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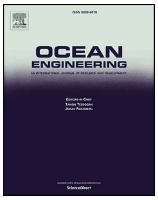

Research paper

Dynamic risk modelling of maritime accidents based on HFACS-PV and Bayesian Networks

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ABSTRACT

This study develops a probabilistic dynamic risk assessment framework for grounding and collision/contact accidents in narrow waterways by integrating the Human Factors Analysis and Classification System for Passenger Vessels (HFACS-PV) with Bayesian Networks (BN). Marine accident reports from the Dover Strait (2004–2020) were systematically analysed to identify human, organisational, technical, and environmental risk factors, which were subsequently structured into a Bayesian Network to model their interdependencies and dynamic influence on accident occurrence. Conditional probability tables were derived from accident data and supplemented through structured expert elicitation. The resulting model enables real-time inference and predictive risk estimation under evolving operational conditions. Model performance was evaluated using detailed grounding and collision case studies, demonstrating its capability to replicate accident evolution and quantify the contribution of key causal factors. The results indicate that unsafe acts, particularly decision-based and perceptual errors, combined with deficiencies in voyage planning, supervision, and situational awareness, dominate accident causation in the Dover Strait. The proposed framework provides a quantitative decision-support tool for vessel traffic services and maritime operators, supporting proactive risk mitigation and safety optimisation in high-density and constrained navigational environments.

1. Introduction

Marine accidents, particularly grounding and collision/contact incidents, have long been a significant concern in maritime safety. Numerous accident analysis studies have been conducted to identify their causes and develop preventive measures. According to these studies, key factors contributing to collision/contact accidents include violations of the Convention on the International Regulations for Preventing Collisions at Sea (COLREG) rules, inadequate lookout, ineffective use of bridge navigation equipment, poor visibility, and heavy traffic (Chauvin et al., 2013; Feng et al., 2025; Kujala et al., 2009; Montewka et al., 2012; Uğurlu et al., 2015; Uğurlu et al., 2015; Yildirim et al., 2017). Similarly, common causes of grounding accidents have been identified as insufficient passage planning, position-fixing errors, inappropriate chart usage, fatigue, and adverse weather and sea conditions(Mullai and Paulsson, 2011; Uğurlu et al., 2015; Uğurlu et al., 2015; Uğurlu et al., 2015; Yildirim et al., 2017). Despite these findings, marine accidents continue to occur at relatively high rates. Between 2008 and 2017, the UK's Marine Accident Investigation Branch (MAIB) recorded 102 accidents in UK waters, 58% of which were either collision/contact or grounding incidents (MAIB, 2017a). Moreover, studies conducted by Liverpool John Moores University (LJMU) and Karadeniz Technical University (KTU) found that 60% of grounding and collision/contact accidents around the Istanbul Strait (IS) occurred in shallow waters, less than 12 miles from the coast (Uğurlu, et al., 2015; Yildirim et al., 2017, 2019). Narrow waterways, such as the Dover Strait (DS), share similar characteristics, such as proximity to the coast, dense traffic, and potential shallow waters. Therefore, identifying high-risk areas for marine accidents in such narrow waterways, along with implementing preventive measures, remains a crucial task.

1.1. Marine accident analysis background

Coastal and narrow waterways are frequent sites of marine accidents (Bateman et al., 2007; Huang et al., 2013; Squire, 2003; Uğurlu and Yıldız, 2016; Ulusçu et al., 2009). Despite advances in maritime

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technology and international safety regulations, accidents in these areas persist, posing significant risks to maritime operations (Akhtar and Utne, 2014; Macrae, 2009; Uğurlu et al., 2017). Between 2015 and 2020, the European Maritime Safety Agency (EMSA) recorded an annual average of 2660 accidents, with year-to-year reductions never exceeding 7% (EMSA, 2024). The limited global progress in reducing accidents raises questions about the effectiveness of current safety measures (Kujala et al., 2009; Schröder-Hinrichs et al., 2012; Uğurlu et al., 2020).

In narrow waterways, navigational safety relies on systems such as traffic separation schemes, pilotage, and vessel traffic services (Praetorius and Hollnagel, 2014; van Westrenen and Praetorius, 2014). However, challenges like dense local traffic, strong currents, sharp turns, glare, complex topography, limited anchorage, and high transit volumes continue to endanger navigation (Başar, 2010; Köse et al., 2003; van Westrenen and Praetorius, 2014). The DS, one of the busiest and most hazardous waterways, exemplifies these risks: roughly 150,000 to 200,000 ships transit annually (Aydogdu et al., 2012; Emecen Kara, 2016; Qu et al., 2012). The predominant accident types, collision, contact, sinking, and grounding, are strongly linked to the structural and environmental features of narrow waterways and high traffic density (Chauvin et al., 2013; Graziano et al., 2016; Martins and Maturana, 2010; Uğurlu et al., 2015a,b,c; Yıldırım et al., 2019; Squire, 2003; Yildiz et al., 2021). Consequently, this study focuses on these four accident categories.

1.2. Marine accident contributing factors

Marine accidents are often attributed to a range of underlying human and environmental factors. Among these, fatigue remains one of the most persistent causes, typically resulting from excessive workloads, insufficient rest, and commercial pressures. Such conditions are common on under-manned vessels or where operational schedules are poorly managed, leading to reduced alertness and impaired decision-making (MAIB, 2017b). Distraction is another critical factor influencing navigational performance. Navigation is a cognitively demanding task requiring continuous attention; however, distractions frequently arise from paperwork, technological interactions, communication with crew members, and external stimuli. These disruptions can significantly affect an officer's ability to maintain situational awareness and ensure safe vessel operation (Maglić et al., 2016, 2020).

Similarly, over-reliance on electronic navigational aids can compromise safety. Although modern navigation technologies enhance awareness and assist decision-making, they cannot replace the judgment and accountability of the Officer on Watch (OOW). The ultimate responsibility for safe navigation and timely action remains with the OOW, regardless of technological support (Tsimplis and Papadas, 2019; Turna and Öztürk, 2020). External influences also play a substantial role in accident causation. Adverse weather, sea states, and the unpredictable behaviour of nearby vessels are factors beyond the control of the crew but can still result in serious incidents. Documented cases include collisions at berth, drifting at anchorage, and losses caused by storms, surges, or sudden heavy weather. These are occurrences that persist even when navigational rules are correctly followed (Silva et al., 2014; Tabri et al., 2009).

The influence of teammates and task deviation further compounds these risks. Human error continues to be a major contributor to maritime accidents despite international regulatory efforts. The International Maritime Organization (IMO) addresses these issues through the International Safety Management (ISM) Code and the International Convention on Standards of Training, Certification, and Watchkeeping for Seafarers (STCW) (IMO, 2008; IMO, 2022). Nevertheless, deviations between prescribed procedures and actual practices at sea remain common, as demonstrated by the Hoegh Osaka grounding (MAIB, 2016a). Limited research has examined this discrepancy between “work as imagined” and “work as done” within maritime operations (De Vries, 2017; Praetorius et al., 2015). The Dover Strait, one of the busiest and most constrained waterways in the world, with approximately 500 vessel transits each day (MCA, 2010), exemplifies the complex human and operational challenges of maritime navigation. This study investigates marine accidents in the Dover Strait by applying the Human Factors Analysis and Classification System (HFACS) and Bayesian Networks (BN) to accident reports, with the aim of identifying human-factor-related causes and their interdependencies.

1.3. Human factor analysis and classification system for passenger vessels

HFACS-PV offers a structured, hierarchical framework for analysing human, organisational, and environmental contributions to maritime accidents. By extending traditional HFACS to include Operational Conditions, it systematically captures the influence of dynamic environments, traffic density, and navigational constraints, making it particularly relevant for complex, high-risk areas such as narrow straits. Its multi-level structure, which covers unsafe acts, preconditions, supervision, organisational influences, and operational conditions, enables identification of both active failures and latent systemic deficiencies, promoting comprehensive root-cause analysis and consistent, traceable accident classification. HFACS-PV is also compatible with probabilistic modelling approaches, such as Bayesian Networks (BNs), facilitating transformation of qualitative accident data into quantitative, predictive risk models.

However, HFACS-PV is primarily retrospective and dependent on the quality of investigation data, which may introduce subjectivity. It does not inherently quantify causal strength, requiring integration with complementary modelling tools for probabilistic risk assessment. Despite this, HFACS-PV is highly suitable for research on maritime risk in narrow straits, where dense traffic, constrained manoeuvring, and variable environmental conditions interact with organisational and human factors. Its inclusion of Operational Conditions and hierarchical structure supports both systematic causal analysis and dynamic, predictive risk modelling, providing a robust foundation for safety optimisation and proactive decision support in challenging maritime corridors.

1.4. Dynamic risk modelling with Bayesian Networks

Dynamic risk modelling has been widely recognized in the literature as a powerful approach for safety and risk analysis in marine and offshore operations. Assessing the risk of hazards and failures in these environments is inherently complex due to the multitude of factors and countless possible scenarios in which incidents may occur. While various techniques exist to support risk analysis, this study focuses on BNs, which have seen extensive application in the maritime industry.

