3. Proactive Maritime Traffic Management Utilizing Dynamic Accident Networks (DANs)

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Abstract: Maritime safety in high-traffic areas, including narrow waterways, Traffic Separation Schemes (TSS), and port approaches, is a long-standing concern requiring advanced tools to address multifactorial risks and support operational decision making. Despite advancements in maritime technology and navigation systems, operational conditions, human and organizational factors remain critical in accident causation. Even in the era of autonomy and digitalization it is relevant, where manned, partially unmanned, and unmanned ships will coexist across different degrees of autonomy (D1-D4). Traditional accident analysis models often lack the capacity to dynamically incorporate real-time and complex operational variables. The maritime industry mostly relies on occurrence and casualty investigation reports to learn from the past and prevent in the future. To move towards proactivity, this study introduces a dynamic accident prediction model that integrates the Human Factors Analysis and Classification System (HFACS) with Bayesian Networks to assess and mitigate risks effectively in real-time and support operational decision making. Utilizing marine casualty data and incorporating expert insights, the model provides a probabilistic framework to support proactive decision-making for vessel traffic service (VTS) operators, ship masters and other maritime stakeholders. The model's application aims to enhance navigational safety and operational efficiency, by offering insights for decision making that will ultimately reduce accidents and enhance sustainable maritime operations.

Keywords: Multi-criteria decision making; Bayesian belief networks; Human and organizational factors; Maritime traffic management; Marine casualties and incidents

1. Introduction

High-traffic marine areas, serving as arteries of global trade, playing a crucial role in the global economy (Meza et al., 2022; Yıldız et al., 2024). Some examples of these areas, including but not limited to narrow waterways like Turkish Straits System, Singapore Strait, English Channel, Malacca Strait, Suez Canal, and the Panama Canal, facilitate the movement of a significant portion of the world's trade volume. According to the United Nations Conference on Trade and Development (UNCTAD), over four fifth by volume are carried by sea and are handled by ports worldwide, emphasizing the importance of sea routes (UNCTAD, 2024). High traffic in narrow waterways, combined with complex environmental conditions, operational conditions and human factors, poses substantial challenges to navigational safety (Gao et al., 2024; Yildiz et al., 2022). Studies indicate that high traffic density significantly increases the risk of marine casualties and incidents (Pelot and Plummer, 2009; Tonoğlu et al., 2022). Furthermore, environmental factors such as heavy seas, fog, ice, and strong currents complicate navigation and risk management. Human errors, often stemming from fatigue, poor decision-making, or inadequate training, continue to be a leading cause of maritime incidents (Dominguez-Péry et al., 2021; Maternová et al., 2023; Oraith et al., 2021).

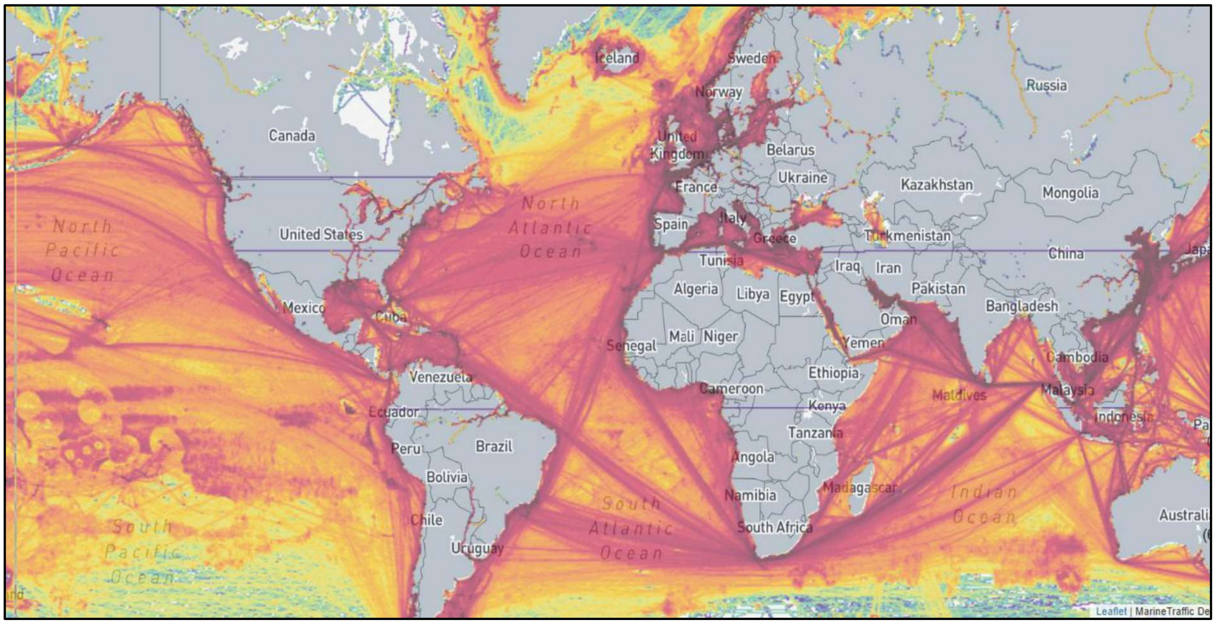

Figure 1. Vessel traffic density map (AIS Marine Traffic, 2025).

