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OVERVIEW OF ECONOMIC RISKS IN CASE OF EQUIPMENT FAILURE OF MODERN SHIPS

ОГЛЯД ЕКОНОМІЧНИХ РИЗИКІВ У РАЗІ ВІДМОВИ ОБЛАДНАННЯ СУЧАСНИХ СУДЕН

Summary. *Introduction. Failure of ship equipment is one of the most important factors affecting the economic efficiency and safety of shipping. The article substantiates the main economic risks caused by technical malfunctions on seagoing vessels, which include financing of losses, delayed deliveries, increased insurance premiums and environmental sanctions.*

Objective. To identify the main risk factors, including equipment wear and tear, technical errors during maintenance, unskilled personnel and the use of low-quality components.

Materials and methods. To minimize the risks, we used and implemented predictive maintenance systems based on digital monitoring technologies. periodic training of crews, formation of reserve funds for emergency repairs. Mathematical models for assessing equipment reliability, maintenance efficiency, and financial risk management were also considered.

Results. The study found that the main economic consequences of ship equipment failure are financial losses for repairs, vessel downtime, breach of contract, increased insurance premiums, and environmental fines. The key causes of failures include wear and tear of machinery, maintenance errors, unskilled personnel, and the use of low-quality spare parts. To minimize the risks, it is proposed to introduce predictive maintenance based on digital monitoring, automated diagnostic systems, crew training, and the creation of reserve funds for emergency repairs. Calculations have confirmed that an integrated approach to risk management can reduce the number of failures, cut financial losses, and improve the efficiency of ship operations.

Prospects. The research shows the need for an integrated approach to technical risk management, where a combination of technological, organizational and financial strategies and appropriate measures will help reduce equipment failures, efficiently use money for repairs and maintenance, and increase the level of safety of navigation.

Key words: *maritime transportation, maritime transport, reliability, equipment reliability, probability of failure, navigation safety, maintenance, navigation risks, condition monitoring, malfunctions, automated systems, process control, forecasting;*

Анотація. *Вступ. Відмова суднового обладнання, одна з найголовніших чинників, що здійснюють вплив на економічну ефективність і безпеку судноплавства. Стаття обґрунтовує головні економічні ризики, які спричинені технічними несправностями на морських суднах та які включені до фінансування збитків, затримку поставок, підвищення страхових премій та екологічні санкції.*

Мета. Визначити головні чинники ризику, серед яких є зношеність обладнання, технічні помилки під час технічного обслуговування, некваліфікований персонал та використання неякісних компонентів.

Матеріали та методи. Для мінімізації ризиків використані та впроваджені системи предиктивного технічного обслуговування на основі цифрових технологій моніторингу. періодичного навчання екіпажів, формування резервних фондів для проведення аварійних ремонтів. Також розглядалися математичні моделі оцінки надійності обладнання, ефективності технічного обслуговування та управління фінансовими ризиками.

Результати. Дослідження виявило, що основними економічними наслідками відмови суднового обладнання є фінансові втрати на ремонт, простої суден, порушення контрактів, зростання страхових внесків та екологічні штрафи. Ключовими причинами відмов є зношення механізмів, помилки у технічному обслуговуванні, некваліфікований персонал і використання неякісних запчастин. Для мінімізації ризиків запропоновано впровадження прогнозного технічного обслуговування на основі цифрового моніторингу, автоматизованих систем діагностики, підвищення кваліфікації екіпажу та створення резервних фондів для екстреного ремонту. Розрахунки підтвердили, що комплексний підхід до управління ризиками дозволяє зменшити кількість відмов та скоротити фінансові втрати та підвищити ефективність експлуатації суден.

Перспективи. Дослідження свідчать про необхідність комплексного підходу до управління технічними ризиками, де поєднання технологічних, організаційних та фінансових стратегій а проведення відповідних заходів допоможе зменшити відмови обладнання, ефективно використовувати гроші на ремонт та технічне обслуговування, підвищити рівень безпеки судноплавства.

Ключові слова: *процес судноводіння, морський транспорт, безвідмовність, надійність обладнання, ймовірність відмови, безпека судноводіння, технічне обслуговування, навігаційні ризики, моніторинг стану, несправності, автоматизовані системи, управління процесами, прогнозування.*

Problem formulation. Shipping is a critical sector of the global economy, but failure of ship equipment can pose significant economic, environmental and operational risks. Existing maintenance methods do not always allow for the timely detection of potential malfunctions, which underscores the need to implement predictive maintenance and digital monitoring to minimize risks.

