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Principles And Patterns of Cause-Effect Relationship Formation in The System of Safe Ship Operation

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ABSTRACT

The article is devoted to the study of the principles and regularities of formation of cause-and-effect relationships in the system of safe operation of ships. It is determined that the safety of navigation is influenced by numerous factors, including the technical condition of the vessel, crew competence, navigation conditions, cargo characteristics, port infrastructure and environmental requirements. The author proposes a comprehensive assessment methodology that involves identification of key factors, determination of their weighting coefficients and probabilities of occurrence, and calculation of integral safety indicators at each stage of the operational process. Particular attention is paid to the role of the human factor and the interaction of socio-technical components in ensuring safety. The developed model allows to take into account the interrelationships between technical, navigational, technological and environmental safety components and to predict the overall level of flight safety. The results can be used to improve safety protocols, increase the efficiency of risk management and make informed decisions in the maritime industry.

1. Introduction.

The maritime industry is a vital pillar of world trade, facilitating the transportation of goods and resources over vast distances. In a dynamic and complex maritime environment, ensuring the safety of vessel operations becomes paramount. The safety of these operations is not simply a product of technical specifications or navigational protocols, but rather a complex interplay of various sociotechnical factors.

Consideration of a ship as a socio-technical system involves a comprehensive analysis of the interaction between the human factor, technical subsystems, and organizational and operational processes. The human factor remains crucial, as the crew operates complex technical equipment, ensures continuous monitoring of operating parameters and makes decisions in a changing marine environment. The technical component includes maintaining the structural integrity of the hull, the reliability of ship mechanisms and systems, and compliance with established safety regulations and standards. A separate group of risks is represented by navigational tasks related to the impact of meteorological factors, variability of sea conditions, and the need to perform maneuvers in complex port areas.

Thus in [16] proposed an IoT-based Smart Ship System aimed at enhancing ship safety through real-time monitoring and data-driven decision-making. The works [37, 44] presented a Data-Driven Decision Support System focusing on the structural safety

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of ships in waves and introduced an EEG-Based Driver Fatigue Monitoring system within the Human–Ship–Environment System, offering insights into ship braking safety by addressing human factors. The paper [21, 22] develops an operational safety evaluation system for ship locks using extension evaluation and combination weighting methods, emphasizing risk assessment and management. The Planned Maintenance System of a training ship to enhance shipping safety, emphasizing the importance of maintenance practices in preventing accidents offered in [2]. The authors in [13] assessed ship maneuvering safety in waterway systems, highlighting the importance of navigational risk assessment for safe navigation. In [14, 36] proposed a safety system for ships in harbors and investigated ship safety officers' perceptions and attitudes toward near-miss management systems, shedding light on the human factor in safety management [41]. The comparison of the power systems of conventional and autonomous ships regarding safety assessment, addressing the unique safety considerations of autonomous vessels carried out in [18].

In [9] conducted a quantitative effectiveness analysis to enhance safety management system implementation on ships and offered a comprehensive review of safety zone establishment and quantitative risk analysis during ship-to-ship LNG bunkering. The papers [15, 43] explored safety and compliance in high-voltage shore connection systems and presented the design of a new energy ship power safety monitoring system based on the Internet of Things, showcasing technological advancements for enhancing safety in ship operations. In [17] offered ship safety policy recommendations for Korea using system dynamics, focusing on policy interventions to enhance maritime safety. Additionally, [1, 7, 31] considered organizational dynamics and societal responses during crises, providing insights into modeling organizational energy-entropy. The works [26, 27, 29, 30, 32] contributed to various aspects of environmental efficiency and navigation safety, covering vulnerability assessment of critical ship equipment, environmental efficiency of ship operations, ship information security risks, navigational safety assessment, and measures to ensure navigation safety while reducing environmental impact. The safety and security monitoring system for shipborne networks and determination of energy-efficient operation modes of propulsion electrical motors studied in [20, 42].