Additionally, the evolution of maritime technology has started introducing unmanned vessels, which coexist with manned ships across various stages of autonomy (Degree 1) to fully autonomous operations (Degree 4) (Kim et al., 2022; Nakashima et al., 2024). This integration presents both opportunities and challenges for collision avoidance and traffic management in congested waters (Felski and Zwolak, 2020; Levander, 2017). Marine casualties and incidents are rarely the result of a single cause and usually occur as a result of complex interactions between environmental factors, operational conditions, human error, equipment failures, and navigational complexities (Dominguez-Péry et al., 2021; Kasyk et al., 2023). Figure 2 presents an illustration of occurrence of marine casualties using Reason's Swiss Cheese Model (Reason et al., 2006).

Major incidents in high-traffic zones not only disrupt global supply chains but also have severe economic and ecological impacts. For example, the collision in the Strait of Malacca in 2017 resulted in significant oil spills, disrupting traffic and causing extensive environmental damage (ITOPF, 2018). Similarly, the blockage of the Suez Canal by the Ever Given in 2021 underscored the vulnerability of these chokepoints, halting $9 billion worth of daily maritime traffic and impacting global markets (Allianz, 2021). Thus, enhancing navigational safety in these critical areas is imperative to sustain the efficiency of global trade routes and mitigate the potential for catastrophic incidents.

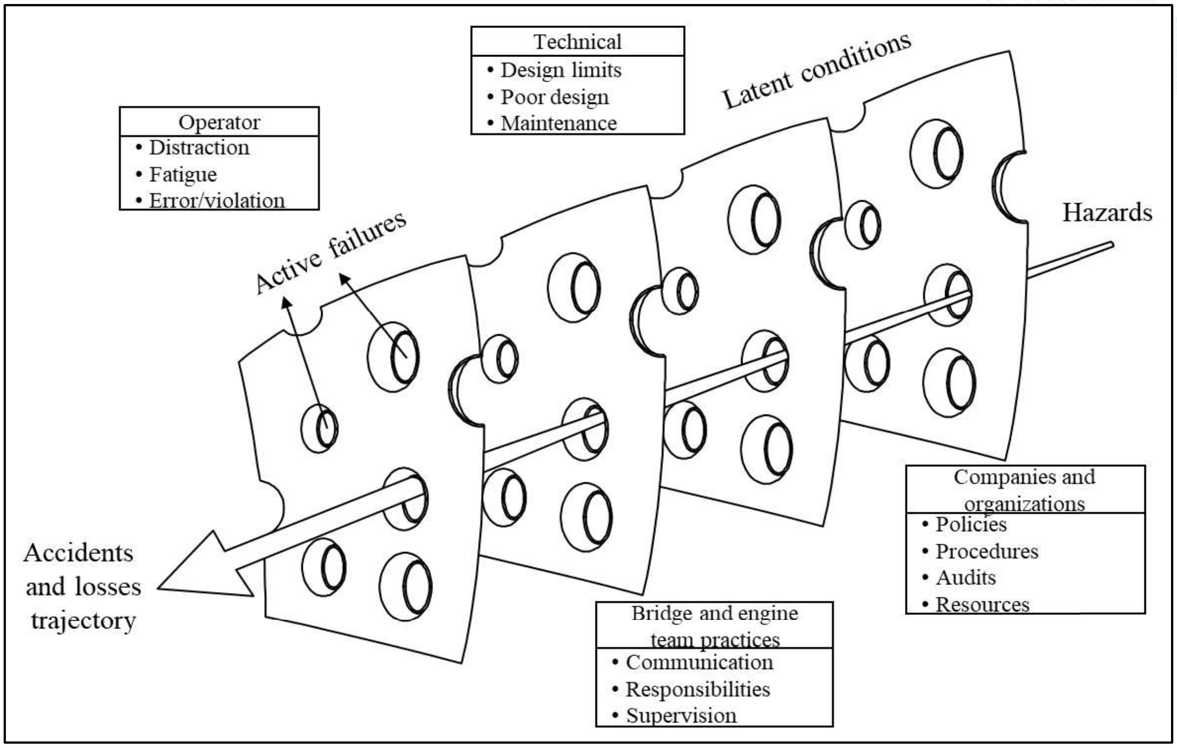

Figure 2. Marine casualties' occurrence pattern along with Swiss Cheese Model

2. The need for a decision support system for maritime traffic management

The necessity for an advanced traffic management system supported with an accurate decision support system in high-density maritime areas is driven by the escalating complexity of navigational environments. As maritime traffic continues to grow, especially in key chokepoints, the task of managing such areas becomes increasingly intricate. UNCTAD predicts that seaborne trade volumes will continue to rise, projecting an annual growth rate of 2.1% from 2023 to 2028 (UNCTAD, 2024). This surge underscores the critical need for robust systems capable of handling heightened traffic densities efficiently. Additionally, the integration of autonomous vessels into existing fleets of manned ships introduces new dynamics into maritime traffic management. Autonomous vessels operate with varying levels of independence from human operators, from semi-autonomous systems that require human oversight to fully autonomous systems that operate independently. This mixture poses unique challenges for collision avoidance and traffic coordination (Felski and Zwolak, 2020; Kim et al., 2022).

