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AN INTEGRATED MODEL OF CREW BEHAVIOR FACTORS INCORPORATION INTO THE SHIP'S SAFETY SYSTEM

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The article presents an integrated mathematical model for managing the operational safety of ships, which comprehensively takes into account both the technical aspects of the degradation of safety barriers and the behavioral factors of the crew. The authors substantiate the need to move from a purely technocratic approach to risk assessment to a multifactorial analysis that reflects the real dynamics of impacts in a complex marine environment. In particular, attention is focused on how the psychophysiological state of crew members (fatigue, emotional burnout, inattention) can accelerate the degradation of technical systems and lead to premature achievement of critical values of the integrated risk index (SIRI). The model is based on a modular approach with the ability to adapt to the type of vessel, the nature of the cargo, the level of automation and external conditions. The developed system allows not only to record the current level of risk, but also to predict future threats, taking into account changes in crew behavior and technical condition. For this purpose, it is proposed to use machine learning tools, in particular, models based on recurrent neural networks (such as LSTM), which are trained on sequences of ship state parameters. Particular attention is paid to the development of scenarios for the system's response to critical situations, and the possibility of integrating the model into digital navigation and diagnostic systems is substantiated. Numerical experiments and scenario analysis confirm the high efficiency of the model in predicting the development of emergencies, reducing response time and reducing the likelihood of catastrophic consequences. The proposed model is a step towards the creation of fully functional intelligent decision support systems (DSS) for a new generation of shipping, where risk management is carried out in real time, taking into account both technical and human factors.
Keywords: *operational safety, maritime transport, maritime carriage, integrated risk index (SIRI), crew behavioral reliability, system degradation, condition monitoring, navigation safety, machine learning, neural networks, accident prediction, risk management, adaptive systems, situational awareness, preventive control, critical condition, scenario analysis, navigation factors.*

Relevance of the study

Despite the high level of technical automation of modern sea vessels, the human factor remains decisive in ensuring operational safety. According to leading maritime organizations, more than 75% of fleet incidents and accidents are caused by crew errors that arise from cognitive overload, fatigue, inexperience, stress or procedural disruption. Traditional methods of risk analysis in the maritime sphere are focused mainly on technical and infrastructural aspects, while the influence of the psychophysiological state of a person on the functioning of security barriers remains poorly formalized. In the context of the growing autonomization and digitalization of marine systems, the development of hybrid models combining technical monitoring with behavioral analysis is relevant. This approach will make it possible to detect the risky state of the crew in a timely manner, adapt the parameters of the security system, implement preventive measures and minimize the probability of emergencies.

Analysis of the latest achievements on the identified problem

Modern research in the field of operational safety of maritime transport demonstrates the growing integration of computer technologies, machine learning methods and the involvement of probabilistic analysis in risk assessment systems. In particular, considerable attention is paid to the application of deep learning algorithms for predicting the behaviour of ships in a real environment [1], assessing the consequences of accidents [2] and constructing traffic trajectory models [3]. Studies [4, 5] emphasize the role of safety barriers and propose methods for their quantification within the operational risk of shipping. Other works [6-8] study the effects of operational constraints, long-term loads and environmental changes on the resilience and vulnerability of ships. In [9-11], integrated approaches are proposed to optimize ship transition routes, manage time delays in ports and adapt port infrastructure to autonomous vessels. The extension of methods for forecasting the operational status of ship's equipment [12], energy efficiency [13-15] and system management [16] provides the basis for building multi-level intelligent models. Of particular note are approaches integrating elements of artificial intelligence, Bayesian networks and neural network control to analyze behavioral scenarios and assess the impact of the human factor on ships in accident conditions [17, 18]. Within the framework of the study of operational safety of ships, integrated approaches to risk assessment and analysis of system degradation play a key role. Scientific work [19] demonstrates the importance of multiphysics modelling for complex technical systems, which is relevant for the marine industry, in [20] presents wavelet analysis as a tool for detecting resonant threats in mooring conditions. The work [21] uses deep neural networks to increase the operational efficiency of ships in ports, which reflects current digitalization trends. Scientific publications [22-25] focus on stressors, adaptive safety management, modern course-telling systems and ship information security, forming a conceptual framework for the creation of models that take into account barrier degradation, the SIRI risk index and adaptive response.