The authors in [10] discussed the risk management in customs inspection of goods, while [8] proposes an augmented security scheme for shared dynamic data using efficient lightweight elliptic curve cryptography. The paper [40] focuses on dynamic certification and assessment of building life cycles under regular explosive impacts. Meanwhile, [4] explores the operating regime of adsorptive heat-moisture regenerators based on composites, and [5] study the heat exchange equation during the flow of non-Newtonian liquids in technological equipment channels. The paper [6] presents a decision support system concept for designing combined propulsion complexes, and [35] predicts centrifugal compressor instabilities for internal combustion engines. Furthermore, [38] utilizes a multicriteria approach for determining the optimal composition of technical means in the design of sea grain terminals. The authors in [19] focused on the design and optimization of maritime transport infrastructure projects based on simulation modeling methods. Additionally, [39] conducted a comprehensive assessment of hull geometry influence on the maneuvering performance and propulsion system parameters of modernized ships. The work [3] assesses the energy of sorghum cultivation, while [25] evaluates non-specialized vessel acquisition and operation projects for oversized cargo transportation effectiveness. The work [11, 23] determine dynamic loading of freight wagons' bearing structures with actual dimensions and calculates loads on carrying structures of articulated circular-tube wagons with new draft gear concepts. The article [33] selects rational parameters for automated robotic transmission clutch control through simulation modeling, while [12] develops and assesses the quality of an intelligent locomotive decision support system. In [24, 28] explored autonomous ships concept and mathematical models for steering process control and discussed maritime situational awareness for safe ship operation. Works [46, 47] focus on the development and application of mathematical models for analyzing the stress-strain state of complex structural connections, which may be relevant for shipowners in the context of timely fulfillment of charter obligations.

In this context, understanding the causal relationships within the safety of shipboard operations becomes imperative. By disentangling the multifaceted nature of operational safety and identifying the interdependencies between various influencing factors, stakeholders can develop more robust safety protocols and risk management strategies. This study proposes a solution by unraveling the tangled web of cause and effect relationships that determine the operational safety of ships. Through a comprehensive analysis of the various influencing factors, ranging from human factors to environmental conditions, it becomes necessary to deepen the understanding of operational safety in maritime environments. By elucidating these interrelationships, it is possible to contribute to the development of informed decision - making processes and the formulation of effective safety measures in the maritime industry.

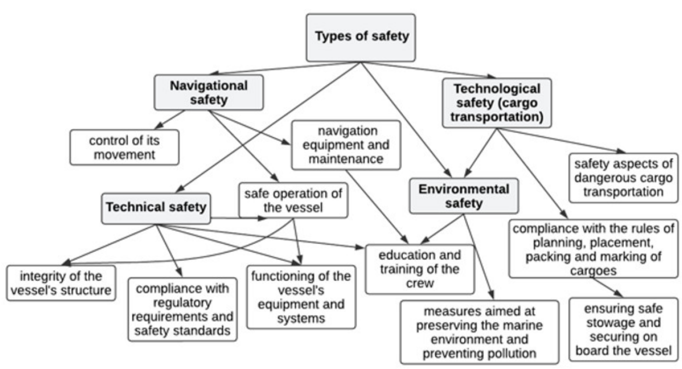
2. Materials and Methods.

The safety of maritime operations is the result of intricate interactions among various factors, encompassing technical, navigational, environmental, and technological aspects. Recognizing ships as socio-technical systems underscores the significant influence of the human element on safety outcomes. Therefore, our investigation focuses on understanding how the safety of each operation is contingent upon a multitude of factors throughout the entirety of the operation process. By acknowledging the pivotal role of humans in shaping safety outcomes, we explore how the crew's actions contribute to either the establishment or compromise of all identified safety dimensions. Consequently, crewmembers not only oversee ship operations and engage with its technical systems but also participate in all associated technological processes alongside personnel from other involved entities, be it in transportation or ship maintenance procedures.

Therefore, by these types of safety we will understand the following:

- Technical safety, which relates to the integrity of the ship's structure, the proper functioning of the ship's equipment and systems, and its compliance with regulatory requirements and safety standards.
- Navigational safety, which covers aspects of safe operation of the vessel, control of its movement, condition of navigation equipment and maintenance, as well as education and training of the crew in the field of safe ship operation.
- Technological safety (cargo transportation), which covers safety aspects of dangerous cargo transportation, compliance with the rules of planning, placement, packing and marking of cargoes, as well as ensuring their safe stowage and securing on board the vessel.
- Environmental safety includes measures aimed at preserving the marine environment and preventing pollution of water resources through compliance with international norms and standards, use of environmentally friendly fuel, efficient waste management, pollution monitoring and control, as well as education and training.

Figure 1: Decomposition of integrated ship safety.



