

## SOURCE ANALYSIS AND CONSIDERATION IN THE FIELD OF THREATS AND MARITIME SAFETY

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**Purpose:** The purpose of this article is to examine various methods of risk assessment and safety management in maritime shipping. The paper compares both traditional methods and modern technology-based solutions, which are gaining in importance in the context of increasing maritime traffic, port expansion, and threats resulting from a dynamically changing environment, especially in restricted areas with high traffic density.

**Design/methodology/approach:** The study analyzed numerous scientific publications from Poland and abroad. It focused on comparing different approaches to navigational risk assessment from deterministic to probabilistic and on the applications of modern technologies such as artificial intelligence, AIS data analysis, and computer simulations. Both classic methods, such as Formal Safety Assessment (FSA), and advanced models based on maneuvering space data were taken into account.

**Findings:** An analysis of the literature shows that there is no single ideal risk assessment method for every case. The best results are achieved with a mixed approach, adapted to the conditions prevailing in a specific water area, the available data, and information about navigational hazards in that area. During the analysis of the methods presented, some loopholes were also identified, particularly in difficult navigation areas such as narrow passages and ports.

**Research limitations/implications:** One limitation is the lack of uniform access to high-quality AIS data and the cost of implementing modern technological solutions in maritime navigation systems.

**Practical implications:** The conclusions from the study may be particularly useful in planning port expansions, such as the planned container terminal in Świnoujście or the FSRU terminal in Gdańsk. Projects of this type require a thorough assessment of navigational risks, especially in areas with high traffic volumes and limited maneuvering space.

**Social implications:** Safer shipping not only benefits the industry, it also protects human life and the environment. The findings of the study can help shape policies that promote environmentally sustainable maritime transport and better port management.

**Originality/value:** The value of the article lies in its combination of theoretical knowledge with a practical look at new technologies supporting maritime safety. The work is aimed at both researchers and practitioners – engineers, port designers and those responsible for maritime traffic management.

**Keywords:** Automatic Identification System, Navigational Safety, Navigational Risk Assessment, Formal Safety Assessment, Risk Assessment Matrix, Logic Tree Method.

**Category of the paper:** Literature review.

## 1. Introduction

Risk analysis in maritime transport has long been a subject of interest for both researchers and shipping safety specialists. Sources on the examined issue are distinguished by classic deterministic approaches and modern probabilistic methods, which allow for a better understanding of the complexity of navigation systems and doubts related to their functioning. In the past, many detailed studies on risk assessment methods have been carried out, covering various aspects of maritime transport risks (Yang et al., 2017; Shin, 2019; Lim et al., 2018). These include factors that influence risk (Yang et al., 2017), quantification of risks associated with maritime transport (Li et al., 2012), uncertainty analysis (Ozturk, Van Dorp, 2006). These methods have been reviewed in a variety of contexts, including maritime security analysis (Yang et al., 2013), on narrow waterways (Li et al., 2012), collision risk in ship traffic (Ozturk, Cicek, 2019). These studies provide us with different approaches to reviewing potential threats in each area. They also show that the modelling characteristics of maritime transport methods depend mainly on the characteristics of the available data (John et al., 2016), and the main limitation is the lack of specific data (Zhang, Thai, 2016; Hänninen, 2014). Classic approaches to risk analysis are based on detailed modelling of the situation and determining potential threats based on known system parameters. Kristiansen (2013) point out that such methods work primarily in situations where accurate data on shipping processes is available, such as waterway parameters, ship size or expected hydrometeorological conditions. These methods focus on the systematic identification of threats and the assessment of their effects. The basic tool here is scenario analysis, in which probable consequences and possible ways of minimizing the risk are determined for each potential threat. An example is system reliability analysis (Reliability Analysis), which highlights that these methods are most effective when precise data on shipping processes is available, such as waterway parameters, vessel dimensions, or forecasted hydrometeorological conditions. These methods focus on the systematic identification of threats and the assessment of their effects. The basic tool here is scenario analysis, in which probable consequences and possible ways of minimizing the risk are determined for each potential threat. One example is the analysis of system reliability (Reliability Analysis), aimed at identifying critical elements of transport infrastructure, as well as assessing the risks associated with failures, which helps prevent navigation errors and improve safety in transport systems.

A review of available methods for assessing navigation risk and safety shows that research in this area is crucial for science and technology. The methods developed help to identify and minimize threats in maritime navigation. It contributes to the creation of more reliable maritime traffic management systems, the design of safe vessels and environmental protection. It also supports the development of international regulations, such as IMO and SOLAS, by integrating innovative simulation and statistical technologies.

The originality of this work consists in a critical synthesis of existing risk analysis methodologies combined with a novel interpretative framework that explicitly relates modelling effectiveness to the quality and structure of available maritime data. The study moves beyond traditional reviews by identifying systemic constraints in current risk assessment practices and by proposing an integrated approach for analysing navigation safety under uncertainty. This perspective provides a new methodological lens for evaluating navigational hazards in the studied water area with high ship traffic density, particularly in environments characterized by incomplete datasets and dynamic operational conditions.

## **2. Research Methodology**

The analysis was based on publications from the last 15 years, representing essential studies in the field of maritime safety. Both the latest research and older studies, which are still considered the foundations of this field, were taken into account. The selection of literature was not based solely on its relevance, but primarily on its substantive value, impact on scientific development and usefulness in the context of the discussed risk assessment methods and techniques. Thanks to this comparison, it was possible to determine both contemporary trends and proven theoretical foundations.

The scope of the analysis included quantitative methods (e.g. FTA, ETA, QRA), probabilistic approaches, analyses based on data from vessel monitoring systems such as AIS, qualitative techniques (e.g. Formal Safety Assessment – FSA) and simulation analyses and predictive models. Both classical techniques such as fault tree analysis (FTA) and modern methods based on spatial data and stochastic models are discussed. Each source is assessed for its usefulness and consistency in the context of the issues discussed. Key methods, their practical application, advantages, limitations and possibilities of integration with modern technological systems, such as spatial data analysis tools or artificial intelligence technologies, were compared. Based on the collected information, a critical comparison of methods was made, taking into account differences in their approach to hazard identification, risk assessment and implementation of countermeasures. The results of the comparison are presented in tabular form, facilitating comparison and conclusions. The literature review was limited to materials available in English and Polish. Due to the review nature, detailed case studies were not

included, focusing on universal and commonly used techniques. This methodology allowed for a comprehensive comparison of available maritime risk assessment tools, providing a basis for further research and optimization of methods in this area.

