The ship safety evaluation and analysis on the multilayer model case study

Oleksiy Melnyk1*, Oleg Onishchenko1, Oleksii Drozhzhyn2, Oleg Pasternak1, Marina Vilshanyuk2, Sergiy Zayats1, and Gennady Shcheniavskyi1

1Department of Navigation and Maritime Safety, Odesa National Maritime University, Odesa, Ukraine,  
2Department of Fleet Operation and Shipping Technologies, Odesa National Maritime University, Odesa, Ukraine

Abstract. The article provides an in-depth analysis of the various methodologies used to assess the safety of seagoing vessels during their operational phase. Central to this analysis is the 'layers of safety' model, which identifies potential safety risks at different levels of the vessel. An extensive review of safety models widely used in the shipping industry is provided and the article emphasizes the crucial role of accurate data in their development. In addition, the article advocates the need for various methods to assess the probability of potential hazards, including fire hazards. The article highlights the need to comply with maritime safety rules and regulations and makes recommendations aimed at improving safety methods and techniques. All these measures together contribute to the improvement of operational safety and reliability of maritime cargo transport.

1 Introduction

Introduction. Maritime transport is a complex and unique environment with a high degree of risk. In this context, the development of effective and efficient measures to counteract the occurrence of negative phenomena is an integral part of ensuring the safety of ships, crews and the environment during the operational period, as maritime transportation is an important component of the international trade system and a key to global economic development. Therefore, in order to achieve a high level of reliability and safety of maritime transport, it is important to improve the methods and means of ensuring safety on board ships.

Numerous studies have been conducted to develop effective safety models that allow for the assessment and management of risks associated with various aspects of ship safety. The literature review conducted in this article allows us to consider various aspects of ship safety and models for improving ship efficiency and ensuring ship safety. It takes into account scientific works that address such topics as modelling ship operational safety, hazard prediction using artificial intelligence, safety of ship operations, safety assessment models, etc.


The discourse is further enriched by an exploration of modern technologies aimed at environmental protection measures. This includes an assessment of the current technology landscape and prospects for the adoption of electronic navigation technology [9–13]. Maritime technology, on the horizon of innovation, delves into the concept of crewless vessels as discussed in [14,15]. It also places significant emphasis on discussions regarding security risks within shipping operations, especially pertaining to ship information security [16,17]. There has been dedicated attention to unravelling the origins and implications of security concerns and potential threats within the maritime sector, with a particular focus on ecological issues, ship steering process control, and methodologies for assessing ship safety levels, as found in [18–21].

The quality of risk assessment concerning ship accidents' analysis takes centre stage in [22]. Subjects such as maritime operational safety, innovative methods for appraising ship safety levels, and pathways for safety enhancement are thoroughly examined in [23,24]. Further improvements in the control of technical systems and complexes during a ship's operation are studied in [25]. This theme is further dissected in [26–
With a proposal for the deployment of intelligent incident detection systems detailed in [29,30]. In [31], a simulation-based method is presented for predicting changes in a ship's seaworthy condition under the influence of various factors. The work in [32] focuses on ship safety officers' perceptions and attitudes towards near-miss management systems.

Additionally, [33,34] introduce dynamic safety modelling for ship management performance and conduct a quantitative analysis of the effectiveness of safety management system (SMS) implementation on-board ships. Focused on cruise ship safety management in Asian regions, works [34,35] explore trends and future outlooks for safety practices in the cruise ship industry. They also pertain to the improvement of safety inspection policies for passenger ships, excursion ships, and ferries.

The importance of marine transport safety, encompassing navigation and sea transportation, is addressed in [36,37], where a fuzzy routing algorithm in telematics transportation systems is proposed. Moreover, [38] focuses on oil spill detection using wavelets and morphology in SAR images. Lastly, [39,40] determine energy-efficient operation modes for autonomous swimming apparatus propulsion and present a simple technique for identifying vessel model parameters.