BNs have been used in diverse contexts to assess and manage risk. For example, Cai et al. (2013) applied BNs for quantitative risk assessment in offshore oil and gas operations, while Ma et al. (2024) used BNs to model the evolution of ship fire accidents from causes to consequences, translating operational flowcharts directly into BN structures. Their model was validated through a case study involving Subsea Blowout Preventer operations, informed by the 2010 Deepwater Horizon disaster (Jones et al., 2010). Similarly, Eleye-Datubo et al. (2006) developed a BN-based marine decision support tool to address random uncertainties and simplify risk assessments, supported by Fenton and Neil (2018). Wu et al. (2016) further demonstrated BN applications for prediction and diagnosis of marine systems, integrating the Bayesian Tree (BT) approach to develop and validate the model, a method commonly observed in the literature. Loughney and Wang (2018) and Loughney et al. (2019) also highlighted BNs as an effective tool for estimating the likelihood of various events under uncertainty and for identifying critical areas requiring attention to prevent offshore incidents. BNs offer several advantages over alternative risk modelling approaches. They can integrate diverse data sources, including empirical data and expert judgment, which is particularly valuable when datasets are incomplete or unavailable (Bolstad, 2007). Khakzad et al. (2011) and Abimbola et al., (2014) demonstrated that BNs outperform Fault Tree Analysis (FTA) in safety analysis due to their flexible structure, which can accommodate a wide range of accident scenarios; these advantages are also supported by Wu et al. (2016) and Yeo et al. (2016).

In addition to their analytical power, BNs provide clear visual representations of the modelled systems, facilitating communication, hypothesis formulation, and model expansion. Their capacity for inference allows predictions to be updated dynamically as new evidence or observations are incorporated, making them particularly effective in contexts characterized by uncertainty. This adaptability and ability to integrate multiple information sources render BNs a robust tool for dynamic risk modelling in maritime operations.

1.5. Novelty and structure

The novelty of this research is the comprehensive assessment of marine accidents in the Dover Strait via the HFACS-PV method, and the transition of this static trend analysis to a dynamic risk model. Changes are not made to the HFACS-PV methodology, but innovation resides in the transition of the HFACS-PV analysis to a dynamic risk prediction model for the Dover Strait. This dynamic risk assessment model not only identifies key human and technical risk factors but also provides a flexible foundation for improving navigational safety in the Dover Strait and potentially other narrow waterways.

The remainder of this paper is organized as follows: Section 2 presents the generic methodology and the research framework for HFACS-PV and BN analysis; Section 3 outlines application of the research framework to a narrow water way case study, in this case the Dover Strait; Section 4 discusses the analysis and findings from the case study; and Section 5 concludes with key insights and recommendations for future research.

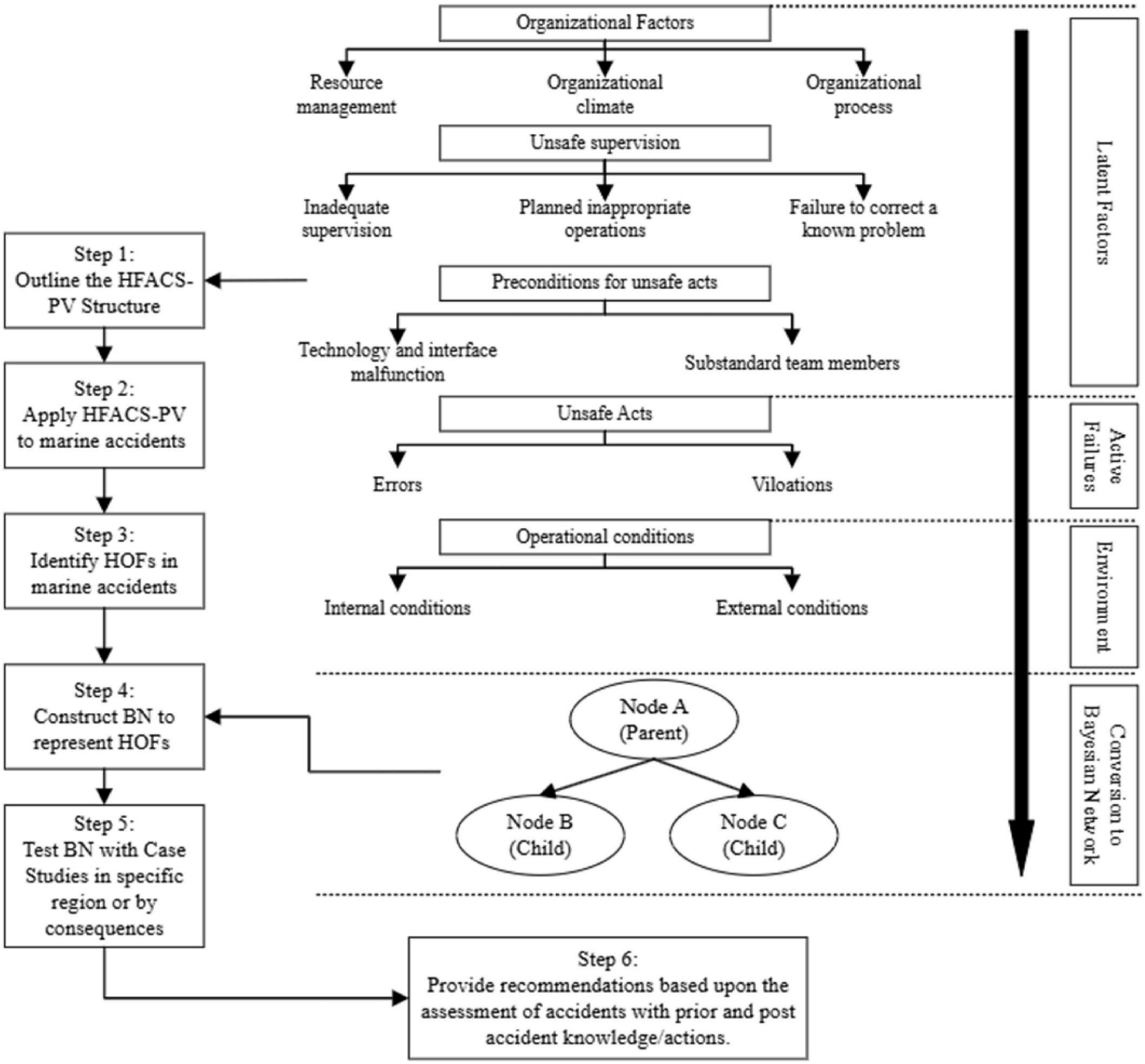

Fig. 1. Research framework.

2. Identification of risk factors through HFACS-PV

2.1. Scope and methodology

This study proposes an integrated analytical framework combining the Human Factors Analysis and Classification System for Passenger Vessels (HFACS-PV) with Bayesian Network (BN) modelling to systematically investigate Human and Organizational Factors (HOFs) contributing to marine accidents. The framework enables both qualitative accident investigation and quantitative probabilistic analysis of causal relationships between contributing factors. The methodological process consists of six sequential stages, as illustrated in Fig. 1.

2.1.1. Step 1 - development of the HFACS-PV analytical structure

The first stage involves outlining the HFACS-PV structure (Fig. 2) to provide a systematic taxonomy for identifying HOFs associated with marine accidents. HFACS-PV extends the traditional HFACS framework by incorporating preconditions and violation categories relevant to complex socio-technical systems such as maritime operations. The framework organizes accident factors into hierarchical levels representing different layers of the maritime operational system:

- Organizational Factors including resource management, organizational climate, and organizational processes.
- Unsafe Supervision including inadequate supervision, planned inappropriate operations, and failure to correct known problems.
- Preconditions for Unsafe Acts including technological or interface malfunctions and substandard team member conditions.
- Unsafe Acts comprising operator errors and violations.
- Operational Conditions including both internal and external environmental conditions influencing operations.

This hierarchical structure reflects the interaction between latent organizational conditions and active operational failures, consistent with contemporary accident causation theories in high-risk industries.

2.1.2. Step 2 - application of HFACS-PV to marine accident data

In the second stage, the HFACS-PV framework is applied to a dataset of marine accident investigation reports. Each accident case is systematically reviewed to extract contributing factors described in official reports or investigative records. Identified causal elements are coded and categorized according to the predefined HFACS-PV taxonomy. This process transforms qualitative accident narratives into structured analytical data, enabling consistent classification of contributing factors across multiple accident cases. The structured dataset forms the empirical basis for identifying recurrent human and organizational factors involved in maritime accidents.

2.1.3. Step 3 - identification of human and organizational factors

Following classification, the most significant HOFs contributing to accident occurrence are identified. These factors represent recurring causal elements across accident cases and may include issues such as inadequate training, poor communication, fatigue, equipment interface problems, or ineffective supervision. Identifying these factors allows the analysis to move beyond individual accident descriptions and toward recognizing systemic patterns influencing safety performance within maritime operations.