Traditional accident analysis and prediction models, which often rely on historical data and static parameters, struggle to accommodate the dynamic interactions and continuous changes in autonomous and manned vessel operations. These models frequently fail to capture the nuances of mixed environments, which are characterized by varying degrees of autonomy and human involvement (Kaber, 2018; Lyons et al., 2021). Consequently, there is a marked need for updated models that can dynamically adapt to the evolving conditions and provide accurate risk assessments in real-time. Traditional, reactive approaches to maritime safety are insufficient and that has been noticed long back since 1960s and shifted the focus on, proactive measures, predictive risk assessment, real-time traffic management with decision support systems for operators (Luo and Shin, 2019).

To address these complexities, there is a need for real-time decision support systems that can assist Vessel Traffic Services (VTS) Operators, ship masters, bridge team members and other maritime stakeholders. Such systems are designed to provide immediate, data-driven insights into potential navigational risks and optimize traffic flows within congested maritime zones. By leveraging advanced algorithms and real-time data, these decision support systems can enhance situational awareness and decision-making processes, thereby improving safety and efficiency in maritime operations (Baldauf et al., 2020). Therefore, this study is focused on addressing the need for improved safety and efficiency in high-traffic maritime areas by achieving the following objectives.

i. To develop a hybrid model for predicting marine accidents in high-traffic maritime areas by recognizing the limitations of current predictive models, the study aims to develop a hybrid model that combines quantitative and qualitative data analysis techniques.
ii. To integrate the Human Factors Analysis and Classification System (HFACS) with Bayesian Networks for dynamic and real-time risk assessment: HFACS provides a framework for identifying and analyzing human error aspects of accidents, which are a significant cause of maritime incidents. Integrating HFACS with Bayesian Networks, which offer probabilistic insights based on causal relationships, this study aims to facilitate dynamic and real-time risk assessment.
iii. To propose areas of improvement for reducing accident probabilities and improving decision-making by analyzing the data generated through the hybrid predictive model and the integrated HFACS-Bayesian framework.

4. Overview of accident analysis models

Accident analysis models are essential tools in identifying the root causes of incidents and developing effective prevention strategies (Wong and Pawlicki, 2025). Traditional models in marine casualty analysis often focus on either human error or technical failures. These models, while providing valuable insights into specific sides of accident causation, typically do not address the complex interplay between various elements such as human factors, organizational processes, and environmental conditions. Studies have shown that focusing solely on one aspect can lead to an incomplete understanding of accident causation and potentially overlook critical preventive measures (Salehi et al., 2021; Zarei et al., 2022).

In response to the limitations of traditional models, hybrid models have emerged as a promising alternative. Hybrid models integrate multiple qualitative and analytical methods to provide a more comprehensive understanding of accident causation (Tonoğlu et al., 2022; Yildiz et al., 2021). These models leverage the strengths of individual approaches to address the multifaceted nature of marine casualties and incidents, enhancing both the depth and breadth of analysis. For instance, hybrid models can simultaneously evaluate human factors, technical conditions, and environmental influences, providing a holistic view of the risk landscape.

Among the tools used in these hybrid models, the Human Factors Analysis and Classification System (HFACS) and Bayesian Networks are noteworthy and frequently used in literature. HFACS is a widely recognized framework for identifying and classifying human errors involved in accidents. Developed initially for aviation and later adapted for maritime contexts, HFACS facilitates a structured analysis of human errors from multiple levels, including organizational influences, unsafe supervision, and conditions of operators' actions (Ergai et al., 2016; Li and Harris, 2006; Salmon et al., 2012; Theophilus et al., 2017; Uğurlu et al., 2018).

Bayesian Networks, on the other hand, offer a probabilistic approach to modelling the causal relationships between various risk factors. These networks are capable of incorporating uncertainties in the data and can update their predictions as new information becomes available, making them highly effective for dynamic and complex environments like maritime traffic (Yang et al., 2008; Yeo et al., 2016; Yıldız et al., 2024). The application of Bayesian Networks in maritime safety allows for real-time risk assessment and decision-making support, adapting to changing conditions and operational contexts. Bayesian Networks based DANs represent occurrences as a network of interconnected operational conditions, human and organizational factors, capable of incorporation real-time data to dynamically update risk assessments, and to simultaneously analyze wide range of factors, vessel characteristics, weather conditions, traffic patterns, and human factors.