It is important to emphasise the need to develop and implement a comprehensive toolkit to prevent accidents in the operation of ships and technical systems. This toolkit should include advanced technologies, rigorous safety protocols and proactive monitoring measures. By emphasising the need for proactive monitoring of adverse events to prevent incidents and accidents, this approach has the potential to improve the overall safety record of offshore operations. The integration of advanced technology, rigorous safety procedures and a proactive attitude will enable the maritime industry to move towards a future characterised by enhanced safety, efficiency and sustainability.

One of the main problems faced by modern shipping is an effective risk assessment in the field of maritime transportation. It includes difficulties in assessing the likelihood of various emergencies, analysing the consequences of such situations and accounting for uncertainties related to the safety of the vessel in the marine environment. Another problem may be the inconsistency between the different safety models used to ensure the operational safety of ships, partly because such models are developed by different organisations or in different countries and do not have common standards and protocols. This can make it difficult to share information, compare data and make coordinated decisions in the area of maritime safety. In addition, it is important to consider the human factor in safety models, as crews play a crucial role in ensuring safety on board, and it is necessary to take into account the human factor when developing safety models and training crews.

The purpose of the article is to study and analyse maritime safety models and identify the main problems faced by these models. Thus, the main objective of this article is to analyse the problems associated with maritime safety models in order to develop recommendations and improve existing models to ensure more effective and reliable safety in the maritime sphere.

2 Materials and methods

Risk assessment in solving the safety problems of ships as technical systems involves a systematic approach that takes into account various factors that affect risk. There are different approaches to risk assessment:

The engineering approach is based on the analysis of breakdown and accident statistics. It helps to determine the probability of certain events occurring and conducts a probabilistic safety analysis.

The modeling approach uses simulation of the impact of harmful factors on humans and the environment. This approach helps to analyze the consequences of events and their impact on the system.

The expert approach involves interviewing experienced experts who can assess the likelihood and consequences of events based on their experience and knowledge.

The sociological approach examines public attitudes toward various risks. It relies on surveys and public opinion analysis to understand risk perception and its social impact.

The risk assessment process also needs to take into account the uncertainties that may also affect the safety of the ship's operation. Uncertainty analysis involves taking into account possible variations and contingencies in order to take into account different scenarios and develop measures to reduce risk.

The use of safety models is a structured approach to assessing the level of safety in a particular industry, and shipping is no exception. It is a comprehensive approach that takes into account many factors, such as safety standards, risks and hazards, risk management processes, technical specifications, etc. The goal of the modeling approach is to ensure the safe operation of the system and prevent potential accidents and events. It can be presented in the form of mathematical models, schemes, diagrams, tables and other graphical or textual formats and covers the process of analyzing and assessing risks, taking measures to eliminate identified vulnerabilities and deficiencies, as well as monitoring and controlling compliance with safety standards.

Examples of some common safety models used in modern shipping are the Maritime Safety Model, the Ship Safety Model and the Maritime Safety Risk Model. All of them are based on many years of research and experience gained by specialists and scientists in the maritime industry.

The Maritime Safety Model is a comprehensive system used to assess and manage safety risks in the maritime industry. It is a structured approach to identifying, analyzing, assessing and controlling risks associated with maritime operations in order to prevent accidents, incidents and other safety-related events. The model covers a wide range of factors affecting maritime safety, including ship design and construction, equipment and systems, crew training and experience, operating procedures, environmental conditions,
regulatory compliance and human factors. It also takes into account the specific characteristics of different types of ships, such as cargo ships, tankers, passenger ships and fishing vessels and usually consists of several stages, including (Table 1):

**Table 1. Main stages of the maritime safety model**

<table>
<thead>
<tr>
<th>Hazard identification</th>
<th>This stage involves identifying potential hazards that could cause damage to people, the vessel, cargo, and the environment, such as collisions, grounding, fires, and pollution.</th>
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<tbody>
<tr>
<td>Risk assessment</td>
<td>This stage involves assessing the probability of occurrence and consequences of each identified hazard using various methods, such as fault tree analysis, event tree analysis, and butterfly analysis.</td>
</tr>
<tr>
<td>Risk management</td>
<td>It involves the development and implementation of measures to control and mitigate identified risks, such as implementing safety procedures, improving ship design, conducting training and education, and improving communication and cooperation between stakeholders.</td>
</tr>
<tr>
<td>Monitoring and review</td>
<td>It involves continuous monitoring and evaluation of the effectiveness of risk management measures, as well as making the necessary adjustments to ensure safety and compliance with regulatory requirements.</td>
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</table>