2.1.4. Construction of the Bayesian Network model

In the fourth stage, a BN model is developed to represent the causal relationships between the identified human and organizational factors. A BN is a directed acyclic graph in which nodes represent risk factors or accident variables and directed edges represent probabilistic causal relationships Parent nodes represent influencing factors, while child nodes represent outcomes affected by those factors. Conditional Probability Tables (CPTs) are used to quantify the strength of relationships between nodes. The BN model enables probabilistic inference, allowing the estimation of accident likelihood under different combinations of contributing factors and the identification of critical risk pathways within the maritime operational system.

Several step-by-step procedures exist for constructing BN models, helping ensure consistency, reliability, and confidence in the final model. While procedures may vary depending on the context and available data (Loughney and Wang, 2018), they generally follow common steps:

1. *Define the domain and project scope* – Establish model boundaries, such as representing a sequence of events within a system or environment (e.g., maritime environment), starting from an initial event or events and ending in major consequences.
2. *Identify objectives* – Specify the model's intended outcomes; here, the focus is on component interactions and their probabilities.
3. *Select relevant variables* – Determine parameters pertinent to the problem, initially guided by a sequence-of-events diagram or

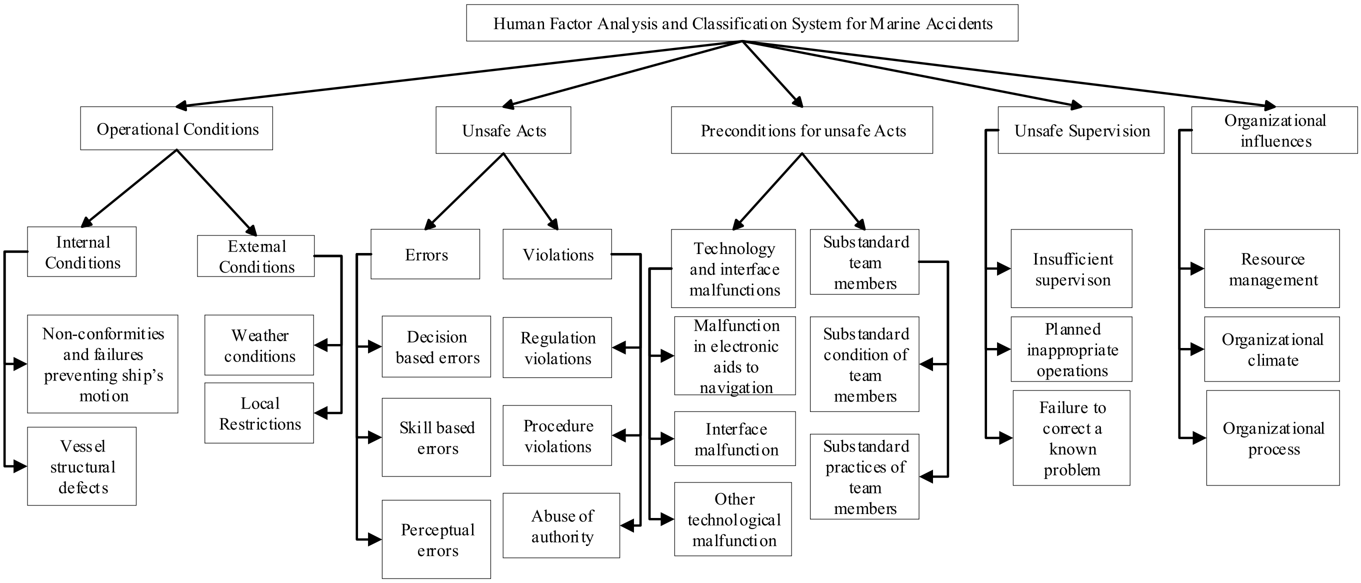

Fig. 2. HFACS-PV structure (Uğurlu et al., 2018).

framework, such as HFACS-PV, keeping the number of nodes manageable.

4. *Create nodes* – Refine the list of variables into model nodes based on literature review, available data and subjective data should there be gaps in objective data.
5. *Establish arcs* – Connect nodes in BN software (BayesFusion's GeNIe (academic version)) according to causal sequences, ensuring no factors are omitted.
6. *Populate probability tables* – Gather data from experts, literature, industrial projects/reports, and databases to construct marginal and conditional probability tables.
7. *Analyse the model* – Use BN software to run simulations and test for inconsistencies by inserting evidence.
8. *Validate the BN* – Apply a three-axiom validation procedure to ensure robustness: (i) small changes in parent node probabilities produce corresponding changes in child nodes, (ii) influence magnitudes of parents on children remain consistent, and (iii) combined influences of multiple parent attributes exceed those of subsets.

This structured methodology provides a systematic framework for developing, testing, and validating BN models while maintaining clarity and confidence in the results. This process is applied to the HFACS-PV result and used to allocate nodes and generate the Bayesian Network in Figs. 3 and 4.

2.1.5. Development of safety recommendations

The final stage involves interpreting the BN results to generate evidence-based safety recommendations. By analysing the probabilistic influence of different factors on accident occurrence, the framework identifies critical areas where interventions can most effectively reduce risk. Recommendations may address improvements in organizational policy, training programs, supervision practices, operational procedures, or technological interfaces. Through this approach, the framework supports proactive maritime safety management by enabling stakeholders to prioritize interventions targeting the most influential human and organizational risk factors.

2.2. Applicability of the framework

The proposed framework is designed to be applicable across a wide range of marine accident types and operational environments. As maritime operations generally involve human decision-making, supervision, and organizational management structures, the HFACS-PV taxonomy provides a transferable basis for analysing accidents regardless of vessel type, geographic region, or regulatory context. Furthermore, the probabilistic nature of BNs allows the integration of region-specific operational conditions, such as weather patterns or traffic density, enabling the framework to adapt to different maritime environments while maintaining its core analytical structure.

Fig. 1 illustrates the proposed research framework integrating the HFACS-PV with BN modelling to investigate marine accidents involving human and organizational factors. The framework begins with the development of the HFACS-PV structure, which categorizes accident causes into hierarchical levels including organizational factors, unsafe supervision, preconditions for unsafe acts, unsafe acts, and operational conditions. Accident investigation data are then analysed and classified according to this taxonomy, enabling the identification of key HOFs contributing to accident occurrence. These factors are subsequently incorporated into a BN model, where nodes represent causal variables and directed links represent probabilistic dependencies between them. The BN model captures the relationships between latent organizational failures, supervisory deficiencies, operational conditions, and frontline human errors. Model validation is conducted using accident case studies to ensure that the network accurately reflects real-world operational scenarios.

Finally, the probabilistic analysis produced by the BN model supports the development of targeted safety recommendations aimed at reducing accident risk. The framework provides a systematic approach for analysing marine accidents and identifying critical safety interventions across different vessel types, operational contexts, and geographical locations.

3. Application of methodology to a case study: the DOVER Strait

3.1. Human factor analysis and classification system for passenger vessels (HFACS-PV)

Uğurlu et al. (2018) applied HFACS to 70 collision and contact accidents involving passenger vessels but found the traditional structure inadequate for this context. To address this limitation, they developed a modified framework, the Human Factors Analysis and Classification System for Passenger Vessels (HFACS-PV), specifically designed to analyse human factors in passenger vessel accidents. The HFACS-PV model comprises five primary levels: Operational Conditions, Unsafe Acts, Preconditions for Unsafe Acts, Unsafe Supervision, and Organizational Influences. The key distinction from the conventional HFACS is the addition of Operational Conditions, which account for environmental and situational factors. Each accident is associated with at least one operational condition, which, rather than directly influencing unsafe actions, serves a complementary role by enabling or amplifying unsafe behaviours that lead to accidents. Accordingly, these environmental elements are analysed independently from the preconditions for unsafe acts. A summary of the HFACS-PV structure and its hierarchical levels is presented in Fig. 2, while detailed explanations of the framework can be found in Uğurlu et al. (2018) and Yildiz et al. (2021).

This study evaluates the applicability of the HFACS-PV and BN Research framework outlined in Fig. 1, by applying the methodology to marine accidents in the Dover Strait (DS). The methodology, shown in Fig. 1, consists of six sequential steps. Step 1 provides descriptive information on the HFACS-PV structure to ensure clarity and understanding. Step 2 applies the HFACS-PV framework to grounding and collision/contact accidents in the DS between 2004 and 2020, excluding sinking incidents due to the occurrence of only a single case during the study period. Unlike conventional HFACS models, HFACS-PV comprises five hierarchical levels, with the primary modification being the inclusion of environmental factors (Operational Conditions). This fifth level captures how environmental conditions contribute to transforming unsafe acts into accidents. Step 3 involved the analysis of marine accidents. In this analysis ground in and collision accidents are utilised as they have been determined to be most common accident consequences in narrow waterways, such as the Dover Strait (Yildiz et al., 2022b; Loughney et al., 2023). In this geographical area, 17 grounding and 10 collision/contact accidents in the DS between 2004 and 2020 to identify human and organizational factors (HOFs) using the HFACS-PV framework. In Step 4, these identified HOFs are used to develop a BN model structured according to HFACS-PV. Step 5 tested the BN using two case studies: one grounding and one collision incident. Finally, Step 6 generated recommendations based on the accident analysis. Accident reports were sourced from multiple investigation bodies, including the IMO's Global Integrated Shipping Information System (GISIS), the European Maritime Safety Agency (EMSA), the Marine Accidents Investigation Department (Romania), the Maritime and Railway Accident Investigation Authority (Bulgaria), the Marine Accident Investigation Branch (UK), and the Lloyd's Register database.