5. Methodology

5.1. Data collection

The foundation of this study is based on a data collection strategy that involved gathering historical accident data from databases such as the Global Integrated Shipping Information System (GISIS) and IMO member States' national databases such as the Maritime Administrations transport safety databases or transportation safety investigation center/board of the member States. Initially, records of 366 marine casualties and incidents occurred between 2010-2024 were collected from these sources (EMSA, 2024; GISIS, 2024). After data screening and cleaning, 10 duplicate records were deleted, and 76 accident reports could not be retrieved. Ultimately, 280 marine casualty reports, focusing on navigation-related incidents such as strait passage, strait approach, port approach, and coastal traffic zone navigation, have been compiled as the main dataset for this study.

Expert judgements were another input as a dataset used in construction and validation of the accident network. It involved consultation with 10 maritime safety experts, including accident investigators (3 experts), ship masters (2 experts), chief engineers (2 experts) and scientists involved in marine casualty investigations (3 experts) to gain insights that are not readily available in public databases such as accident occurrence patterns as dynamic accident (Bayesian) networks. These experts provided nuanced interpretations of processed casualty data, highlighted and validated lesser-known risk factors or operational conditions.

5.2. Model development

The model development phase began with the establishment of a framework based on the Human Factors Analysis and Classification System (HFACS) for each of the 280 marine casualties. In the utilized HFACS-PV human factors and operational conditions were categorized into four levels: Organizational Influences, Unsafe Supervision, Preconditions for Unsafe Acts, Unsafe Acts and Operational Conditions. Each level addresses different aspects of human factors contributing to marine casualties and incidents, offering a structured approach to understanding the interactions between human errors and other accident causation factors. In the marine casualties and incidents context organizational influences generally refer to the overarching policies, culture, and management practices that shape the operational environment of ships, potentially leading to safety oversights. Unsafe supervision usually refers to failures in leadership and oversight that allow or fail to correct risky practices before they lead to accidents. Preconditions for unsafe acts pave the way for unsafe acts of the individuals, including technical, and human conditions, such as fatigue or inadequate training. Unsafe acts are errors or violations committed by individuals directly involved in operations and usually complete the accident occurrence pattern, which are often seen or found as the immediate causes of incidents. Operational conditions encompass the specific environmental, technical, and situational contexts in which maritime operations occur, such as adverse weather or high traffic density, which can significantly influence the likelihood and severity of accidents (Shappell and Wiegmann, 2000; Uğurlu et al., 2018; Uğurlu et al., 2020; Yildiz et al., 2021).

Integration with Bayesian Networks was the next step in the model development. Bayesian Networks were utilized to estimate prior probabilities of various accident scenarios, considering the interdependencies among HFACS levels (Uğurlu et al., 2020; Yıldız et al., 2024). This probabilistic model is capable to adapt to new information continuously, thereby providing real-time risk assessments.

Constructing the dynamic network model involves four steps *i. Identification of variables*: Key risk factors are identified based on HFACS levels and additional data from historical accident reports and expert input. *ii. Structural modelling:* A network structure is developed to represent causal relationships between identified risk factors. *iii. Parameterization:* Conditional probability tables are created for each node, based on historical data and expert judgments. *iv. Validation and calibration:* The model is iteratively adjusted and calibrated to align with known accident outcomes and expert assessments.

Expert validation was an integral part of the methodology. This phase involved a 3-hour focus group exercise with 10 experts participated in the study as specified above. Essentially the proposed DAN presented to the experts and they reviewed the model's outcomes, provided feedback on its practical relevance, and contributed to refining the probabilistic relationships and assumptions within the model (Uğurlu et al., 2020; Yıldız et al., 2024). This collaborative approach ensures that the model not only reflects theoretical accuracy but also aligns with practical realities in maritime operations. Figure 3 outlines the step-by-step methodology followed in this study.

