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PRINCIPLES OF TRANSPORT MEANS MAINTENANCE OPTIMIZATION: EQUIPMENT COST CALCULATION

Purpose. Justification of principles and methodology for effective calculation of the equipment costs and optimization of transport means maintenance.

Methodology. The results of the presented scientific research were obtained using general and special methods of cognition: abstract and logical analysis, systematization and combination, method of theoretical generalization, method of dialectical cognition, deduction and induction, and statistical analysis. This paper analyzes the relationship between the probability of failure prevention by the maintenance system and the associated costs. The research investigates how the variation in the technical condition change rate influences the length of the operation cycle and the rate of its decline. The study's outcomes are analyzed, including the formation of points of minimum unit costs, the effect of spare parts' cost, and the practical importance of the conclusions drawn.

Findings. This paper outlines the economic methodology for determining the specific expenses of maintaining means of transport. The methodology considers the distribution of expenses for spare parts, labor, and other components. Using this methodology, it is possible to estimate the total costs of maintenance and make informed decisions about the efficient use of resources. It has been determined that the cost of spare parts impacts the efficiency of the maintenance system. Therefore, it is imperative to balance the cost for spare parts and safety, while considering the probability of failure. The method outlined in this work is versatile, which allows its adaptation and application to the specialized road transport.

Originality. The paper further develops the methodological approach to calculating equipment costs for transport maintenance, which is used to improve service efficiency and reduce expenses. The approach enables a comprehensive evaluation of the outcomes of enhancing failure prevention probability through the maintenance system. It also aids in managing unused parts' resources, particularly during short operating cycles.

Practical value. The study's findings can optimize the maintenance system, increase operational efficiency, and enhance the safety and reliability of means of transport, while reducing the costs associated with spare parts, labor, and other maintenance components. This approach aids in conserving resources, reducing operating costs, and is crucial for the financial stability and profitability of management companies.

Keywords: *maintenance, ship equipment, costs, failure prevention, operational efficiency*

Introduction. This article aims to address the problem of balancing scientific accuracy and reasonable cost when maintaining the machinery of cargo ships, necessitating a meticulous attention to detail and precise calculations. The problem is caused by the absence of sufficiently developed scientific methods to determine the cost of equipment and optimal strategies for integrated maintenance, resulting in an ineffective process.

During the initial phase of studying the scientific problem, sea and river means of transport were used as a basis. The method presented in this paper is versatile enough to be adapted and applied to specialized road transport.

The significance of this problem stems from the fact that an improperly calculated equipment cost may result in either underestimation or overpayment for its acquisition and upkeep. The absence of a systematic approach to rationalize the equipment cost can also contribute to inadequate maintenance effectiveness, unforeseeable breakdowns, and an increase in the overall cost of maintaining the ship's machinery.

Thus, solving this issue requires the development of scientific approaches and methodologies to accurately determine maintenance equipment costs and develop optimal strategies for the comprehensive maintenance of shipboard machinery. These science-based methods can help maximize maintenance efficiency, reduce costs, and ensure reliable and safe ship operations.

Various equipment for monitoring shipboard machinery has been developed after 2020, using a new element base. These tools have significantly improved capabilities compared to those used from 2000 to 2010. In particular, they utilize methods of real-time data analysis, artificial intelligence, and digital twins.

Modern real-time data analysis methods enable the collection, processing, and analysis of shipboard machinery information instantly and provide a quick response to changes in their technical condition. This improves maintenance efficiency and prevents malfunction incidents.

The implementation of state-of-the-art monitoring equipment to oversee shipboard machinery through the most recent technologies promotes the effectiveness of maintenance and guarantees the safety and reliability of cargo ships.

Literature review. A review of the most recent research and publications in the field of equipment costs and comprehensive maintenance of shipboard machinery reveals the following key findings:

Several studies aim to identify the best maintenance strategies to increase efficiency and decrease costs [1, 2]. Researchers focus on developing models to predict the condition of machinery, using vibration analysis methods and other diagnostic technologies to detect faults and prevent failures [3, 4].

Some publications highlight the significance of using economic analysis and optimization techniques for estimating equipment costs [5, 6]. Approaches that consider the costs of equipment production, supply, and maintenance, and determine the optimal maintenance level, taking into account risks and productivity losses, have been investigated [7, 8].

According to existing literature, there is a need to integrate information technology and management systems into the process of maintaining shipboard machinery [9]. Sensor-based monitoring and diagnostic systems, web portals, and cloud technologies can be utilized to efficiently collect, analyze, and process data for knowledge-based decisions on equipment maintenance and repair [10].

Several studies have focused on analyzing the impact of environmental factors, such as weather conditions, aggressive environments and equipment wear, on the technical condition and maintenance costs of machinery [11, 12]. The developed models and methodologies assist in evaluating risks and making appropriate decisions regarding the planning of equipment maintenance and replacement [13, 14].

Integrating maintenance with condition prediction is an effective strategy for reducing maintenance and repair expenses and minimizing ship machinery accidents on cargo ships [15]. Research on complex condition-based maintenance suggests a potential reduction in maintenance costs by 25 % [16, 17]. However, these assessments, which are cited in various sources, lack theoretical justifications and are mostly expert opinions.