## 2.1. Approaches to risk quantification and navigational safety

Navigational safety is an important element of maritime traffic management, especially in the face of the growing intensity of maritime transport and the development of ports and waterways. Research in this area includes various assessment methods that enable the identification of threats, analysis of potential emergency scenarios and assessment of the effectiveness of risk minimization actions. When considering navigational safety, tools that allow for risk analysis, determining the probability of threats and their potential effects are important. The most frequently used methods include both classical approaches and modern techniques integrating advanced mathematical models and qualitative analyses. The most important methods include:

- Matrix method – used to visualize risk and its classification in simple analyses.
- Logic tree method – allowing the identification of the causes and effects of specific events.
- Simulation method – enabling the analysis of dynamic scenarios in conditions of environmental variability.
- Formal Maritime Safety Assessment (FSA) – a standard recommended by the International Maritime Organization (IMO), integrating qualitative and quantitative approaches to risk assessment.
- Navigation risk model recommended by IALA – including qualitative and quantitative risk analysis in the context of navigation infrastructure.
- PIANC risk assessment model – dedicated to the analysis of security in ports and inland waters.

By using various techniques, it is possible to adapt the security assessment process to the specificity of a given area, available data and the characteristics of potential threats. Below, a detailed analysis of the above methods is presented, highlighting their advantages, limitations and areas of application in navigation practice.

### 2.1.1. Matrix method

Risk estimation using matrix methods involves determining the categories of consequences and the probability of their occurrence. The advantage of this type of method is that it is easy to use and understand. Thanks to this, it can be used in research where detailed statistical or simulation studies are not required (Bağ et al., 2024). An example of a matrix technique is the ISO Risk Matrix, which is presented in draft of international standard 17776 (ISO, 1999). This standard presents a 5 x 5 risk matrix with consequence and probability categories that are easier for many people to interpret. The ISO 17776 matrix uses 4 types of consequence categories, i.e. people, assets, environment and reputation (Shouman et al., 2021). Figure 1 shows an example of this type of matrix.

Severity Rating	CONSEQUENCE				INCREASING PROBABILITY				
	People	Assets	Environment	Reputation	A	B	C	D	E
					Rarely occurred in E&P industry	Happened several times per year in industry	Has occurred in operating company	Happened several times per year in operating company	Happened several times per year in location
0	Zero injury	Zero damage	Zero effect	Zero impact	Manage for continued improvement				
1	Slight injury	Slight damage	Slight effect	Slight impact					
2	Minor injury	Minor damage	Minor effect	Limited impact					
3	Major injury	Local damage	Local effect	Considerable impact	Incorporate risk reducing measures				
4	Single fatality	Major damage	Major effect	Major national impact					
5	Multiple fatalities	Extensive damage	Massive effect	Major international impact					
					Intolerable				

**Figure 1.** A matrix technique the ISO Risk Matrix.

Source: Shouman et al., 2021.

In practice, the risks assessed using this methodology include, among others: navigational failures, ship collisions, loading accidents or weather-related hazards. In each case, the key is to assess where specific risks lie in the matrix and then plan actions to minimize those risks.

### 2.1.2. Probabilistic approaches to navigation risk analysis and management

Probabilistic methods make it possible to consider the uncertainty associated with various factors affecting navigation safety. The use of these models to analyse the parameters of waterways and navigation systems allows for a more precise assessment of the threats associated with manoeuvring vessels in limited water areas (Gucma et al., 2013).

Fault Tree Analysis (FTA) or Event Tree Analysis (ETA) are commonly used to study complex navigation systems. For example, Marek Żukowicz (2015) in his work on FTA, he highlighted the effectiveness of this method in identifying key failure points in maritime traffic control systems. Methods using the logical tree structure enable quantitative analysis of the risk of an accident in a limited area. In practice, three types of logic trees are used to assess the risk of an accident - fault trees (FTA-Fault Tree Analysis), event trees (ETA-Event Tree Analysis) and risk contribution trees (RCT-Risk Contribution Tree) (Bak et al., 2024). As an example, the logic tree method was used to analyse data related to tugboat accidents in restricted waters. The study Remzi Fışkın et al. (2020) was used to understand what factors (e.g. weather conditions, human error, technical condition of tugboats, work organization, etc.) most often contribute to tugboat accidents in ports. Risk factors that have a decisive impact on navigational safety and tips that can help improve the safety of towing operations in ports are presented. The importance of appropriate crew training, fleet modernization and improved management of operational conditions was emphasized, drawing attention to their key impact on improving navigational safety. A decision tree was used to help to identify relationships between various variables, and logistic regression was used to assess the impact of these variables on the probability of an accident.

The example logic tree used to analyse navigation safety in a selected water area consists of various failure scenarios of the navigation system, sensors and other elements such as accelerometers, gyroscopes and other devices essential for safe navigation.

To sum up, event and fault trees are a tool used to analyse the causes of failures in complex systems. Each potential failure event is broken down into smaller, more detailed causes, creating a hierarchy of possible problem sources. This helps identify critical points in the system that could lead to serious damage, enabling more effective risk management and implementation of preventive actions.

### *2.1.3. Formal Maritime Safety Assessment (FSA) as a risk assessment tool in maritime navigation*

Formal Maritime Safety Assessment (FSA), developed by the International Maritime Organization (IMO) (MSC/Circ.1023 & MPEC/Circ.392) is a key risk assessment methodology used to make regulatory decisions in maritime safety. FSA consists of five stages: identification of hazards (a list of all relevant accident scenarios with potential causes and outcomes), assessment of risks (evaluation of risk factors), risk control options (devising regulatory measures to control and reduce the identified risks), cost benefit assessment (determining cost effectiveness of each risk control option) and recommendations for decision-making (information about the hazards, their associated risks and the cost effectiveness of alternative risk control options is provided). This methodology is particularly helpful in developing IMO regulations, enabling effective risk identification and proposals for actions to improve safety. FSA is also used in planning the development of port infrastructure and in the implementation of navigation decision support systems, especially in the context of modernization of waterways.