This safety model is widely used in the maritime industry, including by ship owners and operators, regulators and classification societies, to ensure safe and efficient operations at sea. It is also constantly evolving and improving as new technologies, regulations and best practices emerge. One of the main tasks of the safety model is to take into account various factors that can affect the safety of a ship. These factors may include technical aspects, such as the condition of equipment and infrastructure, as well as human factors, such as the level of crew training and experience, safety culture, etc. The safety model may also include an assessment of the level of risk and danger in various scenarios, such as sailing in a storm, in ice or fog, and when entering and leaving a port. Based on these assessments, the safety model can provide recommendations for improving ship safety and reducing risks.

The Ship Safety Model is a systematic approach to analyzing and assessing the level of safety on a ship. It is intended to identify potential safety threats and risks, as well as to develop appropriate measures and means to prevent or eliminate them. The ship safety model contains various components and layers of safety that are assessed and analyzed independently of each other. Each safety layer focuses on specific safety aspects and contains appropriate measures and systems. The application of the ship safety model allows for the systematic investigation and assessment of risks and threats at various levels of the ship, ranging from physical aspects (e.g. ship structure, fire fighting systems) to operational aspects (e.g. safety management, crew training). It helps to identify vulnerabilities and potential safety issues and develop measures to eliminate or reduce them.

The Maritime Safety Risk Model is a system used to assess and manage the risks associated with maritime operations. It is a comprehensive approach to identifying, analyzing, evaluating and controlling the risks inherent in shipping in order to prevent accidents, incidents and other safety-related events. It is a tool for analyzing and assessing the risks associated with maritime transportation and allows identifying potential hazards and determining the likelihood of their occurrence, as well as assessing the consequences of these risks. The maritime safety risk model is based on a systematic approach to safety analysis. It takes into account various factors affecting the safety of maritime transportation, including technical aspects of the vessel, human factors, operating conditions, natural and other external factors. The Maritime Safety Risk Model is used to determine the level of risk at various stages of maritime transportation, including route planning, navigation, ship repair and maintenance, emergency response, and other processes. By identifying potential threats and assessing them, the model helps to make decisions to prevent accidents, ensure the safety of crew, vessel and cargo, and reduce environmental impact.

One of the most effective safety tools is the "layers of safety" model, which allows you to assess the level of safety at different levels within a ship. It is based on the assumption that each level within the ship has its own safety level and that the levels can be classified according to the degree of risk.

The "layers of safety" model consists of several layers, each of which represents a separate level within the ship. For example, the first layer may be the bridge and crew cabins, the second layer may be the engine room, the third layer may be the cargo area, and so on. Each layer is assessed based on its characteristics and potential risks. The safety assessment of each layer includes identifying possible safety threats, determining the likelihood of their occurrence, and assessing the consequences if a threat does occur. These characteristics may vary depending on the type of vessel, its purpose, operating conditions and other factors.

Figure 1 shows the organization of two main levels of "safety layers" within a ship: internal and external safety layers within the overall safety of the ship.
Both safety layers interact with each other and contribute to the overall safety level of the vessel as a whole, which makes it possible to systematically analyze and evaluate the safety levels of each layer and take appropriate measures and decisions to eliminate possible safety threats at each level. For example, if deficiencies or risks in the internal safety layer are identified, measures can be taken to improve fire extinguishing systems, introduce additional controls, etc. Similarly, on the external safety layer, measures can be taken to ensure more accurate navigation, improve communication systems, and increase collision prevention measures.