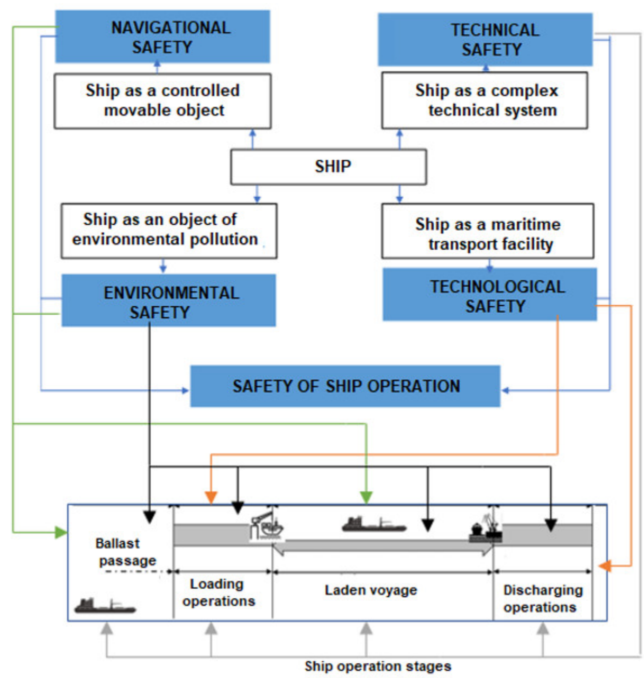
Source: Authors.

Such division into types of safety is necessary for complete coverage of measures, means and methods of ensuring the safety of ship operation, as each type of safety is associated with a certain source of safety violations caused by the influence of various factors. Figure 2 shows the correlation between the selected types of safety and the stages of the ships' operation process, so we will consider the following as the main types of safety:

- Technical safety, which can be considered at all stages of ship operation, as certain ship systems are involved in all operations, including power plants, which additionally are also a major source of environmental pollution. In addition, ballast water discharge is also a potential threat to the environment.
- Navigational safety is related to the movement of the ship, so it is considered when the ship transits in ballast or with cargo.
- Technological safety involves interaction with other participants in the transportation process-taking place at ports of loading/unloading (in particular, cargo placement, securing and transportation technology, ship bunkering, pilotage, etc.).
- Environmental safety of the vessel, which includes a set of measures and technologies aimed at reducing the negative impact of the vessel on the environment during operation.

The totality of these types of safety forms the ultimate safety of all operations of the ship operation process.

Figure 2: Types of safety by stages of the operation process.



Source: Authors.

3. Results.

Thus, at each stage $l = \overline{1, L}$ of the process of the ship's operation S^l - the safety of the ship's operation is the result of events $S^l{}_1, S^l{}_2, S^l{}_3, S^l{}_4$ -, which consist in the fact that technical, navigational, environmental and technological safety is ensured during the ship's operation:

$$S^l = \prod_{i=1}^{4} S^l{}_i, l = \overline{1, L}. \tag{1}$$

Taking into account the independence of four types (components) of ship safety, which were singled out precisely for the possibility and correctness of their separate consideration, the probability of ship safety at the stage of the operation process:

$$P(S^l) = \prod_{i=1}^{4} P(S^l{}_i), l = \overline{1, L}. \tag{2}$$

The number of stages in the ship's operation process requires attention. In Fig. 2 shows four main stages, but in reality, the division into stages, as well as the consideration of operations, can take place with a different degree of detail. Therefore, in this study, the number of stages in the general form L is accepted, but in each case this number is determined taking into account the availability of information, etc. For example, it is possible to separate the entry of the ship into the port and the departure of the ship from the port, during the transition between the ports, the passage of the channel (canals) can be separated.

If a separate type of safety is not considered at a certain stage, it is accordingly not taken into account in (2).

It should be noted that each stage of the ship's operation process corresponds to a set of operations $O^{lj}, l = \overline{1,L}, j = \overline{1,M_l}$, which can be considered with varying degrees of detail. Let the eventS^{lj}- safety of the j-th operation of the ship's operation process $j = \overline{1,M_l}$ at the stage $l = \overline{1,L}$, where M_l - the total number of operations at the l-th stage. It should be noted that, taking into account the different focus and essence of operations, only a part of them affects a specific type (component) of safety $S^l{}_1, S^l{}_2, S^l{}_3, S^l{}_4$.