3.2. Application of HFACS-PV to accidents in the Dover Strait

The HFACS-PV framework (Fig. 2) was applied to 17 grounding and 10 collision/contact accidents in the Dover Strait occurring between 2004 and 2020. Sinking accidents were excluded due to the presence of only a single case during this period. Data on these incidents were obtained from multiple accident databases, primarily the IMO's GISIS and the UK's Marine Accident Investigation Branch (MAIB). Each accident report was carefully examined to identify the human and organizational factors contributing to the accidents, following the HFACS-PV methodology.

3.2.1. Grounding accidents

17 grounding accidents in the Dover Strait were analysed using the HFACS-PV framework. Each accident report was carefully examined to identify human-error-related root causes, and the results were aggregated to highlight the most significant HFACS-PV categories. Table 1 presents the full distribution of categories and subcategories. The number of grounding accidents (17) is the denominator by which the frequency values are calculated. Analysis of Table 1 shows that Unsafe Acts: Errors were present in 29.5% of grounding accidents, followed by Preconditions for Unsafe Acts: Substandard Team Members at 18.2%. Within the Errors category, 70.6% were Decision-Based Errors, 58.8% were Perceptual Errors, and only 23.5% were Skill-Based Errors, indicating that errors related to crew skill level were less significant. The findings highlight that perceptual and decision-making errors by the bridge team account for over two-thirds of grounding accidents. Further examination of Substandard Team Members reveals that Substandard Practices of Team Members occurred in 64.7% of cases, while Substandard Condition of Team Members was implicated in 29.4%. The three leading contributors to grounding accidents are therefore:

- Decision-Based Errors – 70.6%
- Substandard Practices of Team Members – 64.7%
- Perceptual Errors – 58.8%

These results emphasize the critical role of the bridge team's conduct and practices in the preconditions leading to grounding accidents. The next most frequent factor was External Conditions: Weather (52.9%). The observed patterns align with previous literature, which identifies fatigue, distractions, and external influences as key causes of grounding or collision/contact accidents (Akhtar and Utne, 2014; Uğurlu, et al., 2015; Yildirim et al., 2017, 2019). Similarly, teammate influence and task deviation are consistent with the identified substandard practices of team members as major root causes.

3.2.2. Collision/contact accidents

Collision and contact accidents were analysed using the same HFACS-PV methodology applied to grounding incidents (Section 3.2.1). Table 2 presents the percentage occurrence of preconditions for 10 collision/contact accidents in the Dover Strait. The number of collision/contact accidents (10) is the denominator by which the frequency values are calculated. As shown in Table 2, Unsafe Acts: Errors were the most frequent precondition, occurring in 24.1% of cases, mirroring the pattern observed in grounding accidents. The next most influential factor is Internal Conditions, occurring in 13.8% of accidents. Examination of subcategories highlights the following key contributors:

- **Unsafe Acts: Errors (24.1%)**
    - Decision-Based Errors: 70%
    - Skill-Based Errors: 40%
    - Perceptual Errors: 30%
- **Internal Conditions (13.8%)**
    - Non-Conformities and Failures to Prevent Ship Motion (60%)
    - Vessel Structural Defects (20%)

As with grounding accidents, errors in perception and decision-making by the bridge team were central to collision/contact incidents. The prominence of procedural violations further emphasizes the critical need for the bridge team to correctly identify nearby vessels, make timely avoidance decisions, and execute proper procedures. Other contributing preconditions, although less frequent, also play a role:

- **Substandard Team Members (12.1%)**
- **Violations (12.1%)**: Procedure Violations - 30%
- **External Conditions (10.3%)**: Weather Conditions - 40%

These findings indicate that collision/contact accidents typically result from a combination of multiple preconditions. Examples include harsh weather coupled with electronic navigation failures or lapses in bridge team awareness combined with procedural non-compliance. This complexity aligns with previous studies highlighting the interplay of human, environmental, and technological factors in maritime accidents (Uğurlu et al., 2018; Yildiz et al., 2021). The full distribution of

Table 1

Distribution of HFACS-PV Categories for 17 recorded Grounding accidents.

Level 1 (L1)	Level 2 (L2)	Level 3 (L3)	Total	f/acc.[a]	f/acc. (%)	Tot/L2 category[b]	% dis. Per category[c]
Operational Conditions	Internal Conditions	Non-Conformities and Failures to Prevent Ship Motion	6	0.35	35.3%	7	8.0%
		Vessel Structural Defects	1	0.06	5.9%		
	External Conditions	Weather Conditions	9	0.53	52.9%	12	13.6%
		Local Restrictions	3	0.18	17.6%		
	Organizational Influences	Resource Management	2	0.12	11.8%	8	9.1%
		Organisational Climate	2	0.12	11.8%		
		Organisational Processes	4	0.24	23.5%		
	Unsafe Supervision	Insufficient Supervision	1	0.06	5.9%	7	8.0%
		Planned Inappropriate Operations	1	0.06	5.9%		
		Failure to Correct a Known Problem	5	0.29	29.4%		
Preconditions for Unsafe Acts	Technology and Interface Malfunctions	Malfunction in the Electronic Nav Aids	2	0.12	11.8%	4	4.5%
		Interface Malfunction	0	0.00	0.0%		
		Other Tech. Malfunctions	2	0.12	11.8%		
	Substandard Team Members	Conditions of Team Members	5	0.29	29.4%	16	18.2%
		Practices of Team Members	11	0.65	64.7%		
Unsafe Acts	Errors	Decision Based Errors	12	0.71	70.6%	26	29.5%
		Skill Based Errors	4	0.24	23.5%		
		Perceptual Errors	10	0.59	58.8%		
	Violations	Regulation Violations	1	0.06	5.9%	8	9.1%
		Procedure Violations	4	0.24	23.5%		
		Abuse of Authority	3	0.18	17.6%		
						88	100%

[a] Occurrence frequency of HFACS-PV Level 3 categories per accident.

[b] Total number of HFACS-PV Level 2 category occurrences.

[c] Percentage distribution of HFACS-PV Level 2 category occurrences across all accidents.

Table 2
Distribution of HFACS-PV Categories for 10 recorded Collision/Contact accidents.

Level 1	Level 2	Level 3	Total	Freq./acc.[a]	Freq./acc. (%)	Tot/L2 category[b]	% dis. Per category[c]
Operational Conditions	Internal Conditions	Non-Conformities and Failures to Prevent Ship Motion	6	0.60	60.0%	8	13.8%
		Vessel Structural Defects	2	0.20	20.0%		
	External Conditions	Weather Conditions	4	0.40	40.0%	6	10.3%
		Local Restrictions	2	0.20	20.0%		
	Organizational Influences	Resource Management	1	0.10	10.0%	6	10.3%
		Organisational Climate	2	0.20	20.0%		
		Organisational Processes	3	0.30	30.0%		
	Unsafe Supervision	Insufficient Supervision	1	0.10	10.0%	4	6.9%
		Planned Inappropriate Operations	1	0.10	10.0%		
		Failure to Correct a Known Problem	2	0.20	20.0%		
Preconditions for Unsafe Acts	Technology and Interface Malfunctions	Malfunction in the Electronic Nav Aids	1	0.10	10.0%	6	10.3%
		Interface Malfunction	1	0.10	10.0%		
		Other Tech. Malfunctions	4	0.40	40.0%		
	Substandard Team Members	Conditions of Team Members	4	0.40	40.0%	7	12.1%
		Practices of Team Members	3	0.30	30.0%		
Unsafe Acts	Errors	Decision Based Errors	7	0.70	70.0%	14	24.1%
		Skill Based Errors	3	0.30	30.0%		
		Perceptual Errors	4	0.40	40.0%		
	Violations	Regulation Violations	2	0.20	20.0%	7	12.1%
		Procedure Violations	3	0.30	30.0%		
		Abuse of Authority	2	0.20	20.0%		
						58	100%

[a] Occurrence frequency of HFACS-PV Level 3 categories per accident.
[b] Total number of HFACS-PV Level 2 category occurrences.
[c] Percentage distribution of HFACS-PV Level 2 category occurrences across all accidents.

HFACS-PV categories and subcategories for collision/contact accidents is provided in Table 2.

3.3. Development of the dynamic Bayesian Network for accident evaluation in the Dover Strait

This study is an accident analysis that examines marine accidents that have occurred in the Dover Strait, between 2004 and 2020. In this context, a total of 37 marine accidents were taken as the data set to be used in the study. In all these accidents, at least one of the ships involved is subject to IMO regulations (vessels of 500 gross tonnage and above). In this study, only grounding and collision/contact were analysed for the Dover Strait as there was only 1 sinking accident in this area in the time frame under investigation. The steps outlined in Section 2.1.4 have been applied sequentially to develop the BN. The framework and process in Fig. 3 demonstrates the transition from HFACS-PV to BN.