The conclusions from these studies and publications show a wide range of research on the expenses of ship equipment and its intricate maintenance. Further research in this area will aid in developing scientific approaches and practical recommendations for the optimal management of ship systems maintenance.

Unsolved aspects of the problem. Further research should address the issues related to enhancing the scientific validity of the method used to calculate the costs of the equipment used for maintenance of the ship's machinery, in order to contribute to the improvement of maintenance efficiency and cost reduction. This topic and the purpose of the study are motivated by the insufficient development and the lack of scientific and methodological significance of these aspects.

Purpose. This article aims to justify the principles and methods of effective calculation of equipment costs and optimization of maintenance of means of transport.

Methods. The possibility of performing a comparative analysis on the usage of different maintenance methods for shipboard machinery of cargo ships, considering certain assumptions, is considered. The proposed methodology is based on a linear model of technical condition change. Four reasons can be identified that support its use:

1. There is a possibility of missing or having indirect, partial information about the technical condition changes between maintenance periods.
2. The dependence of the change in the technical condition is completed at the time of the maintenance and the next cycle of the process implementation starts anew.
3. The linear model enables the solution of the problem in a general dimensionless form, which minimizes the requirements for initial information about the results of the performed maintenance. Moreover, this model can be applied to any kind of on-board machinery.
4. The results are not significantly impacted using a nonlinear model as long as the probability of failure prevention by the maintenance system is the same for the comparison base.

Hence, the intervals and number of inspection operations are only affected using a nonlinear maintenance model compared to a linear model. If the costs of inspection are not considered, the impact is not significant.

To obtain comparable results, dependencies between the obtained values and the probability of failure prevention by the maintenance system (P_{pre}) are necessary, as previously stated. Once a suitable point with satisfactory results has been selected, it is possible to determine the frequency of scheduled maintenance or condition monitoring, which is necessary for practical use of the obtained results.

The formulas for determining life-cycle costs indicate that the costs for an asset over its entire lifecycle are directly affected by the consequences of failures, the severity of such failures, and the likelihood of being able to prevent such failures. The greater the consequences of failures and the lower the probability of being able to prevent such failures, the higher are the costs that can be expected to accrue during the asset's lifecycle.

The cost function (w) can be applied to analyze unit costs as long as the structure of scheduled and unscheduled maintenance costs does not comprise elements that rely on the duration of the operating cycle. Nonetheless, it is crucial to observe that the situation is not universally applicable and might vary based on the specific case of the maintenance of cargo ships' machinery.

Note that the probability of failure of respective parts (P_{ipre}) and the probability of failure prevention by the maintenance system (P_{pre}) are distinct and not equal. Nevertheless, these probabilities are interrelated, and depend not only on the reliability of the parts, but also on other characteristics. Consequently, losses resulting from the incomplete utilization of the resource are spread over successive maintenance cycles, even though these losses will only occur at the time of the last maintenance cycle.

When calculating the specific costs of the asset's maintenance and cost functions that depend on the maintenance cycle's duration, it is advisable to use the multiplier (R_{res}), which represents the residual life before failure in case this type of maintenance is not performed. The value of (R_{res}) is determined by the minimum resource of any parts that need replacement during maintenance or the resource required for preventive maintenance tasks such as cleaning and inspection for detection. Therefore, the remaining life of a part that is to be replaced during this maintenance can be expressed as follows

$$R_{ires} = R_{res} \cdot n_i.$$

If parts are replaced after several maintenance operations, which typically involve the most expensive parts, then the formula would be as follows

$$R_{ti} = 1 + R_{res} \cdot P_{ipre}(n_i).$$

To calculate the ratio of the remaining service life of the replaced part to the remaining service life prior to maintenance or failure, apply the following formula

$$n_i = \frac{R_{i\,res}}{R_{res}}.$$

The analysis of the operation cycle duration reveals a correlation between the probability of failure prevention and the reduction in the cycle duration. This reduction is more significant for probability values above 0.9. It is worth mentioning that the decline in the cycle duration depends on the variability of the technical condition change rate. This implies that objects with low variability in the possible rate of technical condition change have a certain probability of preventing failures. Therefore, there is an optimal frequency for scheduled maintenance, beyond which a further increase in frequency can result in a drastic increase in the cost of restoring the technical condition.

Optimal parameters of the maintenance system that ensure the lowest unit costs can be determined when modeling and optimizing the maintenance processes of cargo ship machinery. Optimization of the system is influenced by the probability of failure prevention through the maintenance system and depends on the consequences of failures, which uses the coefficient (K). Another significant factor is the nature of technical condition change rate distribution, along with its coefficient of variation (V). These parameters influence the equipment's technical condition change rate and the variation of this process [18]. Taking these factors into account aids in determining the optimal maintenance strategy, reducing costs, and increasing the efficiency of ship machinery operations.

The possible variation in the rate of technical condition's change (V) leads to a shift of the optimal point towards lower probabilities of failure prevention. Moreover, this optimum has less significance. In contrast, a decrease in the coefficient of variation shifts the optimal point to higher probabilities of preventing failure. Simultaneously, significant cost reductions occur during this shift of the optimal point compared to suboptimal values.

Controlling the variation in the rate of change in technical condition is important when designing maintenance strategies for ship equipment. Utilizing optimal coefficient of variation values can lead to better cost reduction and increased reliability of shipboard equipment operation.