An example of such an application is the research published by M.B. Zamana et al. (2014) on the use of the Formal Safety Assessment (FSA) method in analysing the risk of ship collisions, based on data from the AIS (Automatic Identification System). The aim of this research was to develop a collision risk assessment model using AIS and GIS data, especially in the context of calculating collision probabilities in strategic maritime regions such as the Strait of Malacca. This study considers factors such as maritime traffic density, as well as various navigation conditions that may affect the likelihood of collisions, such as overtaking situations or head-on collisions.

The Strait of Malacca is one of the busiest sea routes in the world. Figure 2 illustrates the density of maritime traffic and the areas that have been analysed in the context of assessing navigational safety and risk. The use of FSA in these studies enables the identification of threats, risk assessment, and the proposal of actions aimed at reducing the number of collisions in selected sea areas.



**Figure 2.** Maritime traffic density around the Strait of Malacca.

Source: Zamana et al., 2014.

The use of Formal Safety Assessment (FSA) in risk analysis, including ship collision risk assessment using AIS data, offers both advantages and limitations. This method primarily enables accurate hazard identification, risk assessment, and the development of risk minimization strategies, which support regulatory and operational decision-making. It can be applied in various contexts, from designing regulations and modernizing infrastructure to implementing navigation decision support systems. The use of real data, such as AIS, increases the accuracy of results, enabling more precise threat forecasting. It also incorporates cost-benefit analysis, which helps identify the most effective and cost-efficient preventive actions.

Unfortunately, its complexity requires advanced knowledge in the field of risk analysis, which may constitute a barrier to its wide implementation. For example, to conduct a complete risk analysis in the Strait of Malacca area, researchers had to consider many variables such as traffic density, different weather conditions and marine topography. The study required advanced expertise and extensive resources. Zaman & Santoso (2014) indicate the need for complex analysis and the introduction of appropriate mathematical models, which may require a lot of time and experts. The effectiveness of the FSA application depends on the quality and availability of data. In an area where marine monitoring infrastructure is limited, e.g. AIS data may be incomplete or out of date. In such cases, risk assessment may be difficult, which reduces the effectiveness of decisions made. An additional challenge is appropriate technological support, including the use of advanced computer systems for data processing and analysis.

Formal Safety Assessment (FSA) is an effective tool in maritime risk assessment, enabling decisions to be made based on detailed analysis of threats and impacts. Although this method has many advantages, such as systematicity and versatility, its implementation may be expensive and time-consuming, and requires advanced data processing and appropriate technical resources.

#### *2.1.4. Navigation risk model recommended by IALA (qualitative risk assessment and quantitative risk assessment)*

The recommendations of the International Association of Navigation Marking Services (IALA) can be used to assess the level of navigation risk for both existing and planned ports or waterways. They become useful when designing water bodies, such as expanding infrastructure or changing traffic organization (Bak et al., 2024). The IALA guidelines should be highlighted Qualitative Risk Assessment i Quantitative Risk Assessment (IALA, 2009).

The Port and Waterway Safety Assessment Toll (PAWSAT) is used for qualitative risk assessment. This method was developed for the US Coast Guard, it enables the identification of main safety threats, estimating the level of risk and determining the consequences of accidents. The methodology includes a general risk model for waterways. It aims to consider all factors that affect safety.

The tool for quantitative risk assessment is the IWRAP MK II computer program, which was developed by the Canadian Coast Guard, DTU (Technical University of Denmark) and MSCW (Marine Simulation Center Warnemunde). The created model considers the geometry of routes, traffic intensity and ship parameters. The program builds a model, and then determines the average annual number of possible collisions and entries in the created water area.

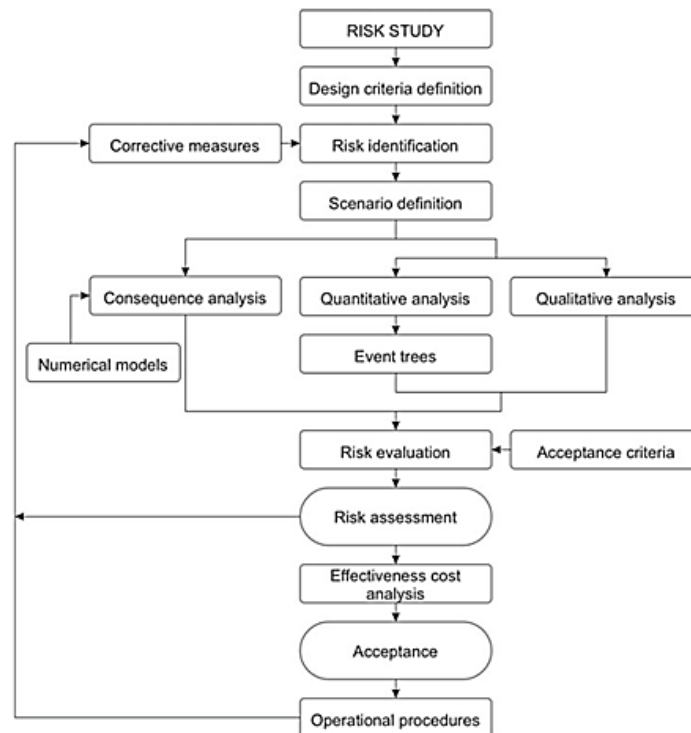
IWRAP MK II (International Waterway Risk Assessment Program) software enables the assessment of the frequency of ship collisions and groundings on a given waterway based on data from the Automatic Identification System (AIS) in a selected water area. The app can compare different shipping routes by assessing the relative frequency of collisions or groundings. The advantage of the program is that the analysis are carried out based on actual data obtained from AIS, and the accuracy of the results depends on the amount of data entered by the user. IALA IWRAP MK II has a wide range of applications in research work including analysis of ship traffic streams in a selected water area, analysis of the width of ship traffic lanes and the location of hydrotechnical structures and navigation infrastructure, determining areas with the highest intensity of sea and inland ship traffic (Anczykowska et al., 2015). It is worth paying attention to several key points related to its use. On the one hand, the effectiveness of the method lies in its ability to accurately identify threats and help make regulatory decisions based on a sound risk analysis. On the other hand, limitations of this method, such as data quality requirements and the need for specialized knowledge, may hinder its widespread implementation, especially in less developed regions.