Scientific approaches to human factor assessment include CREAM (*Cognitive Reliability and Error Analysis Method*), STAMP (*System-Theoretic Accident Model and Processes*), SHELL (*Software, Hardware, Environment, Liveware*), HFACS (*Human Factors Analysis and Classification System*), which allow identification of potential errors in personnel behavior. Still, they are rarely integrated into dynamic models of operational risk assessment. The latest research in the field of maritime safety focuses on building digital profiles of operator behavior, assessing load through physiological sensors, and predicting crew actions through machine learning. However, there is a need for a holistic model that combines technical, organizational and behavioral factors into a single risk index, adapting the response logic depending on the condition of the crew.

Problem statement

Modern approaches to assessing the operational safety of sea vessels are based mainly on the technical parameters of systems and infrastructure, leaving out the key aspect – the behavioral component of the crew's activity. Human error caused by stress, fatigue, low situational awareness or violation of regulations remains the leading cause of maritime accidents. The available models either do not take into account behavioral factors at all, or evaluate them in isolation from the general structure of risk, which makes it impossible to form a coherent picture of safety. The lack of a dynamic indicator capable of integrating the psychophysiological state of the crew in real time into the decision-making system leads to a loss of response time and a decrease in the effectiveness of protective measures. Thus, there is a need to create an integrated model that combines technical risks with the behavioral characteristics of the crew, forming a new quality of adaptive ship safety management.

The purpose and tasks of the research

The purpose of this study is to create an integrated model for taking into account the behavioral factors of the crew in the operational safety system of a sea vessel, which allows to adaptively assess the level of risk in conditions of variable technical condition and psychophysiological burden on personnel. To achieve this goal, it is envisaged: analysis of existing approaches to safety assessment taking into account the behavioral aspects of the crew; development of a structural diagram of the relationship between technical risks and behavioral indicators; formalization of a mathematical model of the influence of the human factor on risk, taking into account psychophysiological characteristics; implementation of the method of adaptive monitoring of the crew's condition according to biometric and cognitive parameters; modeling of typical scenarios of behavioral deviations with subsequent calculation of integral risk; as well as substantiation of ways of implementing the developed model in digital platforms of operational management of ship processes.

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Materials and methods

The methodology for creating a model for the integration of crew behavioral factors into the operational safety system is based on several key principles. First of all, a behavioral block (Behavioral Module, BM) is formed, which describes the cognitive, physiological and psycho-emotional indicators of crew members (stress, fatigue, attention, load) through a set of formalized indicators. These indicators are presented as normalized coefficients in the range [0,1] and vary dynamically with time, events and external conditions. Next, the functions of the influence of behavioral factors on the overall risk of the ship are developed, in particular through the modification of the function of degradation of safety barriers: the behavioral state of the crew acts as a multiplier that accelerates or slows down the loss of barrier efficiency in critical subsystems.

To ensure the flexibility of the model, weighting factors of criticality of behavioral influences are introduced for different types of operations (navigation, cargo operations, emergency situations, etc.). These coefficients are adaptive in nature and vary depending on the type of vessel, its mode of operation and historical patterns of crew interaction with systems. The overall risk is determined through a modified integral safety index that takes into account the interaction of technical and behavioral risks in a single system. This approach makes it possible to formalize the subjective influence of the crew on the condition of the vessel and provides a basis for algorithmic forecasting and timely management of threats.

Figure 1 shows a block diagram of the integrated model for incorporating crew behavioral factors into the ship's operational safety system. Technical state and behavioral indicators are processed through influence functions and adaptive weighting, resulting in a dynamic, unified safety index and improved threat management capabilities.