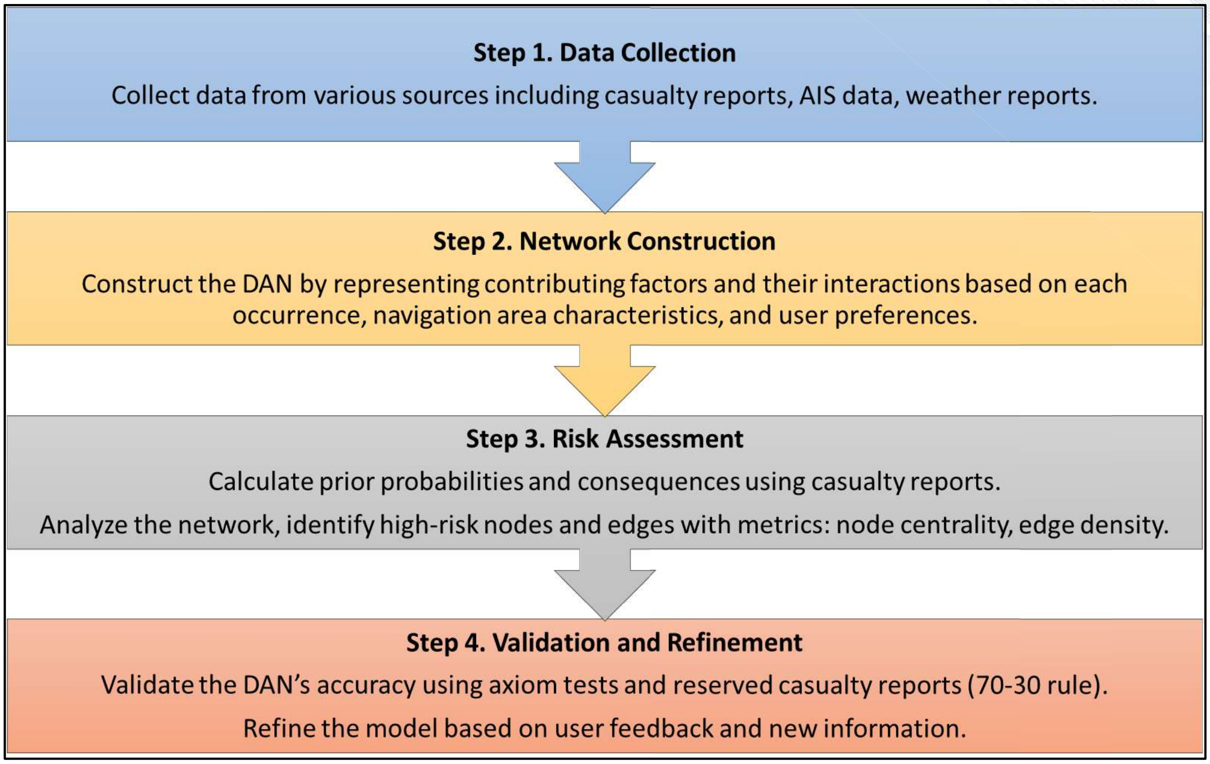

Figure 3. Step-by-step methodology followed in the study

6. Proposed Dynamic Accident Network (DAN)

In high-traffic maritime areas managing navigation and ensuring safety are particularly challenging. These areas, which experience dense maritime traffic and contain numerous navigational constraints, are prone to accidents influenced by a complex interplay of various causal factors (Tonoğlu et al., 2022; Yildiz et al., 2022; Yıldız et al., 2024). Understanding the causes and their interactions is essential for risk assessment and accident prevention.

From the DAN model developed in this study, several key nodes represent causes and causal factors that directly contribute to marine casualties and incidents more frequently than others. These factors are grouped under human, organizational, environmental, and technical domains as reflected with different colors in the Figure 4.

- Organizational Influences; *Safety culture:* A strong safety culture in maritime organizations supports proactive safety and compliance behaviors. *Company's manning strategy and crew assignment:* Adequate staffing and proper assignment of crew roles are crucial to ensure all operations are performed by competent personnel. *Procedures and rules:* Established protocols help standardize operations and reduce the chance of accidents.
- Technical and Operational Supervisory Factors (Unsafe Supervision); *Equipment and facility resources:* The reliability of a ship's equipment and the maintenance status directly impact the risk of mechanical failures. *Voyage and operation planning:* Comprehensive planning is vital to foresee and mitigate potential risks associated with the voyage.