Regarding spare parts costs, it is vital to mention that there are no optimal unit cost points. When the maintenance system's probability of failure prevention increases, more unused life remains for part replacement, especially in short life cycles. Specific cost values rely on parameters characterizing the maintenance system through failure prevention probability and the object of operation's properties, such as coefficient of variation for technical condition rate of change (V) and the distribution law.

It is necessary to analyze and set the parameters of the maintenance system carefully to calculate the unit costs of spare parts. To achieve optimal results, it is essential to balance the probability of preventing failures, unused resources, and the efficiency of using spare parts.

To calculate the dependencies for the specific costs of spare parts in cargo ship machinery maintenance, an appropriate normalization factor is required. This factor should consider the ratio of spare parts costs to other cost components, such as labor and other factors. Additionally, the costs of the maintenance itself should also be taken into consideration.

Calculations like these enable obtaining the dependence of total specific costs, which covers both the cost of spare parts and the cost of other maintenance elements [19]. This method permits a more thorough evaluation of the total costs related to maintenance, and it facilitates informed decision-making regarding resource efficiency.

The analysis of the calculation results indicates that during the maintenance of shipboard machinery on cargo ships, identifying the points of minimum specific costs may or may not be feasible. Fig. 1 provides an example of the dependencies for a lognormal distribution with a coefficient of variation (V) of the rate of change in the technical condition set at 0.5. The coefficient (K) considers the rise in the cost of performing forced maintenance, whereas (K_{ti}) represents the cost of replacement parts as a ratio of the maintenance cost.

The examination of these calculation results indicates that the determination of minimum specific costs is a complex process, which depends on the parameters of the maintenance system and the characteristics of the object of operation. Upon examining the lognormal distribution of the rate of technical condition change with a coefficient of variation ($V = 0.5$), it is evident that the minimum specific costs undergo a shift.

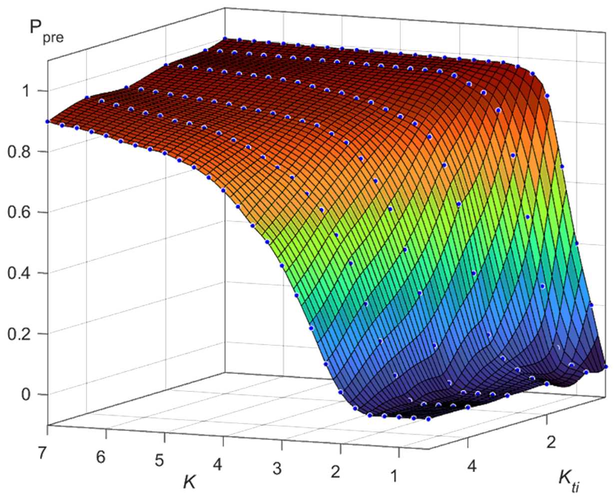

Fig. 1. Dependencies of the probability of preventing failures by the system of scheduled maintenance in the context of the lognormal distribution law of the rate of change in the technical condition and at a fixed value of the coefficient of variation ($V = 0.5$)

The results suggest the necessity of a thorough analysis of the maintenance system's parameters and their effect on specific costs.

It is undeniably true that the higher the cost of spare parts to be replaced in advance during regular maintenance, the less likely failure prevention by the maintenance system should be. From a safety perspective, this situation cannot be justified. To resolve this contradictory situation, performing maintenance with condition prediction becomes the only reasonable solution. This conclusion is drawn from analyzing the maintenance process of ships' machinery on cargo ships. It is highlighted that the maintenance system's efficiency is affected by several factors, including the cost of spare parts. Balancing the cost of spare parts and safety is crucial, while also considering the probability of failure. In these scenarios, utilizing condition prediction plays a significant role in attaining an optimal solution.

Results. The shift from scheduled maintenance to comprehensive predictive maintenance requires an investment in the purchase of equipment, the development of procedures for determining technical condition, and the transition to electronic document management. Clearly, these measures are costly, and in some instances, the expenses can be substantial. In such circumstances, the shipping company's superintendent needs to decide whether to invest in equipment for condition monitoring or on labor and spare parts. The decision can be based on intuition (which is often the case) or a more objective calculation.

In the following section, an approach for evaluating the results of the transition to comprehensive preventive maintenance will be presented. This approach is based on analyzing the actual captured data describing the patterns of changes in technical conditions.

The problem is defined as follows. The ship's machinery has the following known:

1. Parameters characterizing the technical condition of the machinery.
2. Average time between failures.
3. Average rate of change in technical condition based on operational data.
4. Coefficient of variation for the rate of change in the technical condition.
5. Labor intensity of scheduled maintenance (H_{sch}).
6. Labor intensity of unscheduled maintenance (H_{usch}).
7. Labor intensity of one control operation (H_{co}).
8. The average hourly wage of crew members at the Company (q).
9. The cost of the equipment required to implement comprehensive predictive maintenance (Q).
10. The ratio of the cost of replaced parts during maintenance to the cost of maintenance itself (z).

This task is based on the conditional assumption that the rise in unscheduled maintenance costs is only due to an increase in labor intensity.