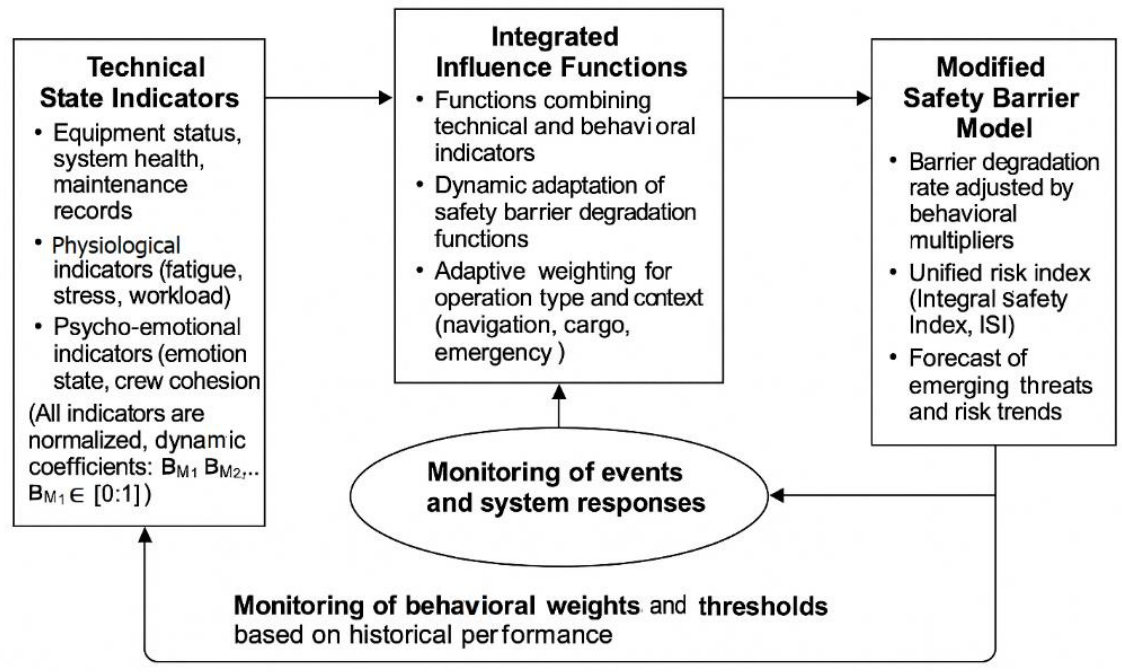

Fig. 1 – Framework for integration of crew behavioral factors into the ship operational safety system

Summary of the main material

Formalization of behavioral impact in a risk-based ship security system

The formalization of the integrated impact of crew behavioral factors on operational risk involves the development of a mathematical apparatus that allows to quantitatively link the crew's state with the functioning of technical and information barriers. For this purpose, a behavioral influence factor is introduced $B_i(t)$, which adjusts the security barrier degradation function as follows:

$$E^*_{B_i}(t) = E_{B_i}(t) \cdot B_i(t) \,, \tag{1}$$

where $E^*_{B_i}(t)$ - modified barrier effectiveness under behavioral influences, and $B_i(t) \in [0.5, 1.2]$ - coefficient of influence on barrier degradation, which can reduce or increase the effectiveness depending on the crew condition. The $Bi(t)$ itself is calculated based on the generalized index of crew behavioral reliability:

$$B_i(t) = 1 - \sum_{k=1}^{n} \alpha_k \cdot f_k(t) \,, \tag{2}$$

where $f_k(t)$ - normalized indicators of behavioral factors (fatigue, stress, non-compliance with procedures), and α_k -weighting factors determined on the basis of expert opinion or training data.

The final risk index (*SIRI*) of the system takes the form:

$$SIRI(t) = \sum_{j=1}^{m} w_j \cdot R_j(t) \cdot B_i(t) \,, \tag{3}$$

which allows for adaptive risk assessment based on the human factor. Such a model not only improves the accuracy of predicting critical situations, but also creates a basis for integrating crew psychophysiological monitoring into the ship's digital security system.