Thus the set of all operations $O^{lj}, j = \overline{1,M_l}$ at the l-th stage, can be divided into four sets by orientation from the point of view of the type of safety: $\Omega_1^l, \Omega_2^l, \Omega_3^l, \Omega_4^l \subset \Omega^l$. Each set $\Omega_1^l, \Omega_2^l, \Omega_3^l, \Omega_4^l$ corresponds to a certain type of safety. It should be noted that these sets may intersect, i.e., some operations belong to several sets at once, since their execution affects different types (components) of safety, but their influence is, of course, different, i.e., to a different degree, the safety of each operation affects the type (component) of ship safety.

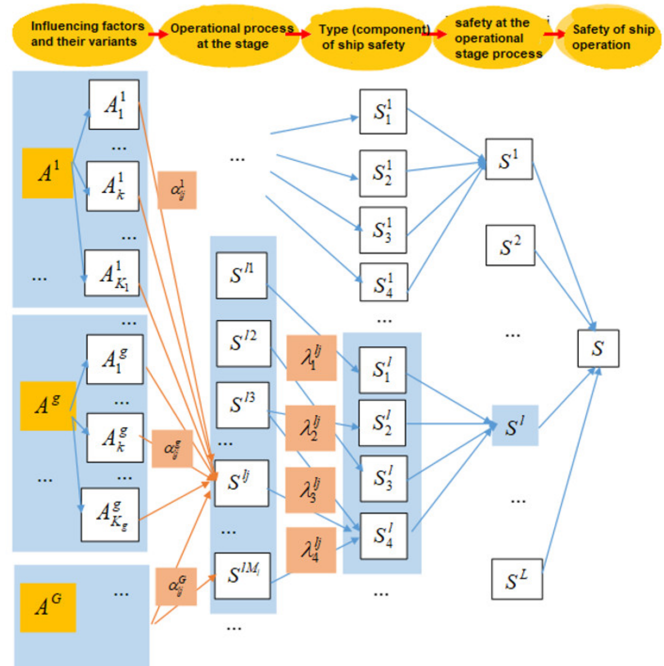
In order to take into account the different degree of influence of the operations of the ship's operation process at a certain stage and a certain type (component) of the ship's safety, it is proposed to introduce weighting factors for consideration $\lambda_1^{lj}, \lambda_2^{lj}, \lambda_3^{lj}, \lambda_4^{lj}, l = \overline{1,L}, j = \overline{1,M_l}$, which will determine the safety importance of each operation for a certain type (component) of safety (Fig. 3). Taking into account the essence of the weighting factors, they must meet the following conditions:

$$\sum_{j\in\Omega_i} \lambda_i^{lj} = 1, i = \overline{1,4}, l = \overline{1,L}, \tag{3}$$

Based on this, having estimates of the probabilities of events $S^{lj}, l = \overline{1,L}, j = \overline{1,M_l}$, namely, $P(S^{lj}), l = \overline{1,L}, j = \overline{1,M_l}$ it is possible to estimate the probability of each type (component) of safety at each stage of the ship's operation process $P(S_1^l), P(S_2^l), P(S_3^l), P(S_4^l)$:

$$P(S_i^l) = \sum_{j\in\Omega_1} \lambda_1^{lj} \cdot P(S^{lj}), i = \overline{1,4}, l = \overline{1,L}. \tag{4}$$

Figure 3: Formation of cause-and-effect relationships in the ship's safety system.



Source: Authors.

In turn, the safety of each operation depends on the influence of many factors $A^1, A^2, ..., A^g, ...A^G$ during the operation process of the vessel, which were mentioned earlier. First of all, weather conditions, the condition of the human element (ship crew), the level of technical condition of the ship, the specifics of the cargo, the level of technical equipment of the ports, the level of safety of port operations, etc. Each of the influencing factors has variants of manifestation, for example, if A^1 - weather conditions, then $A_1^1, A_2^1, ..., A_k^1, ..., A_{K_1}^1$ - variants of the state of weather conditions during the ship's voyage; if A^2 - technical condition of the vessel, then $A_1^2, A_2^2, ..., A_k^2, ..., A_{K_2}^2$ - variants of this state.