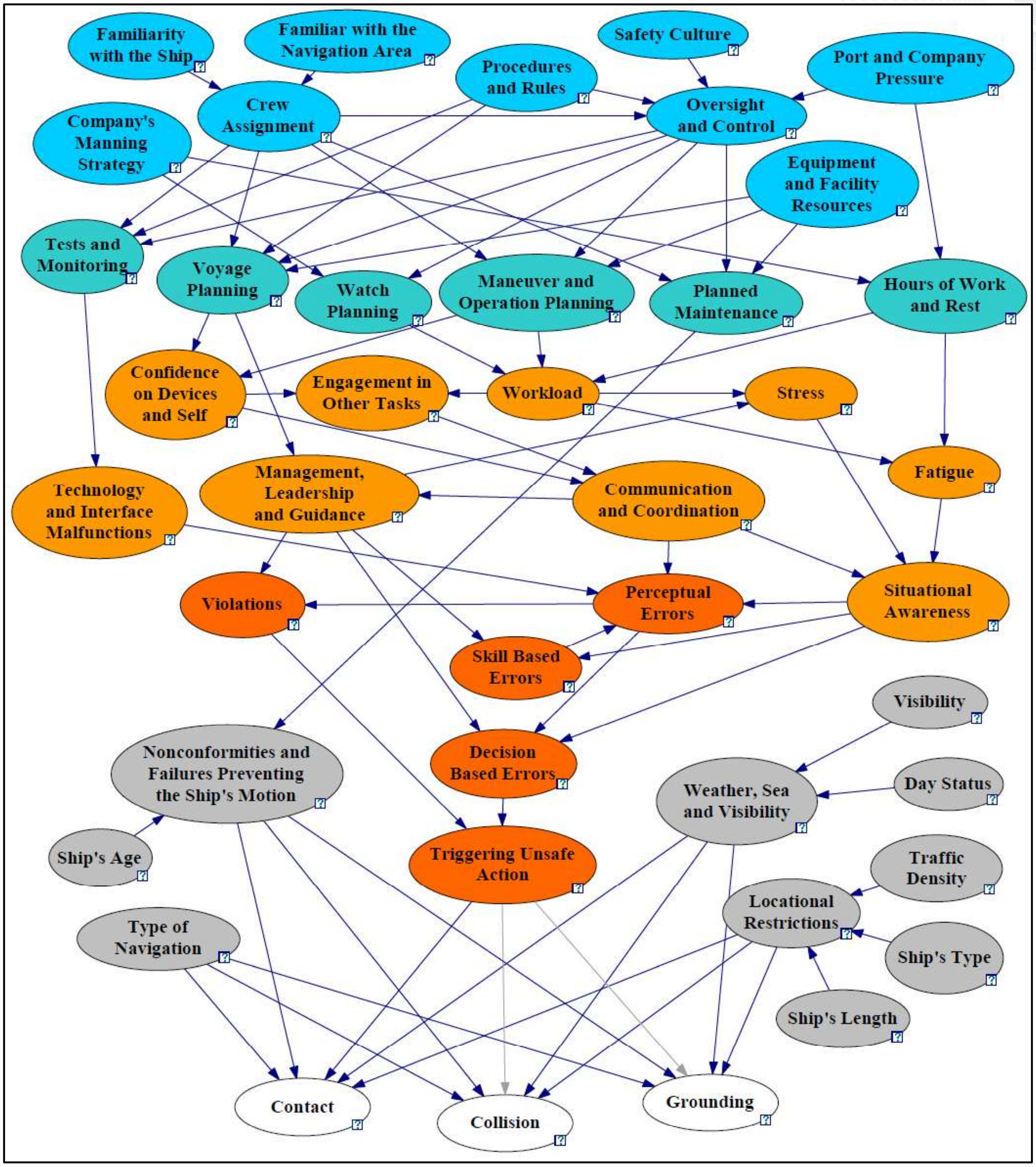

Figure 4. Overview of the proposed Dynamic Accident Network

- Human Factors; *Familiarity with the ship and navigation area:* Proficiency and experience of the crew with the specific vessel and the local waterways significantly affect navigational safety. *Hours of work and rest:* Fatigue related to non-compliance with work and rest schedules can lead to decreased alertness and increased likelihood of errors. *Confidence on devices and self:* Over-reliance or underestimation of navigational aids and personal judgment can lead to critical misjudgments. *Skill-based, perceptual, and decision-based errors:* These errors include misinterpretation of navigational data, poor decision-making under pressure, and execution failures.

- Operational and Environmental Conditions; *Weather, sea, and visibility conditions:* Adverse weather and poor visibility increase the complexity of navigation and risk of accidents. *Traffic density and type of navigation:* High traffic density and the mix of different vessel types (e.g., cargo, tanker, passenger) elevate the potential for conflicts and collisions.

Using the developed hybrid model, this study analyses how these causal factors influence the probabilities of different types of marine casualties and incidents under varying operational conditions in the strait. Factors such as vessel speed, weather conditions, and crew fatigue are modelled to estimate the likelihood of incidents such as collisions, groundings, contact accidents, and sinkings.

The model is capable to predict:

- Collision probability: Heightens in scenarios with high traffic density, especially when compounded by poor visibility or crew fatigue.
- Grounding probability: Increases in areas with geographical constraints, particularly when navigational planning is inadequate.
- Contact probability: Rises in close-quarter situations are often influenced by miscommunications or navigational errors.

The effectiveness of preventive measures such as pilotage and timing adjustments for transits is evaluated, showing considerable reduction in accident probabilities. The case study underscores the importance of a comprehensive approach to understanding and managing the multifaceted risks in high-traffic maritime areas. By addressing the interrelated causes and factors, the hybrid model aids in enhancing maritime safety in high traffic areas.

7. Results and discussion

The application of the DAN model to high-traffic maritime areas has provided insights into the risk factors and their implications for maritime safety. The model highlights several high-risk factors crucial in these environments (Figure 5).

Organizational Influences: Adequate manning and safety culture are shown to be vital, with 91% of scenarios featuring qualified crew assignments and 99% reflecting an optimum safety culture. These factors are directly linked to lower incident rates in the model predictions.

Technical and Operational Supervisory Factors (Unsafe Supervision): Equipment and procedural adequacy are also highlighted, with inadequacies in these areas present in 12% and 14% of scenarios, respectively. These shortcomings can lead to critical operational failures and errors.

Human Factors: Fatigue and stress are prevalent issues, with the model indicating that 44% of scenarios involve fatigue, and 24% involve high stress levels among the crew. These factors substantially increase the likelihood of human errors in decision-making and operation.

Operational and Environmental Conditions: Visibility and traffic density are significant environmental factors affecting risk. The model indicates that poor visibility conditions occur in 1% of scenarios, and high traffic density is present in 30% of scenarios, both of which increase accident probabilities.