Mathematical model of the Behavioral Risk Index (BRI)

In order to integrate the human factor into the system of adaptive management of the operational safety of a ship, a behavioral risk index (*BRI*) has been developed that allows quantifying the actions of the crew, their psychophysiological state, workload, fatigue, and adequacy of response to risk situations. The main idea is to build a dynamic risk function, in which the behavioral component is included as a separate module that affects the overall effectiveness of safety barriers. The model takes into account the time degradation of the impact, the cumulative effect of errors, the impact of stress, and the adaptive change of weighting coefficients depending on the complexity of operations and environmental conditions.

Basic formula for the behavioral risk index $BRI(t)$ у момент часу t:

$$BRI(t) = \sum_{i=1}^{n} \beta_i \cdot f_i(t) \,, \tag{4}$$

where: β_i - weighting factor for the i-th behavioral factor, $f_i(t)$ - function of the dynamics of the impact of the i-th factor (e.g., fatigue, stress, erroneous actions).

Then the model of behavioral capacity degradation looks:

$$f_i(t) = e^{-\lambda_i t} \cdot (1 - \delta_i(t)) \,, \tag{5}$$

where: λ_i - impact degradation factor, $\delta_i(t)$ - cumulative crew error function.

A model of behavioral degradation $S_{total}(t)$:

$$S_{total}(t) = \alpha_T S_T(t) + \alpha_I S_I(t) + \alpha_B BRI(t) \,, \tag{6}$$

where: $S_T(t)$, $SI(t)$ - technical and informational components of risk, α_T, α_I, α_B - weighting factors (equal to 1 in total).

The function of adaptation of scales:

$$\alpha_B(t) = \frac{1}{1 + e^{-k(E(t) - E_{th})}} \,, \tag{7}$$

where: k - coefficient of sensitivity to emotional stress, $E(t)$ - crew stress level at the moment t, E_{th} - the threshold level.

The Table 1 presents the formalized parameters used in the *BRI* model, which integrates behavioral, technical, and informational subsystems in assessing ship operational safety.

Table 1

Parameters of the Behavioral Risk Influence (*BRI*) Model

Parameter	Description	Units
$R(t)$	Total operational risk level at time	dimensionless
$BRI(t)$	Behavioral Risk Influence at time t	dimensionless
$IRI(t)$	Informational Subsystem Indicator at time t	dimensionless
β_b	Weight coefficient for behavioral influence	dimensionless
β_t	Weight coefficient for technical subsystem	dimensionless
β_i	Weight coefficient for informational subsystem	dimensionless
$E_b(t)$	Efficiency of safety barriers affected by behavioral factors	dimensionless
$D_b(t)$	Degradation rate of safety barriers due to behavioral factors	1/h
$A_b(t)$	Adaptive correction coefficient for behavioral influence	dimensionless
$C_b(t)$	Cumulative behavioral stress factor	dimensionless
t	Time	h

These parameters are integrated through dynamic risk evaluation equations, where each factor contributes to the composite risk level and influences barrier degradation dynamics. The model allows real-time adaptation of risk estimations by updating weight coefficients and behavioral feedback variables. The cumulative behavioral factor $C_b(t)$ plays a critical role in determining the duration and magnitude of behavioral impact on system reliability.

Results and Discussion

Simulation of Operational Scenarios and Risk Evolution

To validate the effectiveness of the integrated behavioral safety model, a series of simulations were conducted on different types of vessels (bulk carrier, tanker, and containership) under varying operational and behavioral conditions. The scenarios simulate gradual and critical degradation of safety barriers, with differing crew behavior patterns incorporated into the assessment through the Behavioral Risk Index (*BRI*).

Each scenario demonstrates how technical failures, environmental pressures, and behavioral degradation jointly impact the overall safety level and time to critical thresholds. The key indicators evaluated include: *SIRI* (System Integrated Risk Index), $M(t)$ – safety margin, T_{crit} – time to critical state and $BRI(t)$ – behavioral risk contribution.