To take into account the different degree of influence of the considered set of factors $A^1, A^2, ..., A^g, ...A^G$ let's consider the weighting coefficients $\alpha_{lj}^1, \alpha_{lj}^2, ..., \alpha_{lj}^g, ..., \alpha_{lj}^G$ provided:

$$\sum_{g=1}^{G} \alpha_{lj}^g = 1, l = \overline{1,L}, j = \overline{1,M_l}. \tag{5}$$

Thus, these levers take into account the degree of influence of factors in general on each operation of the ship's operation process – for example, how weather conditions in general affect the safety of operations.

It should be noted that not only the aggregated impact factors have different effects on the safety of operations; seemingly individual manifestations of impact factors have different significance for the safety of operations during a certain stage of the ship's operation. For example, stormy conditions have a greater impact on maneuvering operations and during ship transitions between ports.

It should be noted that the plural is a manifestation of a certain influencing factor $A_1^g, A_2^g, ..., A_k^g, ...A_{K_g}^g, g = \overline{1, G}$ constitutes a complete group of events - in fact, these events are independent and cover all possible options for the manifestation of the impact factor. So:

$$\sum_{k=1}^{K_g} P(A_k^g) = 1, g = \overline{1, G}, k = \overline{1, K_g}. \quad (6)$$

Each manifestation of the factor affects the safety of the operation, so there are a number of conditional probabilities:

$$P_{A_k^g}(S^{lj}), l = \overline{1, L}, j = \overline{1, M_l}, \quad (7)$$

that is, the probability of the safety of each operation $S^{lj}, l = \overline{1, L}, j = \overline{1, M_l}$ and the conditions of the event taking place A_k^g, that is, the specific state of a certain influence factor (its manifestation). In this way, the influence of factors on the probability of the safety of operations is taken into account.

So, having probability estimates (distribution) for each influence factor $P(A_k^g), g = \overline{1, G}, k = \overline{1, K_g}$, it is possible to estimate the safety probabilities of each operation by using the formula of total probability $S^{lj}, l = \overline{1, L}, j = \overline{1, M_l}$ for each stage of the operation process, taking into account the influence of many factors, as well as the probability of their manifestation:

$$P(S^{lj}) = \sum_{g=1}^{G} \alpha_{lj}^g \sum_{k=1}^{K_g} P(A_k^g) \cdot P_{A_k^g}(S^{lj}), l = \overline{1, L}, j = \overline{1, M_l}, \quad (8)$$

where

$$\sum_{k=1}^{K_g} P(A_k^g) \cdot P_{A_k^g}(S^{lj}), l = \overline{1, L}, j = \overline{1, M_l}, g = \overline{1, G} \quad (9)$$

The probability of the safety of operation j at stage l of the ship's operation process, taking into account the impact factor g. In turn, (8) takes into account all influencing factors $A_1^g, A_2^g, ..., A_k^g, ...A_{K_g}^g, g = \overline{1, G}$ and their different degrees of influence using coefficients $\alpha_{lj}^g, g = \overline{1, G}, l = \overline{1, L}, j = \overline{1, M_l}$.

Thus, a chain of assessment of the probability of ship safety is formed:

- influencing factors $A^1, A^2, ..., A^g, ...A^G$, their weight $\alpha_{lj}^1, \alpha_{lj}^2, ..., \alpha_{lj}^g, ..., \alpha_{lj}^G$, manifestations $A_1^g, A_2^g, ..., A_k^g, ..., A_{K_g}^g$, $g = \overline{1, G}$ and the corresponding probability distribution $P(A_k^g)$, $g = \overline{1, G}, k = \overline{1, K_g}$;

- probability of safety operations $P(S^{lj}), l = \overline{1, L}, j = \overline{1, M_l}$ at the stage of the operation process, taking into account the influence of many factors;

- probabilities of each type (component) of vessel safety $P(S_1^l), P(S_2^l), P(S_3^l), P(S_4^l)$ at each stage, taking into account the set of relevant operations $\Omega_1^l, \Omega_2^l, \Omega_3^l, \Omega_4^l$, floating and their degree of influence $\lambda_1^{lj}, \lambda_2^{lj}, \lambda_3^{lj}, \lambda_4^{lj}, l = \overline{1, L}$, $j = \overline{1, M_l}$;

- the probability of vessel safety at each stage of the operation process $P(S^l), l = \overline{1, L}$;