The process of transitioning to a comprehensive predictive maintenance plan for the machinery of cargo ships is considered new and lacks formalization. This method has the potential to increase the maintenance interval between 50 to 65 %, thus extending the operational cycle. It should be noted that regulatory documents do not currently provide a clear procedure for transitioning to comprehensive predictive maintenance [20]. This limitation results from a restriction on maintenance with a delay of more than 50 % from the previous regulated period. Despite this limitation, scheduled maintenance with longer intervals achieved by monitoring between scheduled maintenance will still be valid. Nevertheless, some aspects of maintenance can be completed by forecasting the machinery's condition [21].

Let H indicate the labor required for scheduled maintenance and control (for n control operations) during the operation cycle, given a known probability of preventing failure (P_{pre})

$$H = H_{sch}P_{pre} + (1 - P_{pre})H_{usch} + nH_{co}.$$

The probability of preventing failure can be determined by plotting curves from models of the maintenance process. The initial data related to the technical condition change process is used to plot these curves. Identical methods can be used to determine cycle costs.

Maintenance labor cost implications of failures can be approximated by utilizing the extent of the upsurge in labor intensity due to the failure

$$K_{il} = \frac{H_{usch}}{H_{sch}}.$$

Assuming that the rise in unscheduled maintenance expenses results solely from an increase in labor intensity, the coefficient K_{il} remains constant for both labor intensity and cost ratio. Based on this assumption, we can derive the following relationship

$$S = qH_{usch}(P_{pre}(1 - K_{il}) + K_{il}).$$

This equation can be used to analyze the costs related to the maintenance of shipboard machinery on cargo ships. In cases where parts are replaced before their designated service life ends, either through preventive maintenance or other strategies, an irreversible part of their value is lost

$$S_m = C + S_M = C(2 - M) = C(1 + M_{RL}).$$

The maintenance cost of shipboard machinery on cargo ships can be represented as the sum of two functions. The previously mentioned first function, S, is independent of the duration of the service cycle. The second function represents the expenses incurred by replacement parts, the fees of which depend on the extent of usage. In practice, this cost is the sum of the costs of the entire range of spare parts.

Regarding the aforementioned factors, consider the following expression to analyze the cost per operating cycle

$$W = qH_{sch}\left(P_{pre}(1 - K_{il}) + K_{il}\frac{C(1 + M_{RL})}{qH_{sch}}\right).$$

Considering that the operating cycle duration is

$$T_{sch} = (\Delta T_{sch})P_{pre} + T_{avg}(1 - P_{pre}),$$

with ΔT_{sch} – intervals of scheduled maintenance; T_{avg} – average operating time before failure, during the implementation of scheduled maintenance with the accepted parameters, the duration of scheduled and unscheduled maintenance is ignored.

To define unit costs as the combination of labor costs $w_h(t)$ and spare parts purchase costs $w_m(t)$, it is essential to

$$w(t) = w_h(t) + w_m(t) = \frac{P_{pre}(1 - K_{il}) + K_{il}\dfrac{C(1 + M_{RL})}{qH_{sch}}}{T_{MC}},$$

with T_{MC} – duration of the operation cycle.

To compare the effectiveness of comprehensive predictive maintenance with scheduled maintenance, it is necessary to formulate the task in one of two ways:

1. Both maintenance methods are equally effective in preventing failures; however, the comprehensive predictive maintenance of cargo ships machinery can increase the duration of the operation cycle.

2. When the service life is equal under both maintenance methods, cost reduction of unscheduled shipboard machinery maintenance is achieved.

When comparing maintenance methods with the same preventive properties (P_{pre}) , the maintenance cost, excluding the cost of spare parts, can be assessed using the (T^{-1}_{MC}) multiplier. The dependency of (T^{-1}_{MC}) on the probability of failure prevention (P_{pre}) can be visualized in Figs 2–4. For this scenario, we use a Weibull distribution with a coefficient of variation of 0.4 for the rate of technical condition change (V_v). Maintenance by schedule is illustrated in Fig. 2. Fig. 3 displays maintenance according to condition, for different values of the

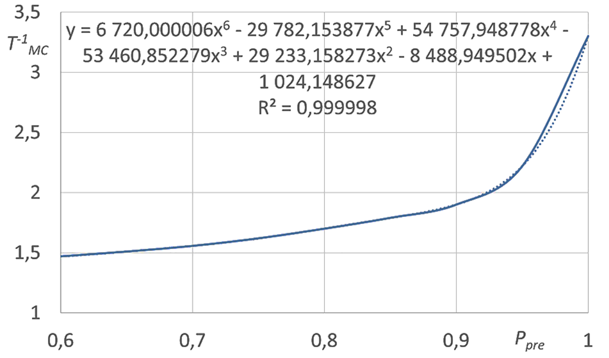

Fig. 2. The parameter T^{-1}_{MC} determines the unit costs of maintenance for the scheduled maintenance method