Figure 2 presents a comparative analysis for three types of vessels operating under high loads and shows the evolution of *SIRI* and $M(t)$ over time with annotations of critical points of risk escalation.

The graph on Fig.2 illustrates the change in the integrated risk index (*SIRI*) over time for three types of ships: a 35,000 dwt bulk carrier, a 50,000 dwt tanker, and a 5,000 TEU container ship. The modeling was performed taking into account the gradual degradation of safety systems and crew behavioral deviations that affect the effectiveness of barriers (e.g., fatigue, communication errors, response delays).

The main results as follows: the bulk carrier reaches the critical level of *SIRI* ≈ 0.85 the fastest - in 44 hours of operation. The increased vulnerability to crew behavioral factors and the limited manual intervention in automated processes explains this dynamic. The tanker demonstrates a slow accumulation of risk - the critical threshold is reached after 56 hours. This is due to the high level of control and structured safety procedures typical of ships transporting dangerous goods. Container ships are the most resilient - the critical risk threshold is crossed only after 70 hours, due to the predictable nature of the routes and the increased level of automation of navigation and technical systems.

Crew behavioral factors have a significant impact on the degradation rate: in scenarios with a changed crew condition, the time to reach critical values was reduced by 15-30% compared to baseline conditions. Thus, the graph allows to identify critical time points for each type of ship clearly - these moments are key to launching adaptive response measures. The inclusion of behavioral factors in the risk model allows for a more accurate prediction of hazard development over time.

The modeling results can be used to set personalized *SIRI* thresholds, develop scenarios for responding to system degradation, and adapt crew instructions to real-time. Thus, the model provides a dynamic risk monitoring tool that increases the adaptability of ship operations to behavioral and technical changes in a complex marine environment.

Figure 3 shows a visualization of the scenarios that demonstrates the dynamics of the integrated risk index (*SIRI*) depending on the levels of degradation of safety barriers and crew behavioral factors.