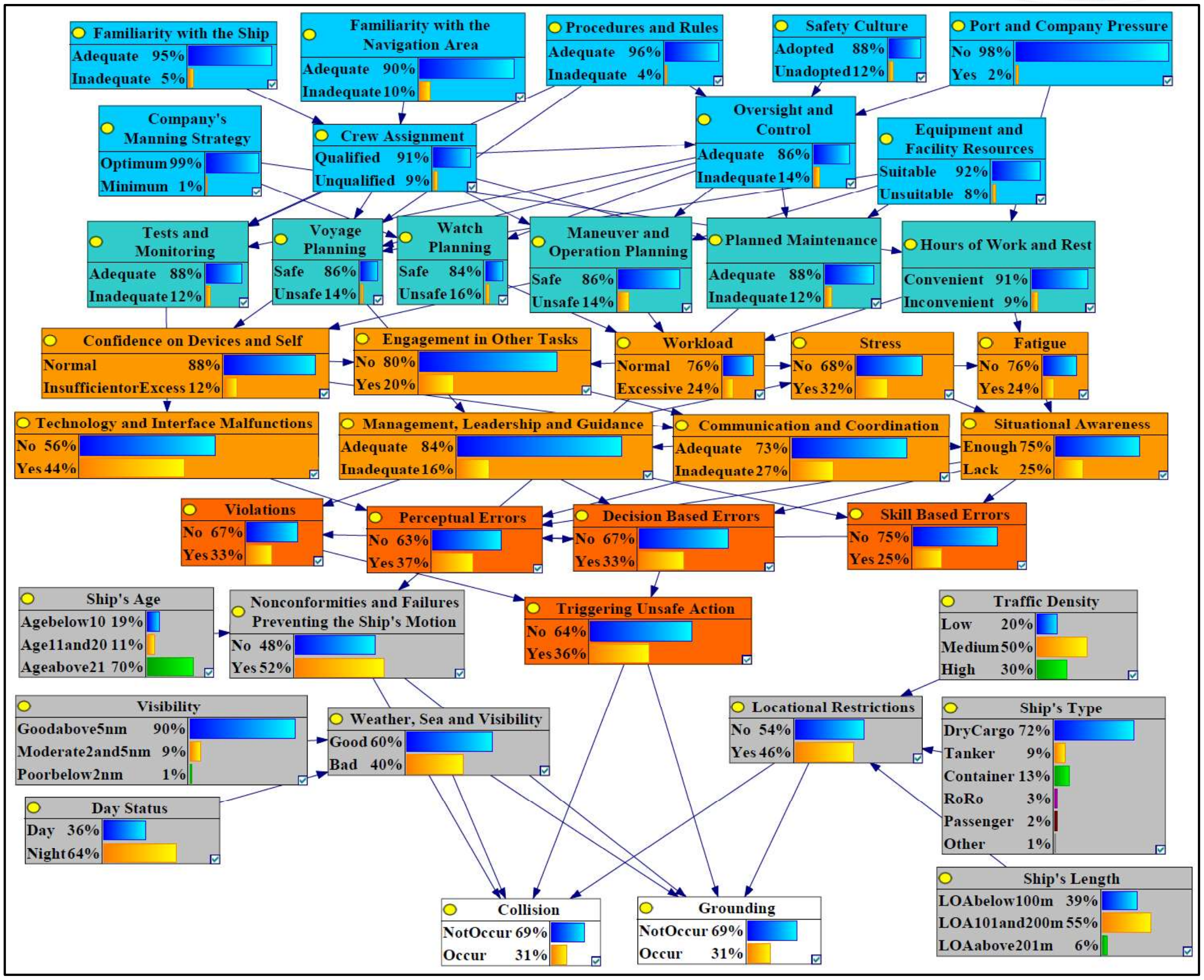

Figure 5. Proposed DAN with probabilities

The DAN model's ability to dynamically predict accidents under varying operational conditions provides actionable insights into real-time decision making. By quantifying the probabilities of different accident types, such as collisions and groundings, which each occur in 31% of scenarios under certain conditions, the model aims to allow VTS operators, ship masters and bridge team members to adjust their strategies based on current risk assessments.

The findings from the DAN model align with existing literature that emphasize the critical role of human factors, organizational practices, and environmental conditions in maritime safety. Furthermore, the model's focus on dynamic and real-time data integration advances the traditional static models used in maritime risk assessments, offering a more nuanced and immediately applicable approach to accident prevention.

Based on the insights gained from the DAN model, several recommendations proposed as follows.

- Enhanced training and resting hour practices: Implementing comprehensive training programs that focus on fatigue management and stress reduction can mitigate human error. Additionally, enforcing strict adherence to rest period policies will help reduce fatigue-related accidents.

- Improving safety culture and oversight mechanisms: Organizations should strive to maintain an optimum safety culture and robust oversight mechanisms to ensure adherence to safety protocols and procedures.
- Equipment maintenance and technological upgrades: Regular maintenance and technological upgrades of navigational and operational equipment are crucial to prevent technical failures.
- Real-time traffic management: VTS operators should utilize real-time data provided by models like DAN to manage traffic dynamically, especially during peak times or adverse conditions.