3 Results and discussion

In the safety layers model, different methods are used to assess the level of safety at each layer. Some of these methods may include the use of algorithms to calculate the probability of safety threats and their consequences. One example that can be used in the safety layers model is the calculation of the probability of a fire on a ship, which can be determined based on various factors, such as the amount of fuel and flammable materials on board, the availability of fire extinguishing systems, operating conditions, and others. In general, it can be represented as follows:

\[ P = (F + S + M + E) \times C \]  
(1)

where \( P \) is the probability of a fire on board (%), \( F \) is the amount of fuel on board (tons), \( S \) is the amount of flammable materials (tons), \( M \) is the availability of fire extinguishing systems and their effectiveness, \( E \) is the operating conditions of the ship, such as temperature, humidity, etc., and \( C \) is a coefficient that takes into account other factors.

To calculate the fire safety model of a vessel, you can use the method of determining the fire risk category. It is necessary to calculate the fire load and fire protection indicators based on the conventional characteristics of the vessel and the technical capabilities of its fire extinguishing systems: Vessel length: \( L = 125 \) m, Vessel beam: \( B = 27 \) m, Vessel side height: \( H = 12 \) m, Draft in cargo: \( T = 9 \) m, Displacement of the vessel: \( D = 25000 \) tons, Automatic fire extinguishing system in holds: CO2, Fire detectors on each deck and in each of the 5 holds, CO2 and powder fire extinguishers near each hold and on each deck (5 decks), Ventilation systems in the holds. The cargo is grain in bulk.

The following formula can be used to calculate the fire load (FL) on an area of 1 m²:

\[ PN = Q / A \]  
(2)

Where: FF is the fire load (j/m²), Q is the amount of energy released during the combustion of materials (j), \( A \) is the area where combustion occurs (m²).

Formula (2) allows you to calculate the fire load on a unit area and is a tool for assessing the energy potential of a fire. Given the fire load, potential risks can be assessed and appropriate measures can be taken to ensure safety on board.

For a ship with a grain cargo, we can assume a fire load of \( Q_i = 350 \) MJ/m².

Thus, the fire load for our ship will be:

\[ PN = Q / S = 350 \text{ MJ/m}^2 / (125 \text{ m} \times 27 \text{ m}) = 1.17 \text{ MJ/m}^2 \]  
(3)

Fire protection (FP) is the amount of fire extinguishing agents required to extinguish a fire on an area of 1 m². To calculate fire protection, we can use the following formula:

\[ PZ = V / S \]  
(4)

where \( V \) is the volume of fire extinguishing equipment efficiency (m³) required to extinguish a fire on the area \( S \) (m²).

For a vessel with an automatic hold fire extinguishing system with CO2, carbon dioxide and powder fire extinguishers in each hold and on each deck, and ventilation systems in the holds, we can assume that the required volume of fire extinguishing agents per 1 m² is \( V = 0.1 \) m³/m². Thus, there will be fire protection for the vessel:

\[ FF = V / S = 0.1 \text{ m}^3/\text{m}^2 / (125 \text{ m} \times 27 \text{ m}) = 0.000296 \text{ m}^3/\text{m}^2 \]  
(5)

Using the obtained fire load and fire protection indicators, we can determine the fire risk category of the vessel. Depending on the values obtained, the vessel can be assigned to one of the following categories (Table 2).

<table>
<thead>
<tr>
<th>Category</th>
<th>The degree of risk</th>
<th>Meaning</th>
</tr>
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<tbody>
<tr>
<td>Category 1</td>
<td>low risk</td>
<td>DER &lt; 2.5 MJ/m², DF &gt; 0.0002 m³/m²</td>
</tr>
<tr>
<td>Category 2</td>
<td>medium risk</td>
<td>2.5 MJ/m² ≤ PS &lt; 7.5 MJ/m², 0.0001 m³/m² ≤ PS &lt; 0.0002 m³/m²</td>
</tr>
<tr>
<td>Category 3</td>
<td>high risk</td>
<td>DER ≥ 7.5 MJ/m², DF ≤ 0.0001 m³/m²</td>
</tr>
</tbody>
</table>

In our case, the vessel has a fire load of 1.17 MJ/m² and fire protection of 0.000296 m³/m². According to the criteria, the notional vessel belongs to category 2 (medium risk) in terms of fire safety.