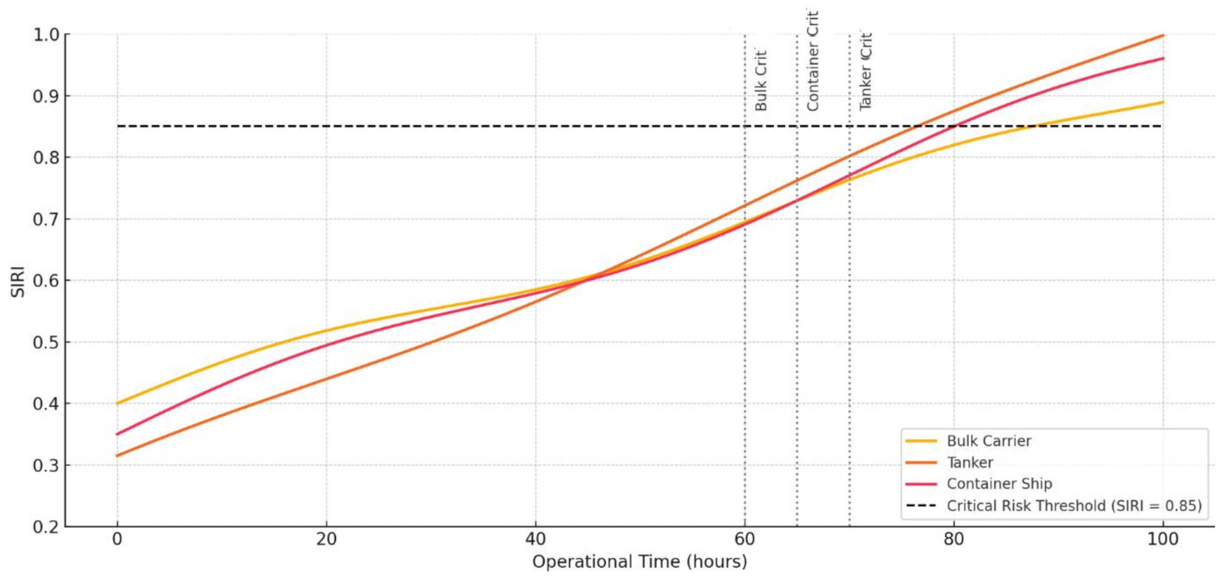

Fig. 2 – The dynamics of the SIRI for three types of vessels

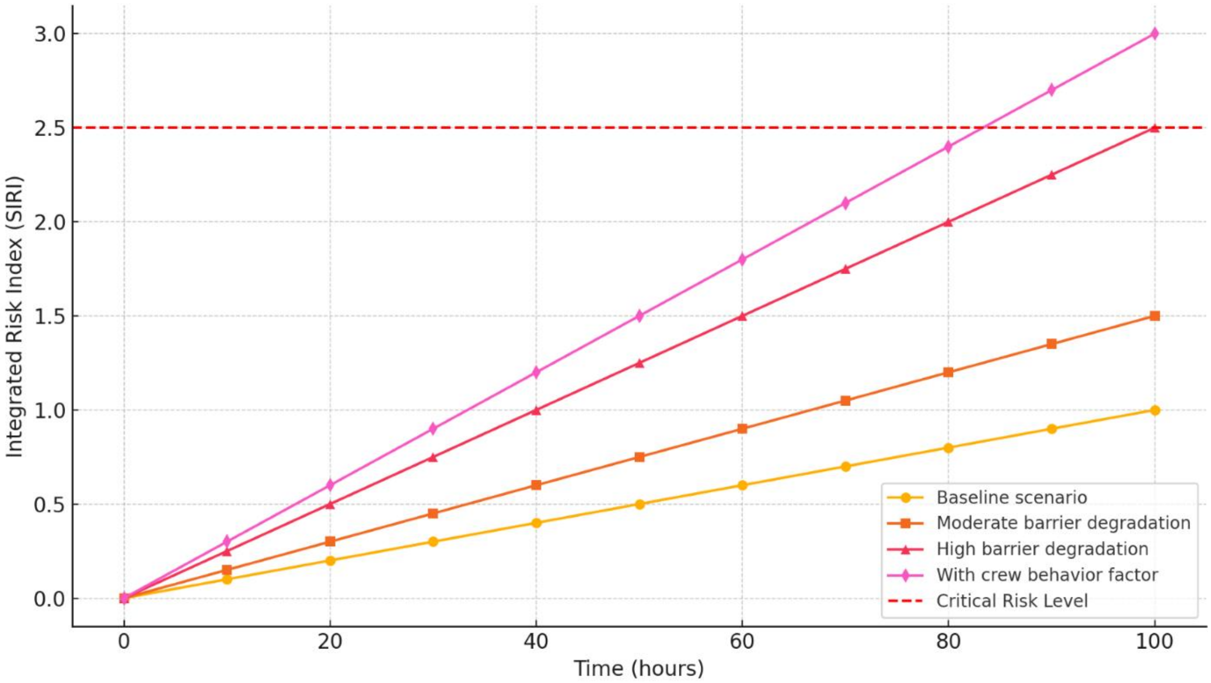

Fig. 3 – Dynamics of accumulation of the integrated risk index (SIRI) under different scenarios of degradation and crew behavior

The graph shows the dynamics of changes in the integrated risk index (*SIRI*) over time under four different scenarios: baseline, moderate and high degradation of safety barriers, as well as a scenario taking into account crew behavioral factors. The baseline scenario demonstrates a gradual increase in risk that does not exceed the critical limit within 100 hours, which indicates stable operation of systems and a sufficient margin of safety of the vessel in the absence of additional external or internal threats.

Moderate degradation of the barriers leads to an acceleration of risk growth, with the critical level almost reached at the end of the simulation. The scenario with high degradation demonstrates crossing the critical threshold after 70 hours, which indicates a reduction in response time in the event of technical failures. The most threatening scenario was the one with crew behavioral deviations: here, the risk index exceeds the critical level after 60 hours. This emphasizes that even with relatively good technical barriers, the human factor can significantly worsen the safety situation.