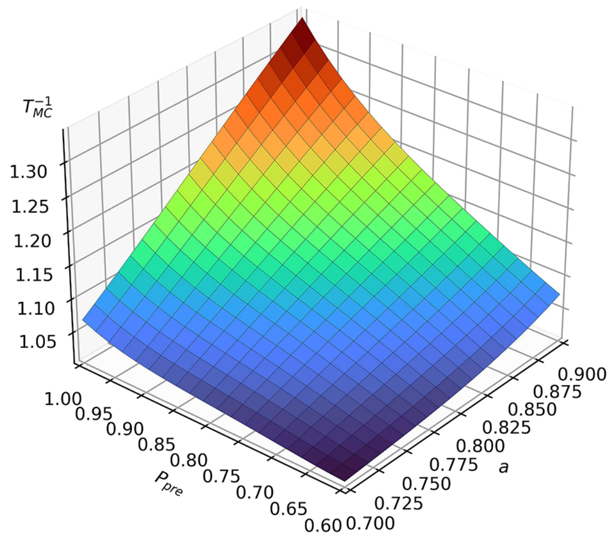

Fig. 3. The parameter T^{-1}_{MC} determines the unit costs of maintenance for the condition-based maintenance method ($V_v = 0.4$)

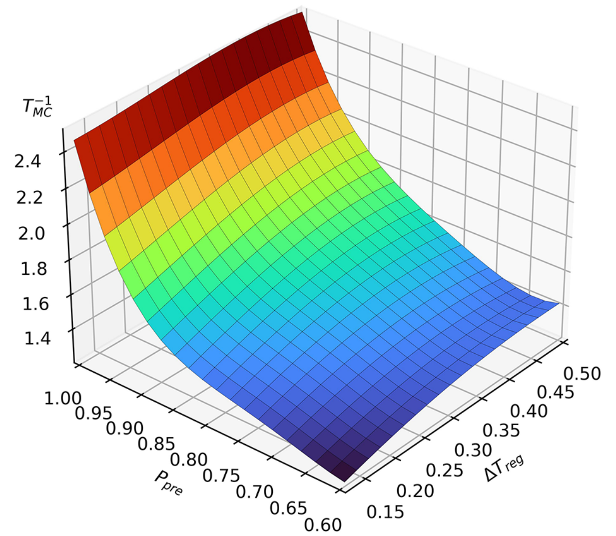

Fig. 4. The parameter T^{-1}_{MC} determines the unit costs of maintenance for the comprehensive predictive maintenance method ($V_v = 0.4$)

unsatisfactory condition parameter (a) set at 0.7, 0.8 and 0.9. Fig. 4 presents the (T_{MC}^{-1}) curves for complex preventive maintenance, with different numbers of control operations between maintenance (2, 4, 8) for the unsatisfactory condition parameter ($a = 0.9$).

Comparing the scheduled and comprehensive predictive maintenance methods of cargo ship machinery, the difference between the value $w(t)$ of the scheduled maintenance method and the cost of comprehensive predictive maintenance $w(t)^*$ could inform whether it is economically feasible to acquire new control equipment at a specific price.

When the annual operating hours of the ship's equipment are known (c), the annual effect is

$$E = (w(t) - w(t)^*) \cdot c \cdot q \cdot H_{sch}.$$

If the equipment costs (Q) and is purchased for (Y), then the justification for its purchase must be a condition

$$E > \frac{Q}{Y}.$$

If the equipment is designed for universal use, meaning it can be used for several (N) shipboard machinery, the condition is more flexible in the initial approximation

$$\sum_{i=1}^{N} E_i > \frac{Q}{Y}.$$

The appearance of the summation symbol in the formula is a result of various initial data used for shipboard machinery, such as the rate of change in technical conditions, the complexity of maintenance, and the consequences of failures.

To provide an illustration, a potential solution to this problem will be presented using a typical dry cargo ship with multiple machinery components as an example. Pumps, electric motors, and fans have been identified as potential targets for condition monitoring between maintenance routines. One possible method for monitoring these targets is through the use of a bearing vibration spectrum analyzer. This equipment enables the determination of the technical state of the rolling bearings. The condition of these bearings significantly affects the service life of the pump sealing rings and the electric motor rotor shaft. Replacing these components in a timely manner helps to maintain the technical state of the connected parts.

Moreover, the spectrum analyzer can monitor the technical condition of such shipboard machinery elements in particular:

1. Bearings. The spectrum analyzer can monitor the condition of bearings in different mechanisms like motors, generators, pumps, and fans. It can identify indications of bearing failure, such as vibration or noise, which may signal a malfunction.

2. Rotors. A spectrum analyzer can assist in monitoring rotor condition in electrical machines, such as electric motors and generators. It can identify rotor unbalance, bearing wear and stator defects.

3. Turbochargers. The technical condition of turbochargers can be monitored using a spectrum analyzer. Abnormalities in the turbocharger, such as vibration, noise, or changes in frequency response, can be detected.

4. Hydropneumatics systems. The spectrum analyzer can be used to monitor the hydropneumatics systems of shipboard machinery, such as hydraulic control systems or pneumatic systems. It allows one to detect problems such as leaks, wear or malfunctioning valves that may affect the system operation.

5. Electrical networks. A spectrum analyzer can detect faults which could damage the electrical equipment on a ship. By detecting faults such as harmonics, overvoltage, or abnormal current flow, a spectrum analyzer can prevent damage to electrical equipment.