By calculating the fire risk category of a vessel, measures can be taken to improve fire protection and reduce the risk of fire occurring and spreading on board.

The results of calculating the fire risk category can be used to take measures to improve the fire protection of the ship and reduce the likelihood of a fire occurring and spreading on board. For example, additional fire detection and extinguishing systems may be installed, a sufficient number of fire extinguishers may be provided on board, regular inspections and maintenance of fire
action to ensure safety and minimize damage (Figure 2).

It is also necessary to determine the time of fire detection and the time of exposure to the combustion product. Let's assume that the fire detection time is 5 minutes and the exposure time to the combustion product (CO2) is 45 minutes. Using these data, the fire hazard of the vessel can be calculated as follows:

\[ P = P_p \times \left( 1 - \frac{T_t + T_r}{T_d} \right) \]  

where \( P \) is the fire hazard of the vessel; \( P_p \) is the probability of a fire on the vessel during one voyage; \( T_t \) is the time of fire detection; \( T_r \) is the fire response time (the time it takes for the crew to start fighting the fire); \( T_d \) is the time of the combustion product. Substituting the values into the formula, we get:

\[ P = 0.005 \times \left( 1 - \frac{5 + 0}{45} \right) = 0.0031 \]  

Thus, the fire hazard of the vessel is 0.31%. Fire hazard assessment allows to determine the effectiveness of the ship's fire protection system and take measures to improve it, and also allows to assess the risks of fire occurrence and spread on board the ship. The main factors affecting the fire hazard of a ship include fire load, fire protection, availability and quality of firefighting equipment, as well as the level of training and readiness of the crew to act in the event of a fire. All of these factors should be taken into account when determining the fire risk category of a vessel and when developing and improving the fire protection system.

A decision tree is a powerful tool and can be used during a fire to organize and manage the firefighting and decision-making process. It can serve as a means of structuring actions and options during a fire, assessing their consequences, and determining the best course of action to ensure safety and minimize damage (Figure 2).

It should be noted, however, that the specific scheme for calculating the probability of fire may vary depending on specific conditions and requirements, and that the use of this example is only one of many methods for assessing ship safety within the layers of safety model. The layers of safety model can be used to assess the safety of a ship during any routine maritime operation, such as during difficult navigational conditions in a passage, and each layer of the model can correspond to different aspects of safety, such as a meteorological layer with an assessment of current meteorological conditions, such as air temperature, water temperature, wind speed, and visibility;

- Navigation equipment layer with an assessment of the availability and efficiency of navigation equipment on board, such as radar, echo sounder, GPS system, etc;
- a layer of the ship's crew with an assessment of competence and professionalism, as well as readiness and ability to respond to emergencies in poor visibility conditions;
- ship safety systems layer with an assessment of the availability and effectiveness of safety systems on board, such as emergency engine shutdown systems, fire extinguishing systems, waterproofing systems, etc;
- environmental safety layer. Assessment of possible consequences in the event of an accident, such as collisions with other vessels or environmental damage. Each of these layers may use different safety assessment methods, including mathematical models, data analysis, and expert judgment. For example, a mathematical model based on data on ship traffic in the area and the total number of ships may be used to estimate the probability of collision with other ships, while an expert assessment by qualified safety professionals may be used to assess the competence of the ship's crew.

4 Conclusion

In general, a safety layers model can be an effective tool for assessing safety during a voyage and enables the assessment of safety levels at different layers within a ship and measures to be taken to address possible safety hazards at each of the layers, thus enabling more effective risk management and improving the overall safety of the ship, analysing and assessing the risks associated with a fire on board and making informed decisions. Such models help to reduce risks on board, improve crew and cargo safety, and contribute to effective emergency management. They can be applied in various areas of maritime operations to ensure higher levels of safety and security. It is important to note that a security levels model is only a tool for analysing and assessing ship security and its effectiveness depends on the quality and reliability of the data on which it is based. It is also necessary to continually update the models and adapt them to changing conditions and requirements to ensure continuous improvement in maritime safety.
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