3.3.1. Gathering the accident data and choosing the appropriate method for accident analysis

The dataset for this study encompasses all recorded marine accidents in the region between 2004 and 2020. According to the IMO (2008) and MAIB (2013), a serious marine casualty involves total vessel loss, fatalities, major environmental damage, severe structural or accommodation damage, main engine immobilization, pollution, or breakdowns requiring external assistance. Conditional Probability Tables (CPTs) were constructed using data from the compiled accident database and supplemented with expert judgment for nodes lacking sufficient data. The identified nodes and CPTs were then modelled in BayesFusion's GeNIe (academic version). The completed Bayesian Network (BN), verified for completeness, is presented in Fig. 4.

Expert opinions were gathered through online surveys to validate model assumptions and refine conditional relationships. Participants received a briefing on the study's scope, dataset, and objectives prior to providing input on hazards and safety measures within the Dover Strait. The HFACS-PV analysis results were shared with experienced ocean-going master's familiar with the Dover Strait. Expert opinions were collected through individual online interviews, during which participants were provided with detailed information about the study's objectives, dataset, and scope. The analysis outcomes were presented for interpretation, with a focus on understanding the influence of operational conditions on accident formation in high-risk areas. Experts also provided insights on existing hazards and the effectiveness of current safety measures in the DS. Based on their feedback, practical recommendations were developed to mitigate or manage operational risks in narrow waterways. Table 3 summarizes expert backgrounds, which include:

- Oceangoing Masters (3) – 10–20 years of sea service, 20–30 Dover Strait transits.
- VTS Operators (5) – Certified masters with 5–13 years at sea and over 3 years VTS experience; 10–100 transits, one holding Chief Officer competency.
- Maritime Pilots (3) – All masters with 10–20+ years' experience and 10–20+ transits through the Strait.
- ITUBOA Official (1) – Former pilot with over 30 years' experience and 20+ Dover Strait transits.
- Maritime Faculty Members (2) – PhD-qualified academics with 5–15 years of sea experience and extensive research backgrounds in maritime safety and accident analysis; 20–50 transits each.

3.3.2. Application of the BN model for the Dover Strait

The BN model developed for the Dover Strait was validated using two case studies: one grounding and one collision accident. For each case, known pre-accident information was input into the BN to calculate the initial consequence probabilities. Subsequently, information revealed during the accidents, representing data that should have been known or communicated beforehand, was incorporated to assess changes in these probabilities. This approach enabled evaluation of the BN's performance under realistic, time-dependent conditions, thereby testing its validity and responsiveness to evolving operational scenarios.

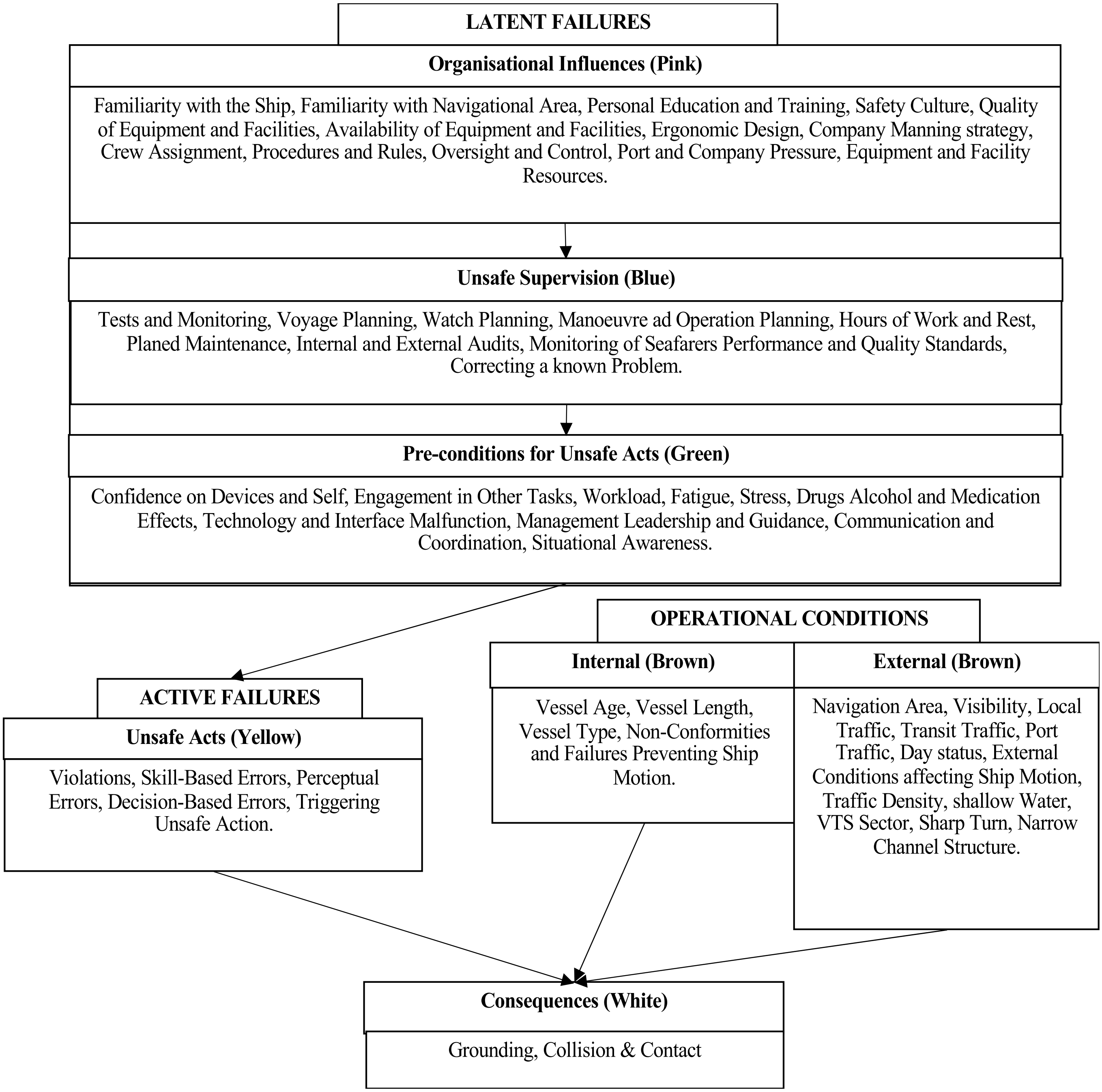

Fig. 3. Structure of HFACS-PV for transition to the BN structure. (The colour in parentheses corresponds to that of the label in the Bayesian Network in Fig. 4.)

4. Analysis and discussion

4.1. Grounding case study – Ovit (tanker)

4.1.1. Narrative

In the early hours of September 18, 2013, the Malta-registered tanker Ovit was transiting the Dover Strait en route from Rotterdam (Netherlands) to Brindisi (Italy) with a cargo of vegetable oil. The vessel's passage plan, prepared using the Electronic Chart Display and Information System (ECDIS), guided the transit. At 02:30, the chief officer relieved the second officer as Officer of the Watch (OOW), accompanied by a deck cadet serving as lookout. Ovit maintained an autopilot-controlled heading of 206° at 12–13 knots, with the OOW monitoring both the ECDIS and radar displays from the port bridge chair. Around 03:00, the heading was adjusted to 225°. As the vessel neared Varne Bank, the deck cadet observed flashing white lights ahead but failed to identify or report them. At approximately 04:17, Ovit passed close to the Varne Light Float, and by 04:34, after a gradual speed reduction, grounded on the Varne Bank (MAIB, 2013a).

4.1.2. BN analysis: grounding

Pre-voyage data were entered into the BN to assess their influence on consequence nodes. As shown in Table 4, the probabilities of contact, collision, and grounding increased by 4%, 5%, and 4%, respectively, when pre-voyage information was applied. This suggests that while the crew possessed sufficient information for an elevated risk of grounding, the magnitude of change was minor, indicating that grounding was not initially a dominant consequence. The relatively higher collision probability reflects deficiencies in voyage planning, captured by the node "Voyage Planning - Unsafe." Although grounding remained an unlikely