For simplification, it was assumed that the average coefficient of variation of the rate of change in the technical condition is $V_v = 0.3$. With a linear model of technical condition change, the characteristics of the system of scheduled maintenance and complex maintenance with technical condition prediction were determined. Fig. 5 displays the primary relationships between the probability of failure prevention (P_{pre}) and the maintenance interval. In the calculations, the ratio of the parameter characterizing the unsatisfactory condition in relation to the emergency condition was used ($a = 0.9$). Assuming equal labor intensity ($H_{sch} = 15$ man-hours) for scheduled pump maintenance, the hourly wage of a crew member is ($q = 10$ \$). The average cost of a set of bearings for the pump, fan, and electric motor, depending on size, is ($C = 20$ \$). Therefore, the cost coefficient can be expressed as $Z = C/qH_{sch}$, which equals 0.13 in this case ($20/(10 \cdot 15)$). During the calculations, it was assumed that the cost of monitoring would be $0.01 \cdot H_{sch}$. Assuming $P_{pre} = 0.95$ as an acceptable probability of preventing failure, it is necessary to perform maintenance with a frequency of $\Delta T_{sch} = 0.6$ relative to the time (t) to ensure such reliability (refer to Fig. 5).

The ratio of real time (T) to mean time between failures (T_{avg}) is defined as the relative time (t). In this case, a high probability was chosen to meet the strict reliability requirements, although an alternate probability could have been selected. If the solutions are followed, this becomes irrelevant. The crucial point is that the probability of failure prevention remains constant for both methods.

The graphs can be used to determine the intervals for monitoring the technical condition (Δt_c). To ensure ($P_{pre} = 0.95$) with scheduled maintenance intervals equal to ($\Delta t_{sch} = 0.9$), the relative frequency of control should be ($\Delta t_c = 0.225$) relative units, as shown in the graph. Furthermore, when considering the cost of replacement parts, the unit cost of maintenance will be ($w(t)^* = 1.5$) relative units, whereas with scheduled maintenance, the cost was $w(t) = 2$ (Fig. 6).

Because of that during the transition to comprehensive predictive maintenance, the frequency of maintenance should be increased from 50 to 65 %, calculations were performed on the model for scheduled maintenance with an increased interval between it and the intermediate check. Two variants of calculations were performed with the intervals ($\Delta t_{sch} = 0.8$) and ($\Delta t_{sch} = 0.9$). By varying the control frequency, it is possible to ensure the same probability of failure prevention ($P_{pre} = 0.95$) and the adequacy of the comparison conditions. The results of the calculations are shown in Fig. 7.

Reducing the scheduled maintenance interval to ($\Delta t_{sch} = 0.8$) will lower the cost of maintenance of the equipment to ($w(t) = 1.82$), but at the same time the probability of preventing failures will decrease to ($P_{pre} = 0.72$).

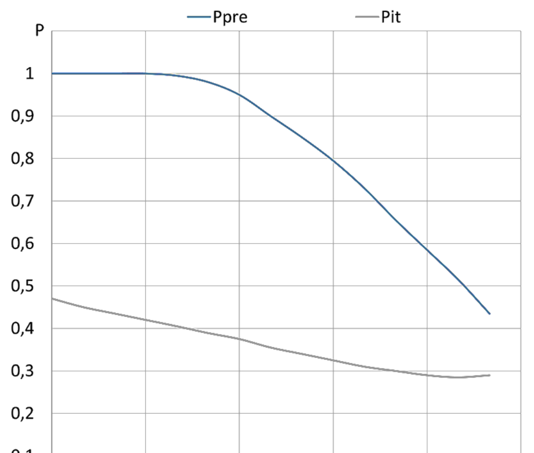

Fig. 5. The relationship between scheduled maintenance frequency and the timeliness and probability of failure prevention

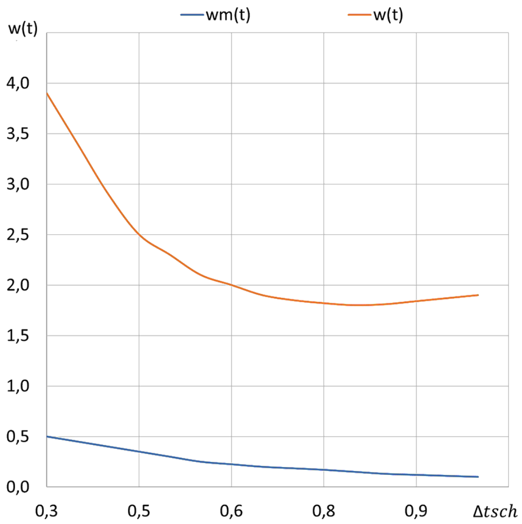

Fig. 6. The relationship between the unit costs of scheduled maintenance and its frequency

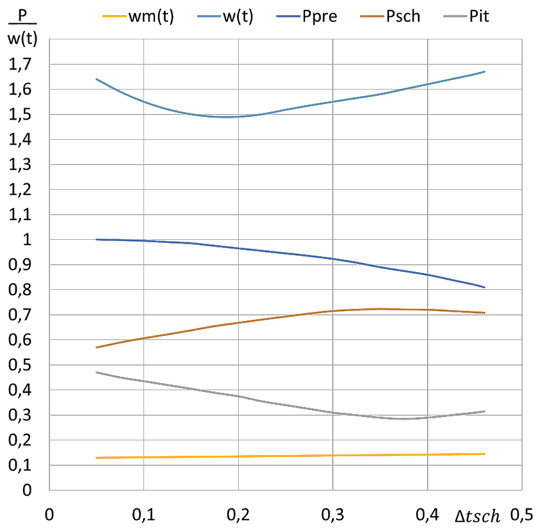

Fig. 7. Modeling results for scheduled maintenance ($\Delta t_{sch} = 0.9$) with intermediate control:

(P_{sch}) – probability of scheduled maintenance; (P_{pre}) – probability of failure prevention; (P_{it}) – probability of timely maintenance; $w_m(t)$ – unit costs for replaceable spare parts; $w(t)$ – unit costs for maintenance

Considering the context, it is recommended to explore an alternative for enhancing the maintenance system. To achieve the required level of failure prevention, an additional control will be introduced between maintenance by maintaining an equal periodicity ($\Delta t_{sch} = 0.8$). Fig. 8 shows the results of these calculations on the same model. To achieve the same result ($P_{pre} = 0.95$), the control should be administered roughly every ($\Delta t_{sch} = 0.39$), as evident from the graphs. Nevertheless, the expenses are likely to be approximately the following ($w(t)^* = 1.65$).

The calculation result is marginally inferior to the case with maintenance frequency ($\Delta t_{sch} = 0.9$) but superior to not performing any control. As displayed in Fig. 8, maintenance timeliness results in ($P_{it} = 0.168$) compared poorly to the case with ($\Delta t_{sch} = 0.9$), where the result is ($P_{it} = 0.35$). This constitutes almost a twofold deterioration. Considering the ratio of spare parts to labor costs was estimated to be much lower than one (0.13), the result of expensive replacement parts would have resulted in significantly more detrimental outcomes. In this instance, maintenance only accounted for the replacement of relatively inexpensive bearings, which have a long unused lifespan, leading to a

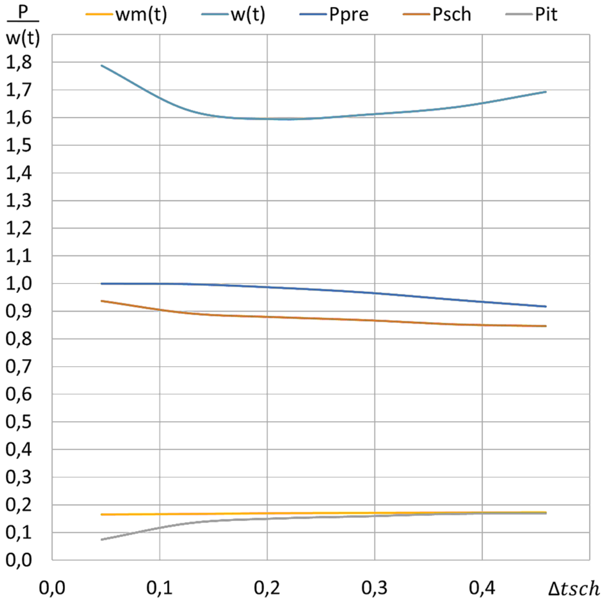

Fig. 8. Modeling results for scheduled maintenance ($\Delta t_{sch} = 0.8$) with additional intermediate control:

(P_{sch}) – probability of scheduled maintenance; (P_{pre}) – probability of failure prevention; (P_{it}) – probability of timely maintenance; $w_m(t)$ – unit costs for replaceable spare parts; $w(t)$ – unit costs for maintenance

more cost-effective option compared to the cost of labor. Efforts to increase the number of technical condition checks would not be effective as unit costs will not be lower than the initial option.

To obtain the annual operating effect when given specific costs in relative time calculations, the following formula can be used

$$E = (w(t) - w(t)^*) \cdot c \cdot q \cdot \frac{H_{sch}}{T_{avg}}.$$

In this scenario, the yearly operating time is about half of the average operating time before failure, calculated as $c = 0.5 \cdot T_{avg}$. In this case, the value is \$/year

$$E = (2 - 1.5) \cdot 0.5 \cdot 10 \cdot 15 = 37.50.$$

Considering a payback period of 5 years for technical condition monitoring equipment, it is advisable to purchase equipment costing less than 37.50 · 5 · 30 = 5625 \$, if at least 30 objects such as pumps, electric motors or fans are monitored. Furthermore, for 50 monitored objects, purchasing equipment up to the price of 37.50 · 5 · 50 = 9374 \$ is economically feasible.

This work yielded the following results:

1. The methodology for the comparative analysis of the application of various methods of maintenance of onboard machinery of cargo ships using a linear model of technical condition change has been developed. This methodology allows solving the problem in a general dimensionless form and can be applied to any ship machinery.

2. Using a nonlinear maintenance model, as opposed to a linear one, affects only the frequency and quantity of control operations performed, without taking the costs of control into consideration.

3. The relationship between the probability of failure prevention by the maintenance system and the value of specific costs is analyzed. It is found that as the probability of failure prevention increases, the duration of the operating cycle decreases, and the rate of decrease depends on the degree of dispersion of the rate of change in the technical condition.

4. A methodology has been developed to determine the unit cost of maintenance, considering the distribution of costs

for parts, labor, and other components. By using this methodology, we can estimate the total costs associated with maintenance and make knowledge-based decisions can be made regarding the efficient use of resources.