#### *2.1.5. Application of the PIANC risk assessment model in the context of navigation safety*

The PIANC risk assessment model is used to analyse and assess risks in water infrastructure projects, such as the construction of ports, terminals and waterways. This method is based on a systems approach that integrates both environmental and technical risk assessments. Key elements of the PIANC model include:

- Qualitative and quantitative analysis – risk assessment is divided into stages: qualitative analysis (identification of potential threats and their effects) and quantitative analysis (modelling the probability and consequences of events).
- Use of probabilistic tools – the method includes techniques such as modelling structural re-liability or simulating emergency scenarios.
- The "Working with Nature" principle – promotes an approach that integrates infrastructure development with environmental protection (PIANC, 2014).

The navigation risk management procedure is presented below (Figure 3).



**Figure 3.** Navigation risk management procedure.

Source: PIANC, 2014.

The PIANC method is a logical and systematic procedure that focuses on identifying all events that may result in a hazardous situation related to the navigation, manoeuvring, mooring and unberthing of ships in canals, as well as those related to water areas. Risk is defined here as the frequency of occurrence of a negative event, i.e. accident, incident, damage. It is calculated as the product of frequency and consequence, which is compared to the acceptance or rejection criteria. A decision must be made as to whether the risk is acceptable without taking any action or whether mitigating measures should be taken to reduce the risk to an acceptable level. Risk management comes down to minimizing losses and maximizing the safety, service, operability and any other economic or social benefits of the project. This model aims to identify a dangerous event and prevent its occurrence, and at the same time minimize damage if it does occur. Risk analysis is defined as part of the risk management process, which aims to systematically use all available information to determine the frequency with which various incidents may occur, as well as the scale of their consequences.

One of many examples is the Port of Geelong, which handles over 600 ships annually, using the PIANC model to use the TideCaster system, integrating numerical forecasts and local environmental data. This enabled, among other things, safe reception of larger ships, optimized traffic management, also considering changing tidal conditions and gradual increase in ship drafts, which was verified using high-precision GPS systems (PIANC Australia & New Zealand, 2018-2023).

#### *2.1.6. Conditions for the use of methods used in the assessment of risk and safety of maritime navigation*

Over the years, it has evolved in maritime transport to become an essential aspect of the approach used by practitioners or managers to assess the acceptability of risk in transport projects. In the past, numerous studies have been carried out in the field of navigation risk assessment, using both deterministic and probabilistic methods. In particular, the latter have evolved to take into account more complex scenarios, such as the stability of a ship after damage or the analysis of traffic in ports. Their development is based on historical data, simulations and models, enabling a more universal and precise assessment of threats in complex maritime systems, such as ports and ocean traffic. The appropriate choice of risk assessment method depends on the specificity of the system being analysed, as well as on the available data. Classical deterministic approaches are more suitable for local analysis where detailed data on hydrographic and navigation conditions are available. In turn, probabilistic methods are better suited for global analysis or in cases where data are incomplete or subject to high uncertainty. These methods have many applications in specific contexts and can effectively assess risk in a variety of settings based on available data (Vassalos, Mujeeb-Ahmed, 2021).

#### *2.1.7. Application of Automatic Identification System (AIS) in navigation risk analysis and improvement of navigation safety*

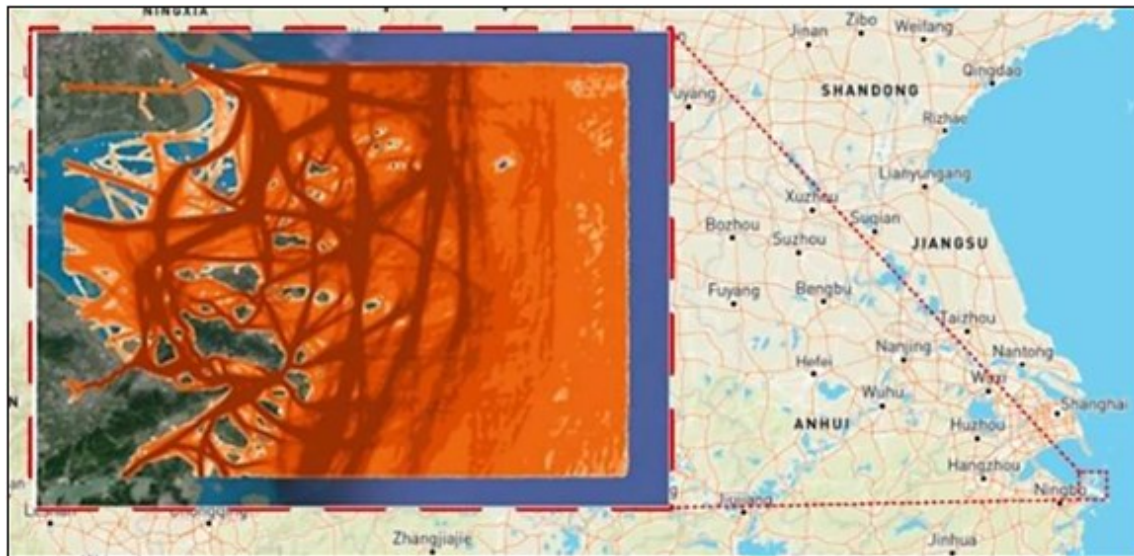
The AIS system provides precise data on the position, speed, course and identification of ships. This information is crucial for real-time identification of potential threats and long-term analysis. The literature highlights the use of AIS in many key areas. Huang et al. (2019) conducted an analysis of the risk of manoeuvring ships in approaches to ports, using data from the AIS system to study the movement trajectories of vessels. Thanks to this, they identified key critical points where the risk of collision is particularly high. Research has shown that AIS data can be used to generate dynamic risk maps to assist ship captains and the Maritime Traffic Control System (VTS) in decision-making. The study Lianbo Li et al. (2018) on ship collision risk assessment also use AIS data to analyse potential hazardous situations, such as reducing the distance between two ships, in real time. In this case, the VCRO (Vessel Collision Risk Index) model was used, which assesses the risk of collision based on AIS data. Historical AIS data is useful for identifying traffic patterns and accidents. They presented an example of such an application Goerlandt & Montewka (2015), who used the data to spatially analyse the risk of collisions in high-traffic areas.