8. Areas of practical applications

The DAN model, developed for assessing and mitigating risks in high-traffic maritime areas, offers several practical applications that significantly enhance safety and operational efficiency. These applications make the model an invaluable decision-support tool for various maritime stakeholders, particularly in managing congested and complex navigational environments. As exemplified below the model can be utilized as a decision-support system to enhance navigational safety by identifying risk patterns and suggesting preventative measures in critical maritime areas (i.e. narrow waterways, congested coastal areas, traffic separation scheme areas, port approaches).

Real-time risk assessment: The DAN model provides a dynamic and real-time assessment of risks based on current environmental conditions, vessel characteristics, and human factors. This feature allows Vessel Traffic Service (VTS) operators and ship navigators to continuously monitor risk levels and make informed decisions promptly. For example, the model can predict the increase in collision risk due to a sudden change in visibility or traffic density, enabling proactive management.

Pilotage, tug assistance, or similar preventive measures: Based on the assessed risks, the DAN model can recommend specific preventive measures to mitigate potential hazards. For instance, it might suggest the engagement of pilot services for vessels entering narrow passages or the use of tug assistance for large vessels under poor maneuverability conditions. These recommendations are tailored to the specific scenarios and conditions assessed, ensuring that measures are both timely and relevant.

Suspensions of transit: In scenarios where the risk level exceeds a predefined safety threshold, the model can advise on the suspension of transits. This application is particularly crucial during extreme weather conditions, high traffic congestion, or when critical navigational aids are compromised. Such suspensions prevent accidents by avoiding the escalation of hazardous situations, thereby safeguarding both human life and environmental integrity.

The model's ability to adapt to various maritime environments and its capacity for real-time data processing make it a valuable tool for contemporary maritime risk management. However, while the DAN model marks an advancement in the field, it is not without its limitations. One such limitation is the treatment of human factors; although the model incorporates elements like fatigue and stress, these inputs are often based on static data, which may not adequately reflect the dynamic nature of human behavior and condition changes over time. Additionally, the model's focus on pilotage and tug assistance is somewhat limited. It provides general recommendations that may not take into account the specific regulations of individual ports or the unique characteristics of different vessel types and sizes.

To address these limitations and enhance the model's utility, several areas of future development are suggested.

- Integration with artificial intelligence (AI) and Wearable Technology for Real-Time Data Input: Future iterations of the DAN model could incorporate artificial AI and wearable technology to collect and analyze real-time data. This would enable more accurate monitoring of human factors, such as crew fatigue and stress levels, by continuously updating the model with real-time physiological and behavioral data from crew members. Enhancements like these would not only enhance the precision of risk assessments but also facilitate more tailored safety measures.
- Expansion to Other Maritime Zones and Varying Operational Scenarios: It is proposed to expand the model's applicability to encompass a broader range of maritime environments and operational scenarios, including ice-covered waters, areas with restricted visibility, or regions with unique ecological or traffic concerns. By broadening the scope of the model to these varied conditions, its relevance and utility as a comprehensive tool for global maritime operations would be significantly increased.
- Enhancements for Autonomous Vessel Operations (D1-D4 Phases): As the maritime industry moves towards increased automation, the DAN model could be refined to better support operations of autonomous vessels across different levels of autonomy (D1-D4 phases). This adaptation would involve addressing the distinct challenges of autonomous navigation, such as algorithmic decision-making, sensor reliability, and interactions between machines and humans during mixed operations. Potential enhancements could include developing specific risk assessment modules tailored to the technological and operational levels of autonomous vessels.

10. Conclusion

This study aimed at contributing to the field of maritime safety and risk management through the development and application of the DAN model. The integration of the Human Factors Analysis and Classification System (HFACS) with Bayesian Networks has enhanced the model’s predictive capabilities. This integration allows for a comprehensive analysis of the causal factors leading to marine casualties and incidents, incorporating both human and operational elements. The model predicts potential accidents by analyzing dynamic interactions among these factors, offering a nuanced approach to risk assessment and enhancing safety across various maritime zones, including narrow waterways, Traffic Separation Scheme (TSS) areas, and port approaches.

The practical implications of the DAN model for maritime safety and operational planning are notable. It can support strategic decision-making by vessel traffic service (VTS) operators and maritime navigators, enabling them to proactively manage risks and prevent accidents. Additionally, the data provided by the model can inform policy formulation, aiding in the development of regulations that enhance maritime safety, such as mandatory pilotage in high-risk areas or improved training protocols for crew members. By identifying high-risk factors and conditions, the model aims to assist maritime authorities in effectively allocating resources to deploy safety measures where they are most needed. To maximize the efficacy and applicability of the DAN model, collaboration among maritime authorities, researchers, and industry stakeholders is essential. Such collaboration will refine and adapt the model to meet the evolving challenges of maritime safety and extend its application to more diverse environments and emerging maritime technologies. This study highlights the importance of risk management tools, and the collaborative efforts required to safeguard maritime domains amidst increasing complexities, thereby promoting a more unified approach to global maritime safety.

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