calculation of the coefficient P_{df} for each node of the locomotive can be performed according to the Table 2.

Table 2

Assessment of the effect of dependent failures on the maintenance system

Node group	Node name	Cost of scheduled node repair	Cost of unscheduled node repair	Cost of unscheduled node repair with account of dependent failures	Assessment of the effect of dependent failures
	Node 1	C_{sch}	C_{unsch}	C_3	P_{df}
	Node 2				
	...				
	Node i				

Originality and practical value

For the first time, it is proposed to use the concept of the effect of dependent failures to calculate the locomotive renewal cost when performing unscheduled repairs, as well as the locomotive life cycle cost.

The method of determining the unscheduled repair costs with consideration of dependent failures was improved in the work; and the coefficient of assessing the effect of node dependent failure on the locomotive maintenance system was introduced.

The calculation method can be used to compare and evaluate variants of the locomotive maintenance system and to develop systems for their diagnosis.

Conclusions

The work analyzed the existing approaches to the management of the life cycle cost of locomotives at the stages of their selection, renewal, modernization and operation.

We substantiated the necessity of improving the methods for assessing the degree of effect of reliability indicators of locomotive units on the choice of the maintenance system and its life cycle cost.

We conducted the analysis of modern approaches to managing the locomotive maintenance system.

It is proposed to use the concept of «effect of dependent failures» when calculating the locomotive renewal cost after unscheduled repairs and the locomotive life cycle cost.

The proposed coefficient of the effect of the node dependent failure on the locomotive maintenance system will allow determining the nodes, the failure of which affects the renewal cost more than their nominal value. Also, this coefficient will help to take into account probable losses due to node failure during the development and adjustment of the locomotive maintenance system.

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ВИБІР СИСТЕМИ УТРИМАННЯ ЛОКОМОТИВІВ ІЗ УРАХУВАННЯМ ВПЛИВУ ЗАЛЕЖНИХ ВІДМОВ

Мета. Основною метою роботи є підвищення ефективності використання локомотивів за рахунок вибору раціональної системи утримання, яка враховує оцінку впливу залежних відмов на вартість їх життєвого циклу. **Методика.** Актуальність застосування підходів LCC (Life Cycle Cost) в локомотивному господарстві пояснюється впровадженням нових локомотивів із бортовими системами управління й діагностування, а також розвитком теорії систем утримання тягового рухомого складу. Вартість локомотива як тягової одиниці перестає бути визначальним фактором. Це пояснюється тим, що витрати на технічне обслуговування та ремонт локомотива за весь період експлуатації значно перевищують його початкову вартість. У роботі проаналізовано наявні підходи управління вартістю життєвого циклу локомотивів на етапах їх вибору, оновлення, модернізації й експлуатації. Обґрунтовано необхідність удосконалення методів оцінки ступеня впливу показників надійності вузлів локомотива на вибір системи утримання й вартість його життєвого циклу. **Результати.** Запропоновано використовувати поняття «вплив залежних відмов» під час розрахунку вартості відновлення локомотива після позапланових ремонтів і вартості його життєвого циклу. Удосконалено методику визначення вартості позапланового ремонту з урахуванням залежних відмов, уведено коефіцієнт оцінки впливу залежної відмови вузла на систему утримання локомотива. Цей коефіцієнт дозволить визначати вузли, відмова яких впливає на вартість відновлення більше, ніж номінальна їх вартість. Також запропонований коефіцієнт допоможе враховувати ймовірні втрати внаслідок відмови вузла під час розробки й коригування системи утримання локомотивів. **Наукова новизна.** Уперше запропоновано використовувати показник впливу залежних відмов для розрахунку вартості відновлення локомотива під час виконання позапланових ремонтів, а також для розрахунку вартості життєвого циклу локомотива. **Практична значимість.** Удосконалена методика визначення вартості позапланового ремонту з урахуванням залежних відмов може бути використана для порівняння й оцінки різних варіантів системи утримання локомотивів і розробки систем їх діагностування.

Ключові слова: вартість життєвого циклу; система утримання; локомотив; залежні відмови; вартість відновлення; позаплановий ремонт

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ВЫБОР СИСТЕМЫ СОДЕРЖАНИЯ ЛОКОМОТИВОВ С УЧЕТОМ ВЛИЯНИЯ ЗАВИСИМЫХ ОТКАЗОВ

Цель. Основной целью работы является повышение эффективности использования локомотивов за счет выбора рациональной системы содержания, учитывающей оценку влияния зависимых отказов на стоимость их жизненного цикла. **Методика.** Актуальность применения подходов LCC (стоимость жизненного цикла) в локомотивном хозяйстве объясняется внедрением новых локомотивов с бортовыми системами управления и диагностики, а также развитием теории систем содержания тягового подвижного состава. Стоимость локомотива как тяговой единицы перестает быть определяющим фактором. Это объясняется тем, что расходы на техническое обслуживание и ремонт локомотива за весь период эксплуатации значительно превышают его первоначальную стоимость. В работе выполнен анализ существующих подходов управления стоимостью жизненного цикла локомотивов на этапах их выбора, обновления, модернизации и эксплуатации. Обоснована необходимость совершенствования методов оценки степени влияния показателей надежности узлов локомотива на выбор системы содержания и стоимость его жизненного цикла. **Результаты.** Предложено использовать понятие «влияние зависимых отказов» при расчете стоимости восстановления локомотива после внеплановых ремонтов и стоимости его жизненного цикла. Усовершенствовано методику определения стоимости внепланового ремонта с учетом зависимых отказов, введен коэффициент оценки влияния зависимого отказа узла на систему содержания локомотива. Этот коэффициент позволит определять узлы, отказ которых влияет на стоимость восстановления больше, чем номинальная их стоимость. Также предложенный коэффициент поможет учитывать вероятные потери вследствие отказа узла при разработке и корректировке системы содержания локомотивов. **Научная новизна.** Впервые предложено использовать показатель влияния зависимых отказов для расчета стоимости восстановления локомотива при выполнении внеплановых ремонтов, а также для расчета стоимости жизненного цикла локомотива. **Практическая значимость.** Усовершенствованная методика определения стоимости внепланового ремонта с учетом зависимых отказов может быть использована для сравнения и оценки различных вариантов системы содержания локомотивов и при разработке систем их диагностирования.

Ключевые слова: стоимость жизненного цикла; система содержания; локомотив; зависимые отказы; стоимость восстановления; внеплановый ремонт

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