Models based on AIS data also enable the determination of optimal routes for ships in real time, considering hydrometeorological conditions and the movement of other vessels. Zhou et al. (2024) used this approach to analyse global maritime accident trends, which enabled the development of dynamic risk reduction strategies in real time.

The global use of AIS data in risk analysis and improving maritime safety in recent years has led to significant innovations in predictive modelling and strengthening security measures. For example, modern approaches based on AIS data enable mapping vessel behaviour, analysing traffic density and predicting collision risk. A review of available research highlights the use of ship trajectory clustering (which means data analysis consisting of grouping the paths of moving vessels) and Bayesian networks in the assessment of navigational risks, including the detection of anomalies in ship traffic. These methods are particularly useful in complex marine environments such as high-traffic ports (Perkovič et al., 2024).

Liu J. et al. (2023) developed a safety analysis method that is based on a network model combining the causal factors of ship collisions with their mutual dependencies. The aim of the study was to determine which factors have the greatest impact on the risk of accidents. The study looked at 300 collision cases in Chinese waters, identifying 98 key factors that include aspects such as observation errors, inappropriate manoeuvres, miscommunication and inappropriate responses to changing navigation conditions. The study also considers other elements, such as weather conditions, technical failures, as well as human factors, which in combination may lead to an increased risk of collision. The use of the network model allowed for precise identification of their mutual dependencies. This allowed for a more precise determination of the role of individual factors, also considering those that, although less likely to cause accidents, have a large impact on their frequency.

Another example of the use of AIS data is a study conducted by Liu Z. et al. (2023) in which a selected sea area was analysed to identify zones with an increased risk of collision. The work identified key factors influencing the risk of collision, such as traffic density, vessel speed and mutual ship trajectories. Moreover, the effectiveness of the developed method was assessed compared to previously used approaches, demonstrating its higher precision in forecasting high-risk situations. Figure 4 shows the maritime traffic analysis area against the background of the map of the eastern China region. A map is visible showing vessel traffic density or potential collision risk, marked with colour intensity (shades of orange and red).



**Figure 4.** Maritime traffic analysis area against the map of the eastern China region.

Source: Liu, 2023.

## 2.2. Artificial intelligence in navigation risk analysis

Artificial intelligence is increasingly gaining importance in the risk modelling process, especially in areas requiring the analysis of large data sets and the identification of complex relationships. Chen et al. (2019) proposed probabilistic ship collision models, where, using ML algorithms, they were able to accurately predict the probability of events based on many variables, such as ship type, weather conditions and traffic intensity. Recognizing patterns in AIS data and other information sources allows for early detection of anomalies in ship traffic, which can indicate potential threats. Xue Yang et al. (2017) developed a framework for analysing the risk of ship activity, using AI to identify dangerous manoeuvres in ports. Systems such as Decision Support Systems are used in decision support systems for ship captains and VTS operators. Luo & Shin (2019) suggest that the integration of AIS data with AI algorithms can significantly improve the effectiveness of early collision warning and increases coordination in crisis situations. Artificial intelligence (AI) with AIS data supports real-time decision-making, which increases the effectiveness of predictive maintenance and the automation of safety procedures. AI-based systems analyse huge amounts of AIS data to detect potential threats and optimize ship routes. These types of solutions are used in smart-navigation technologies that improve maritime traffic management and minimize the risk of accidents (Perkovič et al., 2024).

Mostefa Mohamed-Seghir et al. (2021), in their research, discussed the use of artificial intelligence in preventing ship collisions. The use of AI to predict the risk of collision and optimize ship movements in real time was aimed at improving the safety of maritime navigation. They presented a model for ensuring safe navigation of ships in collision situations. This model considers parameters such as ship manoeuvrability, visibility conditions and the movement of objects in a collision situation. Techniques used - ACNN neural network (Anti-

collision Neural Network) the ACEA algorithm (Anti-collision Evolutionary Algorithm) – made it possible to determine the optimal trajectory of the ship, while ensuring minimum fuel consumption. The results showed that the ACEA technique is more effective in terms of energy savings, but ACNN provides faster computational time. The proposed methods can be used in decision support systems on ships and in applications related to robot movement. Using these methods, navigation systems can effectively avoid collisions while considering both safety and energy efficiency in real time.

### **2.3. Specificity of restricted water areas in the context of navigational safety**

Limited water areas, such as narrow waterways, port channels or terminal approach waters, pose a particular challenge in managing navigation risk. Characteristic features of limited water areas include limited manoeuvring space, variable hydrometeorological conditions, and intense ship traffic. These features require precise planning and implementation of advanced risk analysis and management methods. This involves the need to consider several specific factors, i.e. hydrographic parameters (depth of waterways, width, presence of underwater obstacles and seabed configuration), the intensity of ship traffic, the presence of deep draft vessels and the variety of vessel types (e.g. container ships, ferries, passenger ships). Factors such as strong currents, variable winds, tidal variability and limited visibility due to fog or precipitation also influence it. Research work present a comprehensive risk analysis methodology for vessels crossing narrow waterways, considering an integrated approach to hydrographic, environmental and manoeuvring parameters. The research methodology is based on the analysis of ship movement trajectories, simulation models and assessment of safety criteria.

In order to estimate the safety of navigation on the fairways, it is necessary to determine the probability of an accident and its consequences (Gucma et al., 2022). In limited water areas, such as fairways, the risk is the possibility of damage occurring within a certain period of use (Chen et al., 2019) and is expressed as the product of the probability of an accident and the losses resulting from the accident. There are many methods that allow for a detailed assessment of navigation risk (Dhillon, 2022; Huang et al., 2019; Kite-Powell, Ozturk et al., 2019; Ozturk, Cicek, 2019; Patrician, 1998; PIANC, 1997; Rausand, 2013). In maritime transport, the Formal Safety Assessment (FSA) developed by the International Maritime Organization (IMO) is used to assess safety (PIANC, 1997).