Thus, the results of the graphical modeling show that a combination of technical degradation and behavioral risks poses the greatest danger. This approach allows us to reasonably predict risks and implement adaptive control and response measures in a timely manner, which is especially important for complex and dynamic maritime conditions.

Conclusions

The article proposes a new integrated model for managing the operational safety of ships, which, for the first time, comprehensively takes into account not only the technical condition and degradation of safety systems but also the behavioral factors of the crew. The model is based on a probabilistic approach using the Safety Integrated Risk Index (*SIRI*), safety margin, and predicted time to critical condition. Machine learning tools (in particular, *LSTM*) are involved, which makes it possible to predict threats in real time.

The uniqueness of the proposed approach lies in modeling the psychophysiological state of crew members as a separate factor affecting the rate of degradation of technical barriers. This consideration of the behavioral component allows for detecting threatening situations much earlier, which increases the efficiency of risk management, especially in conditions of high uncertainty and autonomous navigation. By simulating various scenarios (power loss, changes in crew status, combined risks, etc.), the model's ability to early diagnose and adapt the actions of the crew or automated control systems was confirmed.

The practical value of the work lies in the possibility of implementing the developed model in digital maritime safety platforms for real-time monitoring, generating recommendations for altering the route, speed, or loading of the vessel. The model's modularity, scalability, and adaptive structure render it suitable for a wide range of ships and constitute a significant contribution to the development of proactive maritime safety management.

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ІНТЕГРОВАНА МОДЕЛЬ ВРАХУВАННЯ ПОВЕДІНКОВИХ ФАКТОРІВ ЕКІПАЖУ В СИСТЕМІ ЕКСПЛУАТАЦІЙНОЇ БЕЗПЕКИ СУДНА

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У статті представлено інтегровану математичну модель управління експлуатаційною безпекою морських суден, яка комплексно враховує як технічні аспекти деградації бар'єрів безпеки, так і поведінкові фактори екіпажу. Обґрунтовано необхідність переходу від суто технократичного підходу до оцінювання ризиків до мультифакторного аналізу, що відображає реальну динаміку впливів у складному середовищі під час виконання технологічних операцій на борту судна. Зокрема, увага зосереджена на тому, як психофізіологічний стан членів екіпажу (втома, емоційне вигорання, неуважність) може прискорювати деградацію технічних систем і призводити до передчасного досягнення критичних значень інтегрованого індексу ризику (SIRI). Модель побудовано на основі модульного підходу з можливістю адаптації до типу судна, характеру навігаційного переходу, типу вантажу, рівня автоматизації та зовнішніх умов. Розроблена система дозволяє не лише фіксувати поточний рівень ризику, але й здійснювати прогнозування майбутніх загроз з урахуванням змін у поведінці екіпажу та технічному стані. Для цього запропоновано використовувати інструменти машинного навчання, зокрема моделі на основі рекурентних нейромереж (типу LSTM), які навчаються на послідовностях параметрів стану судна. Окрему увагу приділено розробці сценаріїв реакції системи на критичні ситуації, а також обґрунтовано можливість інтеграції моделі у інтелектуальні навігаційно-діагностичні комплекси. Проведені експерименти та сценарний аналіз підтверджують високу ефективність моделі у прогнозуванні розвитку аварійних ситуацій, зменшенні часу реагування та зниженні імовірності негативних наслідків. Запропонована модель є кроком до створення повнофункціональних інтелектуальних систем підтримки прийняття рішень (DSS) для впровадження в практику судноплавства нового покоління, де управління ризиками здійснюється в реальному часі з урахуванням як технічних, так і людських чинників.
Ключові слова: *експлуатаційна безпека, морський транспорт, морські перевезення, інтегрований індекс ризику (SIRI), поведінкова надійність екіпажу, деградація систем, моніторинг стану, безпека судноводіння, машинне навчання, нейромережі, прогнозування аварій, ризик-менеджмент, адаптивні системи, ситуаційна обізнаність, превентивний контроль, критичний стан, сценарний аналіз, навігаційні фактори.*

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