- the probability of safe operation of the vessel during the voyage $P(S)$, which is evaluated taking into account the probabilities of safety at all stages of the operation process:

$$P(S) = \prod_{l=1}^{L} P(S^l). \quad (10)$$

The following conclusions can be drawn based on the calculations performed:

The safe operation of ships depends on many factors including technical characteristics of the vessel, navigational conditions, environmental factors and technological processes. Since the human factor plays a key role in ensuring safety on a ship and especially in ship management, its interaction with technical systems and participation in technological processes have a significant impact on overall safety. Many operations performed in the course of vessel operation are subject to risk, which depends on the state of technical systems, weather conditions, crew condition and other factors. Therefore, the safety of shipboard operations requires consideration of all aspects of the production process; including crew training, ship maintenance and compliance with environmental standards. Thus, understanding of the complex nature of ship operations safety and the influence of the human factor allows developing effective strategies to prevent accidents and minimize risks in maritime activities.

The assessment of ship safety involves a systematic chain of evaluation, starting from identifying influencing factors, determining their weights, considering their manifestations and corresponding probability distributions. This process leads to estimating the probabilities of safety for each operation stage, taking into account the influence of multiple factors, and culminating in evaluating the overall safety of vessel operations during the voyage.

Based on the calculations and analyses conducted, several conclusions can be drawn (Table 1):

The suggested system has already undergone thorough testing and validating procedures during the different simulative studies, mimicking many maritime scenarios and making it suited for real-world maritime applications owing to its robustness. An extensive case study has also been added, which, among other things, clearly shows the usefulness of our system in actual practice with the improvement of maritime safety, along with presenting empirical data that would have supported our approach.

Future research areas for the improved system could involve trials with shipping companies to test and further develop the system in real maritime conditions. These studies would presumably be necessary to determine the sustainability of the longer-term implementation of the system in diverse maritime deployment types. The integration of more advanced modeling techniques, including machine learning and predictive ana-

Table 1: Key aspects of safe shipboard operations and effective risk mitigation strategies in maritime activities.

Aspects	Risk mitigation strategies
Multifactorial Nature of Safety	The safe operation of ships hinges on a multitude of factors encompassing technical aspects of the vessel, navigational conditions, environmental elements, and technological processes
Human Factor Significance	Given the pivotal role of humans in ship safety, especially in ship management, their interaction with technical systems and involvement in technological processes significantly impact overall safety outcomes
Risk in Operations	Many operations during vessel operation are inherently risky, and this risk is influenced by various factors such as the state of technical systems, weather conditions, crew conditions, among others
Comprehensive Safety Approach	Ensuring safety in shipboard operations necessitates a comprehensive approach that includes crew training, effective ship maintenance practices, and adherence to environmental standards
Effective Risk Mitigation Strategies	Understanding the complex dynamics of ship operations safety, particularly concerning the human element, enables the development of effective strategies aimed at accident prevention and risk minimization in maritime activities

Source: Authors.

lytics, shall enable the system to improve the proactive safety management ability.

International benchmarking studies will be undertaken to appraise the system's functioning against different regulatory and operational maritime industry panoramas. Incorporating human-centered approaches and cognitive modeling techniques would help design customized interventions and training programs for enhancing crew performance and safety. The research is in preparation for the integration of new technologies such as IoT sensors, AI-based decision support systems, and remote-monitoring tools, thus facilitating real-time situational awareness and decision-making in maritime security management. The outlined research areas are aimed to allow further development in maritime safety management and, in particular, contributing toward shipping safety enhancement on a global scale.

Conclusions.

The article touches upon a number of key aspects related to ensuring the safety of ship operations, including technical, navigational, environmental and technological components. It is established that the level of safety of each operation is determined by a combination of factors operating at all stages of the production and operational process. Given that ships are sociotechnical systems, safety depends not only on the technical characteristics and serviceability of ship systems, but also on the effective interaction of the human factor with various elements and processes.

Thus, to maintain an appropriate level of safety on board, all elements of the production and operational cycle must be taken into account, including crew training, ship maintenance, and compliance with environmental standards. Awareness of the cause-and-effect relationships in the field of maritime safety creates the basis for developing effective strategies to prevent accidents and minimize risks during maritime operations. On this basis, the importance of an integrated approach to ensuring the safety of navigation and the need for a comprehensive consideration of all factors affecting this process is emphasized.

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