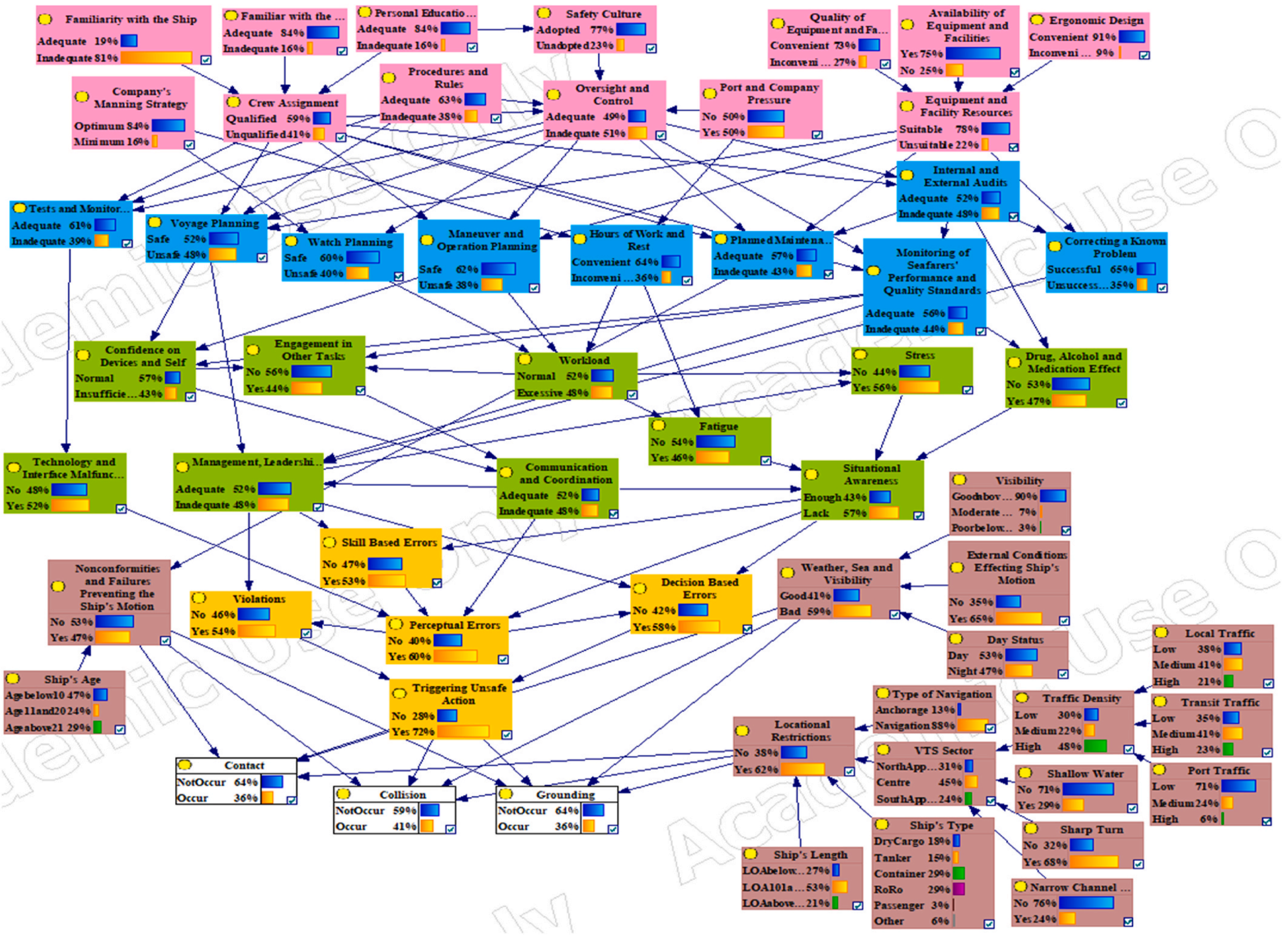

Fig. 4. BN model developed from the HFACS-PV analysis for the Dover Strait.

Table 3
Experts and demographics.

No.	Current rank	Experience in current rank (Years)	Previous sea service Total (Years)	Last competency	Experience master (Months)	Total number of passages through DS
1	FM	8	15	OM	4	>50
2	FM	9	7	OM	11	>20
3	OM	5	12	OM	70	>30
4	VTSO	3	13	OM	24	>90
5	OM	8	14	OM	96	>20
6	OM	6	10	OM	72	>30
7	VTSO	1	5	COO	-	>20
8	MP	3	12	OM	48	>20
9	VTSO	3	7	OM	-	>10
10	VTSO	6	12	OM	72	>15
11	MP	9	8	OM	36	>10
12	VTSO	2	14	OM	72	>100
13	MP	16	20	OM	108	>20
14	ITUBOA	30	30	OM	120	>20

outcome based on pre-accident data, several overlooked factors contributed to the event. The planned track across Varne Bank demonstrated that the route, prepared by the third officer, was unsafe and inadequately verified. His method, zooming in on individual ECDIS legs to identify hazards, was simplistic and prone to oversight. A comprehensive ECDIS validation process would have revealed the danger of crossing the Varne Bank. This oversight underscores deficiencies in planning and situational awareness, as compliance with safe voyage planning is fundamental to navigational safety. While the third officer was qualified and ECDIS-trained, the complexity of this passage required greater supervision and review. Furthermore, although Ayder Tankers Ltd had procedures for defect reporting, no records indicated that the inoperative audible alarm on Ovit's ECDIS had been reported. These shortcomings are reflected in the BN through the nodes “Correcting a Known Problem - Unsuccessful” and “Planned Maintenance - Inadequate.”

Table 5 presents the consequence likelihood with the two nodes “Ship type” and “Ship age” removed. The rationale behind this is that the

Table 4
Ovit grounding - pre-accident information.

Node	Node State	No Evidence	Evidence	Change
Organisational Influences - Cause				
Familiarity with the Ship	Adequate	19%	100%	81%
Personnel Education and Training	Adequate	84%	100%	16%
Quality of Equipment and Facilities	Convenient	73%	100%	27%
Availability of Equipment and Facilities	Yes	76%	100%	24%
Company's Manning Strategy	Optimum	84%	100%	16%
Unsafe Supervision - Cause				
Voyage Planning	Unsafe	48%	100%	52%
Watch Planning	Safe	60%	100%	40%
Correcting a Known Problem	Unsuccessful	35%	100%	65%
Planned Maintenance	Inadequate	43%	100%	57%
Internal and External Audits	Adequate	52%	100%	48%
Preconditions for Unsafe Acts - Cause				
Stress	Yes	56%	100%	44%
Communication and Coordination	Inadequate	48%	100%	52%
Operational Conditions (Vessel, Navigation and Weather Information) - Cause				
Navigational Area	Navigation	88%	100%	12%
VTS Sector	Northern Approach	31%	100%	69%
Ship type	Tanker	15%	100%	85%
Ship Length	LOA101-200m	53%	100%	47%
Ship age	Below 10years	47%	100%	53%
Visibility	Good above5nm	90%	100%	10%
External Conditions Affecting Ship Motion	No	35%	100%	65%
Local Traffic	Low	38%	100%	62%
Transit Traffic	Low	35%	100%	65%
Port Traffic	Low	71%	100%	29%
Sharp turn	No	32%	100%	68%
Narrow Channel	No	76%	100%	24%
Shallow Water	Yes	29%	100%	71%
Consequence - Effect				
Contact	Occur	36%	40%	4%
Collision	Occur	41%	46%	5%
Grounding	***Occur***	***36%***	***40%***	***4%***

Table 5
Ovit Grounding Pre-Accident Grounding consequence – without ship type and age.

Node	Node State	No Evidence	Evidence	Change
Grounding	Occur	36%	54%	18%

type and age of a vessel do not necessarily determine the likelihood of a collision. Groundings are generally the result of human error or uncontrollable external effects, such as heavy weather. These two nodes remain in the BN as they influence the likelihood of sinking accidents. For instance, an oil tanker might have a double hull, or the hull in an older vessel might have compromised structural integrity; these affect the likelihood of sinking. These nodes are parent nodes that effect child nodes but do not solely influence the child node. The child nodes in question are “Nonconformities and Failures Preventing Ship's Motion” and “Local Restrictions”. In the Dover Strait vessel age and type are not a vital consideration given the navigation area. It can be seen from Table 5 that these two nodes (“ship age” and “type”) have a great effect on the consequence nodes as the magnitude of change for a grounding increase from 4% to 18%. Having this information at the pre-accident stage for the Ovit vessel would raise massive cause for concern and could potentially lead to the mitigation of the accident, as the issues of inadequate voyage planning and maintenance as well as the failure to correct a known problem (audible alarm in the ECDIS) could be addressed.

Table 6 shows the nodes and states that have been updated considering information known to the Ovit crew and the shipping company that was not highlighted or reported prior to the accident but should have been. Similarly, the Unsafe Acts have been updated based on the human behaviour during the voyage. Under organisational influences the nodes “Personnel Education and Training”, “Quality of Equipment

Table 6
Ovit grounding - post-accident information.