Construction or modernization of waterways in a limited area and in the event of a change in the conditions of safe operation, the basic principle is to identify the threat (Chen, 2019; Guema et al., 2020). Currently, two approaches are used to design the parameters of waterways and to determine the safe operation of ships on waterways, i.e. empirical methods and simulation methods (Rausand, 2013).

Deterministic or probabilistic methods make it possible to determine safe widths of ship manoeuvring areas (Rausand, 2013). These types of methods include, among others: PIANC (PIANC, 2014), CIRM (Gucma et al., 2015), Spanish (Pueros Del Estado, 2007), Japanese

(Japan Institute of Navigation, 2003) Canadian (Canadian Coast Guard, 1999) & USA CA (USACA, 2006, 2008). The selection of an appropriate empirical method is determined by criteria, i.e. the type of waterway, the manoeuvres performed on it, as well as its reliability and cost-effectiveness.

The simulation methods that are currently used are based on the construction of a non-autonomous real-time model, where the ship's movement is controlled by a navigator with unspecified qualifications. For this purpose, Full Mission Bridge Simulators (FMBS) are used. Unfortunately, the research methodology requires significant workload in connection with the construction of simulation models of ships and water areas, as well as conducting many real-time simulation experiments with an appropriately large number of manoeuvres performed by qualified navigators.

#### **2.4. Integration of Human Reliability Analysis (HRA) and Organizational Safety Culture**

In areas with high maritime traffic density, such as the Baltic Sea, and in particular in areas such as traffic separation schemes (TSS), port approaches, pilotage areas, and narrow waterways, navigation operations are characterized by strong temporal and functional coupling. Decisions are made by the navigator under time pressure, while processing multiple sources of information (ARPA, AIS, ECDIS, VHF) and under high cognitive load.

Research clearly shows that in such conditions, maritime accidents are rarely the result of a single “human error.” Much more often, they are the result of interactions between people, technology, procedures, and organizational conditions, which is consistent with modern models of systemic accidents (Reason, 1997; Leveson, 2011). Analyses of collisions in confined waters show the recurrence of factors such as ineffective communication, deficiencies in Bridge Resource Management (BRM), inadequate planning, and imperfections in organizational oversight (Abramowicz-Gerigk, 2019).

A key step in the development of human factors analysis is to take into account the concept of human performance variability. According to the Safety-II and resilience engineering approaches, people constantly adapt their actions to current conditions, and this adaptability is the main reason why systems usually function correctly (Hollnagel, 2017). Performance variability only becomes a problem when it overlaps and resonates with other variabilities in the system, e.g., with a simultaneous increase in traffic intensity, deterioration of visibility, VHF communication overload, and crew fatigue. In such conditions, even routine activities can lead to dangerous situations. Functional Resonance Analysis Method (FRAM) One of the most commonly used tools for analyzing performance variability is FRAM – Functional Resonance Analysis Method (Hollnagel, 2017; Hollnagel, 2012). This method describes operations as a set of related functions, analyzes how the variability of one function affects others, allows the identification of conditions conducive to “functional resonance”.

The application of FRAM in the analysis of maritime collisions and port operations confirms its usefulness in areas with high traffic density (Patriarca et al., 2020). Performance variability is a natural link between human factors and organizational safety culture, as it is the organization that sets the boundaries of safe adaptation.

The primary formal tool for safety management in shipping is the Safety Management System (SMS) implemented in accordance with the ISM Code (IMO, 2018). Although ISM provides a consistent organizational framework, numerous studies indicate that its effectiveness depends on the quality of implementation rather than the mere existence of procedures. Scientific publications show that key elements of safety culture in shipping include:

- leadership and management commitment,
- a culture of reporting and learning,
- the relevance of procedures to “real work”,
- competence and training management,
- fatigue management (Teperi et al., 2019; Arslan et al., 2016).

## **2.5. Practical use of the results of the analysis of methods and models for maritime assessment and safety**

The practical use of the analysis of maritime navigation risk and safety assessment methods may become crucial in future port expansion projects, such as those implemented in Świnoujście and Gdańsk. In the context of the development of container terminals, it is important to conduct a detailed assessment of navigational safety on the waterways leading to these terminals. Risk analysis, using both methods, will enable the identification of potential threats related to ship traffic, including collisions and other navigation incidents. The practical application of these methods allows the development of effective risk minimization strategies, which is particularly important in areas with high maritime traffic. As part of planned investments, such as the construction of new quays or fairways, the assessment of navigational safety is important to ensure safe and effective ship operation. The implementation of these analysis will also enable the adaptation of port infrastructure to change operational conditions, ensuring adequate manoeuvring space and minimizing the risk of congestion or collisions.

In the port area of Świnoujście, the expansion of the container terminal required the use of simulations of the movement of large vessels and an analysis of the impact of the depth of the waterway on their manoeuvring ability. In the analysis of the expansion of the port in Gdańsk, probabilistic models for assessing the risk of collision and grounding were used, using AIS data and historical navigation events (Gucma et al., 2022).

Modern technologies that support risk management are becoming more and more important. The best example of this is VTS systems (Vessel Traffic Services), which integrate AIS data with other sources, enabling dynamic traffic management. In addition, the previously mentioned developing artificial intelligence helps predict potential events, such as units passing too closely or the risk of leaving the track.