5. Research showed that spare parts cost impacts maintenance system efficiency. To achieve an optimal solution, it is important to balance safety and the cost of spare parts while considering the probability of failure. Condition prediction plays a significant role in achieving optimal solutions.

The results obtained can enhance the efficiency of maintenance for shipboard machinery, reduce costs, and increase the reliability and safety of operations. These results can be practically applied in planning maintenance and in making knowledge-based management decisions in shipping companies.

Conclusions. The scientific validity of the cost of equipment purchased for maintaining the technical machinery of cargo ships requires meticulous attention to detail and accurate calculations. It is important to note that in this instance, the cost of equipment was justified based on average asset costs and the results obtained are approximate. However, for a more precise justification, it is possible to calculate the cost for each individual asset before proceeding to comprehensive predictive maintenance. The calculation methodology remains consistent in such scenarios. The calculated results offer an opportunity to analyze the overall effects and make knowledge-based decisions.

These facts demonstrate the significance of adopting a scientific approach and conducting research to determine the equipment cost and evaluate the effectiveness of shipboard machinery's comprehensive predictive maintenance.

The cost of equipment for ship machinery maintenance is justified scientifically based on research and actual data. When determining the cost of equipment for complex maintenance with a forecast for its technical condition, the following facts can be considered:

1. Research on previous cases of comprehensive predictive maintenance demonstrates that this approach enhances maintenance efficiency and reduces the costs of unscheduled maintenance.

2. Research in ship machinery maintenance has confirmed that the utilization of a vibration spectrum analyzer can monitor the technical condition of components like bearings, electric motors, and fans.

3. The estimation of equipment costs depends on the size and complexity of the maintenance asset. The cost of a set of bearings for pumps, fans, and electric motors can be estimated based on their production and delivery costs.

4. Studies on the impact of maintenance frequency on the probability of failure prevention have shown that increasing the frequency of maintenance improves prompt identification of potential problems and reduces the risk of failure.

5. The methodology proposed in this research for determining the cost and efficiency of equipment for comprehensive predictive maintenance of cargo ship machinery has considerable versatility. It can be adapted and applied to various types of assets requiring maintenance, including specialized road transport. This expands the methodology's potential use and value, providing an opportunity to apply the knowledge and experience gained to a broader context.

6. Despite the specificities of shipboard machinery, it is significant that the fundamental principles and methods employed in this research can be applied to other assets. Therefore, this methodology could provide a valuable contribution not only in the field of ship transportation but also in the realm of road transport.

Subsequent research can focus on developing specific modifications of this methodology for other types of vehicles, including road transport [22], agricultural machinery [23], and mining machines [24]. This approach will enable a gradual transition from general recommendations to more precise and accurate models and solutions.

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Принципи оптимізації технічного обслуговування засобів транспорту: визначення вартості обладнання

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Мета. Встановлення обґрунтованих принципів і методики ефективного визначення вартості обладнання та оптимізації технічного обслуговування засобів транспорту.

Методика. Результати представленого наукового дослідження отримані за використання загальних і спеціальних методів пізнання: абстрактно-логічний аналіз, систематизація й комбінування, метод теоретичного узагальнення, метод діалектичного пізнання, дедукція та індукція, статистичний аналіз. Виконується аналіз залежності між імовірністю попередження відмов системою технічного обслуговування й питомими витратами. Досліджується вплив рівня розкиду у швидкості зміни технічного стану на тривалість циклу експлуатації та швидкість її зниження. Проводиться аналіз отриманих результатів, включаючи формування точок мінімальних питомих витрат, вплив вартості запасних частин, а також розгляд практичної значимості отриманих висновків.

Результати. У роботі визначена економічна сутність методики визначення питомих витрат на технічну експлуатацію засобу транспорту, ураховуючи розподіл витрат на запасні частини, оплату праці та інші складові. Ця методика дозволяє оцінити сукупні витрати, пов'язані з технічним обслуговуванням, і прийняти обґрунтовані рішення щодо ефективного використання ресурсів. Встановлено, що вартість запасних частин впливає на ефективність системи технічного обслуговування, і потрібно збалансувати витрати на запасні частини й безпеку, ураховуючи ймовірність відмов. Метод, указаний у цій роботі, є універсальним, що дозволяє його адаптацію й застосування до спеціалізованого рухомого складу автомобільного транспорту.

Наукова новизна. У роботі набув подальшого розвитку методичний підхід до розрахунку вартості обладнання, що використовується для технічного обслуговування засобів транспорту, з метою сприяння покращенню ефективності обслуговування та зниженню витрат. Це дозволяє комплексно оцінити результати збільшення ймовірності попередження відмов системою технічного обслуговування, управляти невикористаним ресурсом деталей, особливо у випадку короткого експлуатаційного циклу.

Практична значимість. Представлені результати дослідження можуть бути використані для оптимізації системи технічного обслуговування, підвищення ефективності експлуатації, забезпечення безпеки й надійності транспортних засобів і зменшення витрат на запасні частини, працю та інші складові обслуговування. Це дозволяє зберігати ресурси та знижувати експлуатаційні витрати, що є важливим для фінансової стабільності та прибутковості керуючих компаній.

Ключові слова: *технічне обслуговування, суднові технічні засоби, витрати, попередження відмов, ефективність експлуатації*

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