Analysis of recent research and publications. Studies indicate that ship equipment failure is a key factor in economic risks in shipping, causing financial losses, transportation delays, and increased insurance premiums. In particular, a study by Ceylan & Çelik (2024) highlights the significant risks associated with shipboard boiler failure, where the main critical factors are fluctuations in steam temperature and pressure, safety valve failures, and imbalances in the fuel-to-air ratio [1]. Another study conducted by Ibazebo et al. (2024) applies the Failure Mode and Effects Analysis (FMEA) method to assess the risks of a ship's main propulsion system, emphasizing the critical importance of identifying the most vulnerable components to reduce operating costs and prevent accidents [2]. For newbuildings, Ariany et al. (2023) investigated delays in the delivery of mechanical equipment and their impact on the ferry construction production cycle, identifying installation delays as the biggest risk [3]. Gunnarsson's (2024) study also points to the general vulnerabilities of the maritime transport system, in particular in the Northern Sea Route, where sanctions and changes in technological supply can significantly affect logistics efficiency and transportation safety [4].

Thus, existing research unanimously indicates that the economic consequences of ship equipment failure can be significant due to increased operating costs, reduced ship safety, and increased insurance risks. [5–10]. The use of predictive maintenance, digital monitoring, and effective risk management can significantly reduce potential losses and increase the reliability of shipping operations.

The purpose of the article is to study the economic risks associated with the failure of shipboard equipment and to develop strategies to minimize them. To achieve this goal, the author analyzes the main risk factors, such as wear and tear of machinery, maintenance errors, unskilled personnel, and the use of low-quality spare parts.

Materials and methods. The article uses an analytical approach to assess the economic consequences of ship equipment failure, as well as mathematical models for predicting the reliability of technical systems.

Table 1

Economic consequences

Economic Consequence	Description
Direct Financial Losses	Costs related to repairs, replacement of components, and emergency maintenance.
Delays and Contract Disruptions	Ship downtime leading to financial losses due to penalties, loss of revenue, and disrupted logistics chains.
Increased Insurance Premiums	Frequent technical failures increase the risk of maritime operations, leading to higher insurance premiums.
Environmental Fines	Equipment failures may cause fuel leaks or hazardous substance spills, resulting in fines and reputational damage.

1. Economic consequences of equipment failures

Failure of shipboard equipment can cause significant economic losses, affecting both the immediate financial costs and the long-term efficiency of maritime transportation (Table 1);

In addition, direct financial losses, which include the cost of repairs, replacement of parts and emergency maintenance, can account for a significant portion of the shipowner's operating budget. Downtime and contract disruptions due to equipment failure can cause a vessel to stop, resulting in financial losses due to penalties, loss of cargo transportation revenues, and disruption of logistics chains. Separately, increased insurance premiums and frequent technical malfunctions increase the risk of shipping operations, forcing insurance companies to increase insurance rates for shipowners. Additionally, environmental fines, as equipment failures can cause leaks of fuel or other hazardous substances, which leads to significant fines and damages the reputation of the shipping company.

2. Main risk factors

Shipboard equipment failure is often caused by a combination of technical, human and operational factors. The main causes of such failures are (Table 2):

2.1. Wear and tear and aging of mechanisms

Over time, mechanisms are subject to physical wear and corrosion, which reduces their reliability. The level of wear can be estimated by the formula:

$$R(t) = R_0 e^{-\lambda t} \quad (1)$$

where: $R(t)$ is the probability of failure-free operation at time t, R_0 is the initial reliability of the equipment, λ — failure rate, t is the operating time.

2.2. Errors in maintenance

Improper or irregular maintenance can lead to the accumulation of hidden defects. The effectiveness of maintenance can be assessed through the availability rate:

$$K_g = \frac{T_p}{T_p + T_r}, \quad (2)$$

where: K_g — the availability factor, — T_p — average uptime, T_r — average repair time. The lower the T_r, the higher the technical readiness of the equipment.

2.3. Unqualified personnel

Insufficient training of the crew can lead to improper use of equipment and accelerated wear and tear. This is taken into account in the human factor model:

$$P_f = P_o + \sum_{i=1}^{n} (E_i \cdot W_i), \quad (3)$$

where: P_f — probability of human error, P_o — basic probability of error, E_i — level of complexity of the operation performed, W_i — coefficient of influence of fatigue, stress or other factors. Reducing these indicators is achieved through regular training and process automation**.**

2.4. Use of low-quality spare parts or design defects

Manufacturing defects or the use of uncertified parts can lead to premature equipment failure. The quality control of equipment can be assessed through the defect rate:

Table 2

Main risk factors

Risk Factor	Description
Wear and Aging of Components	Continuous exposure to marine conditions leads to material fatigue, corrosion, and loss of structural integrity over time.
Errors in Technical Maintenance	Inadequate preventive maintenance or improper repairs increase the likelihood of unexpected failures.
Unqualified Personnel	Lack of experience or improper training of crew members leads to mishandling and increased risks of equipment damage.
Low-Quality Spare Parts and Design Defects	The use of substandard replacement parts or inherent flaws in equipment design can result in operational inefficiencies and early failures.