### **3. Future research directions in risk analysis in maritime transport**

Research on risk management in maritime transport is constantly evolving, adapting to new challenges related to increasing ship traffic, changing environmental conditions and the development of new technologies. Modern research increasingly indicates the need to integrate traditional risk analysis methods with modern approaches based on advanced technology. Development based on balance is becoming one of the key challenges in risk management in maritime transport. Liu & Frangopol (2018) highlighted the need to integrate risk with environmental impact assessment. In the context of maritime transport, this means that risk analyses should consider not only technical and operational issues, but also the impact on the natural environment, as well as the sustainable development of the maritime transport industry. Research should focus on the impact of marine accidents on the marine environment, research should focus on developing models that combine classic risk analysis with the assessment of potential impacts on the marine environment, but also new capabilities of artificial intelligence. Modern research should also enable the implementation of solutions that reduce the risk of maritime accidents while minimizing the negative impact on the natural environment. An example may be the development of ships powered by alternative fuels or traffic management systems that allow for the optimization of routes and reduction of pollutant emissions. The risk analysis should also consider aspects of sustainable port development, including water resources management, impact on marine flora and fauna, as well as the reduction of noise and other negative effects of port activities. It is also noted that the use of Big Data analysis in risk management in maritime transport has become the subject of intensive research. Luo & Shin (2019) emphasize the need to further develop big data analysis methods to better understand maritime accident patterns and their causes. The current approach to risk analysis, particularly in the context of maritime accidents, is increasingly dependent on the ability to process large amounts of data in real time. Vessel traffic monitoring systems (AIS and VTS) provide enormous amounts of information that can be used to identify risk patterns. The use of appropriate algorithms may enable the prediction of potential accidents based on the analysis of the behaviour of navigation units in various conditions. The collection and analysis of weather data can be crucial in predicting the risk of collisions or other hazards associated with manoeuvring ships. The use of big data methods in real time allows for preventive actions to be taken. Forecasting models based on the analysis of data from AIS, port sensors or satellites significantly shorten the response time to dangerous situations. It is worth adding that the use of historical data on maritime accidents allows the development of preventive risk management strategies. Using artificial intelligence to analyse past accident patterns will help improve future prevention.

## 4. Results

Literature analysis shows that information received from AIS has become a key tool in navigation risk analyses. They enable monitoring the situation in real time, identifying threats and making decisions about course changes in the event of impending collisions. The use of this data in risk analysis enables better prediction and prevention of incidents in maritime waters. Another conclusion that comes to mind is the role of computer simulations in risk assessment. Mathematical models allow the generation of many possible collision scenarios and other navigation events, which allows for risk assessment in various conditions and on various sections of waterways.

Another key insight is the need to integrate new technologies, such as artificial intelligence and automated systems, in the navigation risk assessment process. New AI technologies enable more precise monitoring of the situation on the fairways and quick decision-making in response to changing navigation conditions. One significant limitation is the availability of accurate AIS data, which may be limited to selected areas or time periods. In regions with weaker marine monitoring infrastructure, this data may be incomplete or outdated, which affects the accuracy of risk analysis performed. Although new technologies such as artificial intelligence offer promising opportunities, their implementation in navigation systems requires large investments in infrastructure and specialized training for personnel responsible for monitoring navigation safety.

Research should be focused on further development of AIS data analysis algorithms and their integration with other monitoring systems. This would help in obtaining more accurate and faster results in risk analysis. Another important direction of research should be the development of more advanced methods for optimizing shipping routes aimed at minimizing the risk of collisions and improving the efficiency of maritime transport. The development of artificial intelligence in risk assessment has the potential to contribute to more precise threat forecasting and faster decision-making in real time.

It is also suggested to study the impact of changing atmospheric and hydrological conditions on navigation safety, which will support the development of more flexible risk assessment models in the face of a changing climate.

A summary of the advantages and disadvantages of various navigation safety assessment methods, presented in the table, allows for a comprehensive comparison of the techniques used. Each method has its strengths, such as analysis accuracy, predictive capabilities and practical application in specific conditions, but also limitations, such as computational complexity or limited access to data. By taking these aspects into account, a method suitable for specific needs and operational conditions can be effectively selected, thereby increasing the effectiveness of navigation safety systems. Attention should also be paid to the variety of available methods for assessing navigational risk and safety, which vary in accuracy, complexity and practical

application. (Table 1). The selection of an appropriate method depends on the specificity of the analysed area, data availability and the goals to be met by the monitoring system. Each method, despite its limitations, makes a significant contribution to improving the effectiveness of navigational safety activities.

**Table 1.**

*Juxtaposition of methods for assessing maritime navigation safety*

<b>Methods for assessing the safety of maritime navigation</b>	<b>Advantages</b>	<b>Disadvantages</b>	<b>Application</b>
<b>Matrix method</b>	<ul style="list-style-type: none"> <li>- Simple and intuitive.</li> <li>- Easy to use (in case of limited data).</li> <li>- Visualization using a table allows you to quickly assess the situation.</li> </ul>	<ul style="list-style-type: none"> <li>- Limited accuracy when analysing complex systems.</li> <li>- Failure to consider the dynamics of variables over time.</li> </ul>	Risk assessment in simple operations such as shipping route planning or local hazard analyses.
<b>Logical tree method</b>	<ul style="list-style-type: none"> <li>- Allows you to analyse the causes and effects of events.</li> <li>- Good for identifying potential system failures.</li> <li>- Useful in decision analysis.</li> </ul>	<ul style="list-style-type: none"> <li>- Focuses on one-off events, ignoring the complexity of dynamics.</li> <li>- Requires detailed input.</li> </ul>	Identification of the risk of failure of navigation devices and communication systems.
<b>Simulation method</b>	<ul style="list-style-type: none"> <li>- Analysis of complex scenarios in dynamic conditions.</li> <li>- Enables you to predict the consequences of various decisions in real time.</li> <li>- Accounts for uncertainty in mathematical models (e.g. Monte Carlo simulations).</li> </ul>	<ul style="list-style-type: none"> <li>- High technical and computational requirements.</li> <li>- Highly dependent on the quality and quantity of input data.</li> </ul>	Analysis of collision scenarios, optimization of shipping routes, assessment of the impact of environmental variables on safety.
<b>Formal Safety Assessment (FSA)</b>	<ul style="list-style-type: none"> <li>- Standard recommended by IMO (International Maritime Organization).</li> <li>- A comprehensive approach including threat identification, risk assessment, and risk minimization strategies.</li> <li>- Allows you to combine qualitative and quantitative analyses.</li> </ul>	<ul style="list-style-type: none"> <li>- Time-consuming and expensive</li> <li>- Requires advanced technical knowledge and large data resources.</li> </ul>	Comprehensive security assessment of operations in ports and shipping lanes, analysis of maritime security policies.
<b>Navigation risk model recommended by IALA</b>	<ul style="list-style-type: none"> <li>- It considers both qualitative and quantitative assessment.</li> <li>- Suitable for analysing the safety impact of navigation infrastructure.</li> <li>- Supported by the international organization IALA.</li> </ul>	<ul style="list-style-type: none"> <li>- May require advanced knowledge and specialized software.</li> <li>- Time-consuming data collection process.</li> </ul>	Assessment of the impact of infrastructure such as lighthouses and buoys on navigational safety.
<b>PIANC risk assessment model</b>	<ul style="list-style-type: none"> <li>- Detailed risk analysis on inland waters and ports.</li> <li>- Takes into account the specificity of local hydrographic and navigation conditions.</li> <li>- Adapted to the needs of planning and development of water infrastructure.</li> </ul>	<ul style="list-style-type: none"> <li>- It mainly focuses on specific aspects of risk, which may limit its use in global analyses.</li> <li>- Requires local hydrographic and navigation data.</li> </ul>	Risk assessment in port and water infrastructure projects, optimization of shipping development plans.