Nodes	Node State	No Evidence	Evidence	Change
Organisational Influences - Cause				
Familiarity with the Ship	Adequate	19%	100%	81%
Personnel Education and Training	*Inadequate*	*16%*	*100%*	*84%*
Quality of Equipment and Facilities	*Inconvenient*	*27%*	*100%*	*73%*
Availability of Equipment and Facilities	Yes	76%	100%	24%
Company's Manning Strategy	Optimum	84%	100%	16%
Familiarity with Navigational Area	*Inadequate*	*16%*	*100%*	*84%*
Unsafe Supervision - Cause				
Voyage Planning	Unsafe	48%	100%	52%
Watch Planning	Safe	60%	100%	40%
Correcting a Known Problem	Unsuccessful	35%	100%	65%
Planned Maintenance	Inadequate	43%	100%	57%
Internal and External Audits	*Inadequate*	*48%*	*100%*	*52%*
Preconditions for Unsafe Acts - Cause				
Stress	Yes	56%	100%	44%
Communication and Coordination	Inadequate	48%	100%	52%
Situational Awareness	*Lack*	*57%*	*100%*	*43%*
Management, Leadership and Guidance	*Inadequate*	*58%*	*100%*	*42%*
Confidence on Devices and Self	*Insufficient*	*43%*	*100%*	*57%*
Unsafe Acts - Cause				
Perceptual Error	*Yes*	*60%*	*100%*	*40%*
Decision Based Error	*Yes*	*58%*	*100%*	*42%*
Skill Based Error	*Yes*	*53%*	*100%*	*47%*
Operational Conditions (Vessel, Navigation and Weather Information) - Cause				
Navigational Area	Navigation	88%	100%	12%
VTS Sector	Northern Approach	31%	100%	69%
Ship type	Tanker	15%	100%	85%
Ship Length	LOA101-200m	53%	100%	47%
Ship age	Below 10years	47%	100%	53%
Visibility	Good above5nm	90%	100%	10%
External Conditions Affecting Ship Motion	No	35%	100%	65%
Local Traffic	Low	38%	100%	62%
Transit Traffic	Low	35%	100%	65%
Port Traffic	Low	71%	100%	29%
Sharp turn	No	32%	100%	68%
Narrow Channel	No	76%	100%	24%
Shallow Water	Yes	29%	100%	71%
Consequence - Effect				
Contact	Occur	36%	43%	7%
Collision	Occur	41%	49%	8%
Grounding	***Occur***	***36%***	***43%***	***7%***

and Facilities" and "Familiarity with Navigational Area" have all been updated with observed evidence in a negative manner (Inadequate, Inconvenient, and Inadequate respectively). This is to highlight several issues that were revealed after the accident.

The issue with training relates to the fact that while ECDIS training was undertaken by the ship's master and deck officers, it had not equipped them with the level of knowledge necessary to operate the system effectively. While their training satisfied the requirements of STCW and ISM, they were unaware of the importance of critical safety settings and the significance of the system's alarms. The training which the ship's officers had attended was apparently either ineffective, insufficient, or both. Furthermore, given that it was discovered that the voyage was poorly planned, and despite the route being checked, the fact that it passed over the shallow Varne bank was not identified as an issue, indicating a lack of knowledge of the navigation area. This is further reinforced by the fact that the passage through the Dover Strait was treated in exactly the same way as a passage in open water, and although the lights from the cardinal buoys marking the Varne Bank were seen by the lookout, they were not reported. It was also further clarified that following the accident that the ECDIS audible alarm was inoperative, and the crew were aware of this defect but didn't report it.

Under Unsafe Supervision one node has been updated with evidence: "Internal and External Audits – Inadequate". The serious issues with the navigation in terms of the master's lack of familiarisation with ECDIS and the lack of an audible alarm in ECDIS were not identified during the vessel's audits and inspections. What is also a concern is that a detailed Ship Inspection Report Programme (SIRE) occurred 10 days before the grounding but did not identify the crew's lack of competence in using ECDIS, or the significant defect with its audible alarm. Continuing through the analysis, three nodes are updated under Preconditions for Unsafe Acts: "Situational Awareness - Lack", "Management, Leadership and Guidance - Inadequate" and "Confidence on Devices and Self - Insufficient". The latter of these three nodes relates to the master's lack of confidence in utilising the ECDIS system as well as the highlighted onboard dysfunctional management and the lack of sufficient leadership by the master. Thus, it was very difficult for safety culture to be developed and instilled on the master's bridge. The node "Situational Awareness" is updated as the chief officer did not know that the vessel had grounded. It was only when an engineering alarm sounded, he became aware that something was wrong. Even then, it is evident that he thought that the ship halted due to a machinery issue.

Under Unsafe Acts three nodes are updated: "Perceptual Error", "Decision-Based Error" and "Skill Based Error", all as "Yes". This means all errors of these types have been observed or have occurred and have led to the development of the accident. Decision and Perceptual errors are related to the actions of a number of crew members. For example, the chief officer did not check the route ahead to identify potential navigational hazards or the navigational marks that may be encountered during their watch. Thus, the chief officer was unaware that the vessel's route passed over the shallow Varne bank. There was also level of ignorance related to the identification of the cardinal marks indicating the dangers. Similarly, the east and west cardinal marks were visible at a range of 5 nm. These could potentially have been seen by the OOW and the lookout approximately 25 min the grounding. This is deemed to be enough time in which to identify the buoys, highlight the error in the passage plan, and take corrective action.

After including all the evidence, the BN and Table 6 show a 7% increase in the likelihood of grounding, rising from 36% to 43%. This increase reflects the magnitude of change due to the inclusion of post-accident information that could have been addressed and reported beforehand. Although this is not a substantial increase, removing vessel age and type from the analysis, since they have limited impact on groundings, reveals a significant rise in the likelihood of a grounding incident, as shown in Table 7. In this case, the likelihood jumps from 36% to 59%, a 23% increase. This is a significant increase in the occurrence likelihood and one that could have influence on the operation and management of the vessel to address some if not all of the highlighted issues that ultimately led to the grounding of the Ovit Tanker.

Table 7
Ovit Grounding Post-Accident Consequences - without ship type and age.

Nodes	Node State	No Evidence	Evidence	Change
Grounding	Occur	36%	59%	23%

4.2. Collision case study – Saga Sky (general cargo) and Stema Barge II (barge)

4.2.1. Narrative

In the early hours of November 20, 2016, Saga Sky was transiting the south-west lane of the Dover Strait when weather conditions deteriorated sharply. Strong headwinds and opposing tidal streams reduced the vessel's speed to 7.2 knots through the water and 5 knots over ground. As conditions worsened to severe gale force 9, with gusts reaching 80 knots, the master increased engine speed to counter reduced headway. However, heavy pitching and the ship's ballast condition caused the propeller to lift clear of the water, leading to engine overspeed and shutdown (MAIB, 2013). Following this, the Coastguard Operations Centre authorised the master to turn into the inshore traffic lane to mitigate loss of propulsion. Despite this, the combined force of wind acting on the aft superstructure and cranes overwhelmed the rudder lift, preventing the turn from being completed. Consequently, Saga Sky maintained a west-north-westerly heading while drifting northwards toward the coast under the influence of wind and sea. Nearby, Stema Barge II was also affected by the same severe weather and lay between Saga Sky and the coast. Although the master of Saga Sky had considered anchoring earlier, the prevailing conditions were deemed unsafe. In a final attempt to avoid collision, the port anchor was deployed to its full length of 11 shackles, followed by the starboard anchor. Despite these efforts, at approximately 08:50 Saga Sky collided with Stema Barge II and issued a "Mayday" at 08:56. The two vessels subsequently remained locked together and ceased drifting (MAIB, 2013).

4.2.2. BN analysis: collision – perspective of Saga Sky

As with the grounding case study, the pre-voyage information is input into the BN to highlight the changes to the consequence nodes. It can be seen from Table 8 that the consequences of contact, collision and grounding all decrease by a change of 10%, for all consequence likelihoods. Thus, it can be assumed that the information that the crew of the Saga Sky had was sufficient that a collision was of a decreased likelihood and the collision consequence was not significant.

Given the information in Table 8, there are four known factors that the crew were aware of and could plan for in relation to grounding or collision. These are the time of day, indicated by the node "Day Status – Night", the harsh weather indicated by the node "External Conditions Affecting Ship Motion – Yes", the water depth shown by the node "Shallow Water – Yes", and "Visibility – Poor, less than 2Nm". However, it should be noted that the prior probability for collision is much greater than that of contact or grounding due to the harsh weather during the night.

Weather forecasts along Saga Sky's intended route had warned of a developing low-pressure system bringing strong to near-gale force winds across the English Channel. Subsequent updates predicted further deterioration, with the 00:15 forecast on 20 November indicating south-westerly severe gale force 9 to violent storm force 11 conditions, accompanied by very rough to high seas. Company guidelines for heavy weather navigation required proper route planning based on forecast conditions and mandated weather updates at intervals not exceeding 6 h. Despite these advisories, the master did not sufficiently adjust the voyage plan in response to the worsening weather, leaving the vessel vulnerable to being overpowered by the storm. This lack of action is

Table 8
Saga sky pre-accident information.

Nodes	Node State	No Evidence	Evidence	Change
Organisational Influences - Cause				
Familiarity with Ship	Adequate	19%	100%	81%
Company Manning Strategy	Optimum	84%	100%	16%
Familiarity with Navigation Area	Adequate	84%	100%	16%
Personnel Training & Education	Adequate	84%	100%	16%
Port & Company Pressure	No	50%	100%	50%
Availability of Equipment	No	25%	100%	75%
Quality of Equipment	Convenient	73%	100%	27%
Operational Conditions (Vessel, Navigation and Weather Information) - Cause				
Type of Navigation	Navigation	88%	100%	12%
VTS Sector	Northern Approach	31%	100%	69%
Ship type	Dry Cargo	15%	100%	85%
Ship Length	LOA101-200m	53%	100%	47%
Ship age	Below 10years	47%	100%	53%
Local Traffic	Low	38%	100%	62%
Transit Traffic	Low	35%	100%	65%
Port Traffic	Low	71%	100%	29%
Sharp turn	No	32%	100%	68%
Narrow Channel	No	76%	100%	24%
Shallow Water	Yes	29%	100%	71%
External Conditions Affecting Ship Motion	Yes	65%	100%	35%
Visibility	Poor Less than 2 nm	3%	100%	97%
Day Status	Night	47%	100%	53%
Consequence - Effect				
Contact	*Occur*	*36%*	*26%*	*−10%*
Collision	*Occur*	*41%*	*31%*	*−10%*
Grounding	Occur	36%	26%	−10%

supported by the MAIB investigation findings and the vessel's ballast condition, which created an excessive windage area and reduced stability. Moreover, forecast data also warned of a secondary weather system expected to impact the vessel after its passage through the English Channel, further compounding the navigational risk.