Table 3

Ways to minimize risks

Risk Mitigation Method	Description
Predictive Maintenance Systems	Implementation of condition-based monitoring (CBM) and predictive analytics to detect failures before they occur.
Digital Monitoring Technologies	Use of IoT sensors, AI diagnostics, and automated alarms to control the condition of critical ship components in real-time.
Crew Training and Skill Development	Regular educational programs and certification for crew members to improve their competence in handling and maintaining equipment.
Emergency Repair Funds	Establishment of financial reserves to cover urgent repair costs, preventing major financial losses and delays.

$$D = \frac{N_d}{N_t} \times 100\%, \quad (4)$$

where: D — defect rate in %, N_d — number of defective parts, N_t — total number of parts.

This ratio can be reduced through supplier control, regular inspections, and the use of certified materials. Thus, the risk of shipboard equipment failures can be reduced through a competent system of ship maintenance management, the introduction of modern diagnostic methods, improved personnel training and strict quality control of spare parts.

3. Ways to minimize risks

To reduce economic losses associated with ship equipment failure, it is necessary to implement comprehensive technical, organizational and financial measures (Table 3);

3.1. Predictive maintenance systems

Predictive Maintenance (PdM) is based on the analysis of the actual state of the equipment using sensors and machine learning algorithms. This helps to reduce the likelihood of unexpected breakdowns and reduce repair costs.

Formula for calculating the effectiveness of predictive maintenance:

$$E_{PdM} = \frac{C_r - C_p}{C_r} \times 100\%, \quad (5)$$

where: E_{PdM} — efficiency of PdM in %, C_r — average cost of reactive (emergency) maintenance, C_p — the cost of predictive maintenance. The more E_{PdM}, the more efficiently the predictive maintenance system is implemented.

3.2. Digital monitoring technologies

The use of smart sensors, IoT devices and artificial intelligence allows for real-time monitoring of shipboard equipment. Machine learning algorithms can analyze trends in the operation of engines, hydraulic systems and generators, reducing the risk of accidents.

The effectiveness of digital monitoring can be expressed through the equipment availability factor:

$$A = \frac{U}{U + D} \times 100\%,$$

where: A — equipment availability factor, U — equipment uptime, D — downtime due to malfunctions.

3.3. Crew training and emergency repair reserves

Insufficient crew qualifications are one of the key causes of equipment malfunctions. Regular training, the use of simulators, and updated training programs can reduce the impact of the human factor. To ensure financial sustainability, shipowners should create reserve funds to cover emergency repair costs. This helps to avoid significant losses in the event of sudden breakdowns.

4. Discussion

Failure of ship equipment is one of the key challenges for the shipping industry, as it causes significant economic, environmental and operational risks. The analysis of risk factors and methods to minimize them can lead to several important conclusions on how to improve the efficiency of ship maintenance management.

Implementation of Predictive Maintenance (PdM) is one of the most effective strategies to prevent sudden failures. The use of IoT sensors, machine learning, and data analytics systems allows for the prediction of possible malfunctions and maintenance on an as-needed basis rather than a strict schedule. This significantly reduces repair costs and increases the operational life of the equipment.

Innovative digital technologies, such as remote equipment condition monitoring, allow crew and shipowners to monitor the status of ship components and systems in real time. Identification of trends in changes in equipment operating parameters (e.g. temperature, vibration, pressure) allows for timely response to potential threats. This helps to minimize vessel downtime and reduce the risk of serious breakdowns.

The quality of crew training plays a critical role in ensuring the smooth operation of the vessel. Training personnel in the proper use and maintenance of equipment reduces the likelihood of human error, which is a common cause of accidents. Regular training and simulations help staff respond more quickly to emergency situations, which in turn increases the overall level of safety and reliability of ship systems.

One important aspect of risk management is the formation of emergency repair reserve funds. Shipowners and operators should anticipate possible costs associated with emergency repairs and include these funds in their financial planning. This allows them to avoid significant economic losses in the event of a failure of critical ship systems and to quickly restore its operation.

Conclusions. Minimizing the risk of ship equipment failures requires a comprehensive approach that combines technological solutions (digital monitoring, automated diagnostic systems), organizational measures (crew training, improved maintenance protocols), and financial instruments (fund reserves, risk insurance). These methods help reduce the number of accidents, increase shipping efficiency and reduce ship maintenance costs. In order to avoid serious economic losses due to the failure of ship equipment, it is necessary to implement predictive maintenance, use digital monitoring technologies, train personnel and build up reserve funds. Comprehensive technical risk management will increase safety of navigation, reduce vessel downtime and ensure the stability of the fleet in the long term.

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