Source: Own work based on the analysis of methods and tools for maritime safety assessment.

As a result, matrix and logic tree methods are simple to use but limited in precision, while simulation and FSA methods offer more advanced and comprehensive analysis but require more resources and advanced technology. IALA and PIANC models are used in specialized analyses related to infrastructure and local navigation conditions.

## 5. Discussion

The conducted literature analysis on methods that ensure maritime safety is crucial for the practical implementation of these methods in navigational safety management. The article compares deterministic and probabilistic approaches, but the comparison is largely descriptive. From a practical point of view, this is important. Reference should be made to those methods that have clearly defined criteria, such as input data requirements, the ability to take uncertainty into account, computational cost, interpretability of results, and suitability for water bodies subject to spatial or organizational constraints. Deterministic approaches are generally simpler to implement and less computationally demanding, while probabilistic methods allow for a more realistic description of the variability of traffic and environmental conditions, resulting in greater complexity. Most of the methods currently used to assess navigational hazards, especially in confined waters, are based on data from the AIS system, which, although made available by some national administrations, often contain millions of vessel positions, and databases containing information on ship traffic in a selected area over several years, with sufficient position density, can exceed one billion records. The accuracy of this data varies, as described by Wawruch, R. (2018) - description of errors and AIS data reliability or by Harati-Mokhtari, A., Wall, A., Brooks, P., & Wang, J. (2007). - Analysis of errors in static and dynamic data. Despite the wide range of tools available, including collision risk analysis, probabilistic models, and computer simulations, their practical application requires adaptation to the specific conditions of each area, such as maritime traffic intensity, geographical characteristics, and port infrastructure. The practical application of the methods discussed in the article in port expansion projects, such as those in Świnoujście and Gdańsk, can significantly improve shipping safety. The use of AIS data and advanced mathematical models enables precise monitoring of conditions on the fairways, identifying potential threats, and developing effective collision avoidance strategies. However, it is worth noting that despite mentioning human factors, most analyses focus mainly on technical aspects. Variability in human performance, decision-making under time pressure, and the influence of organizational safety culture are rarely systematically included in risk assessment models. Meanwhile, many maritime incidents are caused by human error and organizational conditions, so greater consideration of the human reliability analysis perspective could significantly increase the application value of the methods discussed. The implementation of such tools in real conditions allows for optimizing the

development of port infrastructure, taking into account changing operational conditions and ship traffic. However, as research in this area indicates, there is still a need for further improvement in risk analysis methods and the integration of new technologies, such as artificial intelligence or automated systems, which can significantly enhance the efficiency of maritime traffic management in real time. It is also important to note that the effective implementation of these methods requires cooperation between various institutions, including ports, maritime administrations, and navigation companies. The conducted research shows that the integration of theoretical approaches with real data and technologies can contribute to a significant improvement in navigational safety, thereby minimizing the risk of accidents at sea. A review of the literature indicates that hybrid approaches are the most effective, but there is no systematic synthesis of these approaches in the literature. Based on the analyses conducted, typical combinations of methods can be identified, such as AIS-based traffic monitoring combined with probabilistic modeling and computer simulations, supplemented by decision support systems within VTS services. Such “packages” are particularly useful in port areas and waters with high traffic intensity, while simpler hybrid configurations may be sufficient in less complex conditions.

## 6. Conclusions

The topicality and originality of the issues raised regarding maritime safety methods are crucial, especially in the context of dynamically growing maritime traffic, the development of large ports and new threats related to technology and climate change. Research focuses on increasing navigation safety and reducing operational risk. Literature analysis indicates that innovative approaches, such as the integration of environmental data with random variable models, constitute a unique contribution to the development of this area and respond to current challenges. The analysis showed that there are many different risk assessment methods that can be used in the context of navigation safety. Risk assessment methods in navigation safety can be divided into deterministic methods and probabilistic methods, which differ in their approach to analysis and application in different contexts. An important conclusion is that effective navigation safety management requires a combination of both approaches, adapted to the specificity of a given situation and available data. In practice, a hybrid approach is often used that combines both approaches to obtain a more complete risk picture and effectively manage security. Increasing attention is being paid to improving navigational safety, which has led to the emergence of various tools and methods for assessing navigational safety. The literature analysis included an extensive review of foreign and domestic literature. The methods and tools used to assess maritime safety were thoroughly assessed and analysed. A review of the available literature provides a better understanding of the use and integration of method parameters in

individual risk assessments. Moreover, the information obtained from the analysis of available methods and tools for safety assessment allowed the identification of circumstances, trends and shortcomings of these techniques. It also allowed us to know what should be considered when estimating navigation risk on waterways. These include primarily:

- specificity of the reservoir,
- relatively heavy traffic,
- relatively high traffic intensity,
- many variables depending on current meteorological and hydrological conditions,
- specific manoeuvring of the ship, different knowledge of standard phrases used for communication at sea by those in charge of vessels on the move.

The results of the systematic literature review also indicate a gap in the literature regarding navigational safety assessment. All methods of risk assessment to ensure navigational safety discussed above have their advantages and disadvantages. Due to the large number of parameters, features, complexity of the marine environment (its nature), uncertainty and lack of information, there is no common ground to define risk. The most important aspect is the selection of a navigation safety estimation method that considers the most unlikely event scenario, while maintaining realistic assumptions regarding possible crisis situations.

In summary, the selection of appropriate and consistent safety risk assessment methods generally depends on each unique situation and area in which navigation is to be carried out.

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