Table 9 presents the consequence likelihood, for the Saga Sky, with the two nodes “Ship type” and “Ship age” removed. The reasoning for this is stated previously in the explanation of Table 5. With these two factors removed, and the focus being on the physical factors that affect the vessel, the likelihood of a collision decreases only slightly, from 41% to 40%.

Table 10 shows the nodes and states that have been updated considering information known to the Saga Sky crew and the shipping company that was not highlighted or reported prior to the accident. Under Unsafe supervision the nodes “Voyage Planning”, “Correcting a Known Problem” and “Manoeuvre and Operation Planning” have all been updated with observed evidence in a negative manner (Unsafe, Unsuccessful, and Unsafe respectively). This is to highlight issues that were revealed after the accident. Nodes under Preconditions for Unsafe Acts have also been updated, these are “Situational Awareness - Lack” and “Management, Leadership and Guidance - Inadequate”. Unsafe Acts have been updated based on the human behaviour during the voyage, these are perceptual and decision-based errors, both “Yes” indicating that they have been observed. It can be argued that given the information known to the crew on the Saga Sky, a collision was much more likely than possibly anticipated.

Under “Unsafe Supervision”, three nodes have been updated to reflect the behaviour of the master during the accident formation on the Saga Sky. all three of these nodes, Voyage Planning”, “Correcting a Known Problem” and “Manoeuvre and Operation Planning”, are related to the actions of the master in preparation and response to the weather forecast highlighting a severe gale 9 with potential to violent storm 11. It was determined during the handling of the vessel in the adverse weather conditions that, in the absence of vessel specific guidance, the masters were relying on their own knowledge and experience to navigate the storm. It also became apparent that the master was more focused on the second storm that would affect the vessel after leaving the English Channel, as previously mentioned. Thus, the voyage route was not changed, and the vessel continued on the passage instead of halting and

Table 9
Saga Sky Pre-Accident Collision consequence - without ship type and age.

Consequence - Effect - Without Vessel Type or Age				
Contact	*Occur*	*36%*	*36%*	*0%*
Collision	*Occur*	*41%*	*40%*	*−1%*
Grounding	Occur	36%	36%	0%

Table 10
Saga sky - post-accident information.

Saga Sky Collision - Post-Accident Information				
Nodes	Node State	No Evidence	Evidence	Change
Organisational Influences - Cause				
Familiarity with Ship	Adequate	19%	100%	81%
Company Manning Strategy	Optimum	84%	100%	16%
Familiarity with Navigation Area	Adequate	84%	100%	16%
Personnel Training & Education	Adequate	84%	100%	16%
Port & Company Pressure	No	50%	100%	50%
Availability of Equipment	Yes	73%	100%	27%
Quality of Equipment	Inconvenient	25%	100%	75%
Unsafe Supervision - Cause				
Voyage Planning	*Unsafe*	*36%*	*100%*	*64%*
Correcting a Known Problem	*Unsuccessful*	*41%*	*100%*	*59%*
Manoeuvre and Operation Planning	*Unsafe*	*17%*	*100%*	*83%*
Preconditions for Unsafe Acts - Cause				
Situational Awareness	*Lack*	*36%*	*100%*	*64%*
Management, Leadership and Guidance	*Inadequate*	*34%*	*100%*	*66%*
Unsafe Acts - Cause				
Perceptual Error	*Yes*	*46%*	*100%*	*54%*
Decision Based Error	*Yes*	*44%*	*100%*	*56%*
Operational Conditions (Vessel, Navigation and Weather Information) - Cause				
Type of Navigation	Navigation	88%	100%	12%
VTS Sector	Northern Approach	31%	100%	69%
Ship type	Dry Cargo	15%	100%	85%
Ship Length	LOA101-200m	53%	100%	47%
Ship age	Below 10years	47%	100%	53%
Local Traffic	Low	38%	100%	62%
Transit Traffic	Low	35%	100%	65%
Port Traffic	Low	71%	100%	29%
Sharp turn	No	32%	100%	68%
Narrow Channel	No	76%	100%	24%
Shallow Water	Yes	29%	100%	71%
External Conditions Affecting Ship Motion	Yes	65%	100%	35%
Visibility	Poor Less than 2 nm	3%	100%	97%
Day Status	Night	47%	100%	53%
Consequence - Effect				
Contact	*Occur*	*36%*	*47%*	*11%*
Collision	*Occur*	*41%*	*52%*	*11%*
Grounding	Occur	36%	47%	11%

seeking shelter until the storm had passed. Having decided to continue on the passage, there was a concern regarding the vessel's speed and eventually a decision was made to turn the ship to starboard and run with the weather until the storm abated. The rationale for this was for the master to maintain control of the ship and had relied on their knowledge of the manoeuvre having done this multiple times previously, in a different geographical area and in deeper waters. With shallow water of the Varne bank to the vessel's port, the only option was to turn starboard at this point.

The effect of the wind at this point had a major effect on the ship motion and it became apparent that the master should either heave to and/or deploy one or more of the anchors in order to address the vessel's rate of drift. Repeated attempts were made to turn the ship around to run with the prevailing winds, but these were unsuccessful. It was advised by the coast guard to deploy anchors, but the master felt it was too unsafe for the anchor handlers to operate on the forward deck. Efforts to turn the vessel around continued. At this point the collision with the *Stema Barge II* was imminent, with *Saga Sky* drifting at 9 knots. Following the continued delay from the master and their confidence to turn the ship, eventually tug assistance was requested by the master and the order to drop two anchors was given.

If severe weather impedes progress, good seamanship is to heave-to and ride out the storm. It can also include deploying one or more anchors to supplement the ship's propulsion in overcoming the effect of the weather. Although heaving-to may still cause a ship to drift, the rate of drift will be reduced, allowing more time in which to consider anchoring under controlled conditions and/or to seek tug assistance. Therefore, the relevant nodes are updated under Unsafe Supervision, Preconditions for Unsafe Acts and Unsafe Acts to reflect the human factors that occurred and aided with the accident formation.

After incorporating all the evidence, the BN and Table 10 show a 11% increase, in the likelihood of a collision from 41% to 52%. This reflects the magnitude of change due to the inclusion of post-accident information that could have been addressed and reported beforehand. This is a moderate increase in the magnitude of change, but when the vessel age and type are removed from the analysis, it can be seen from Table 11 that the likelihood of a collision incident increases more significantly. The likelihood of a collision increases in magnitude from 41% to 56%, an increase by17%. This demonstrates that if the knowledge of the deficiencies in the operational practices of the company and crew were highlighted prior to the voyage, the likelihood of a collision would have been evident and potentially avoidable.

Table 11
Saga Sky - Post-Accident Consequences - without ship type and age.

Nodes	Node State	No Evidence	Evidence	Change
Contact	*Occur*	*36%*	*53%*	*17%*
Collision	*Occur*	*41%*	*56%*	*15%*
Grounding	Occur	36%	53%	17%

5. Conclusions

This study investigated marine accidents in the Dover Strait by applying the Human Factors Analysis and Classification System for Passenger Vessels (HFACS-PV) and Bayesian Networks (BN) to systematically identify human factor–related causes. Accident reports involving groundings, collisions, and contacts between 2004 and 2020 were examined, with sinking incidents excluded due to their rarity. An accident database was developed from multiple sources and analysed using the HFACS-PV framework to classify causal factors. Findings indicate that grounding accidents were primarily linked to bridge team behaviour, including Substandard Practices of Team Members, Decision-Based Errors, and Perceptual Errors. While collision and contact incidents displayed more complex causal patterns, frequently involving adverse weather, technological malfunctions (e.g., electronic navigation failure), and procedural non-compliance. Nevertheless, “Errors” remained a consistent and dominant factor across both accident types.

Building on these results, a dynamic BN-based risk assessment model was developed to simulate accident causation under varying operational and environmental conditions. Case study testing revealed that incorporating post-accident information, such as vessel condition and crew practices, significantly increased predicted probabilities of grounding and collision. This highlights the critical importance of pre-voyage planning, maintenance, and accurate operational reporting, as well as organisational oversight to ensure adherence to best practices under challenging conditions. Beyond accident analysis, the BN model offers a practical decision-support tool: it can provide real-time risk warnings for vessel operators and Vessel Traffic Operators (VTOs) in the Dover Strait by dynamically estimating the likelihood of incidents under current traffic, environmental, and operational conditions. Such predictive capabilities enable operators to make informed navigational decisions, adjust traffic management measures, and implement preventive actions to mitigate hazards in narrow waterways.

Furthermore, the data is strengthened by its multi-source origin. Accident reports were collected from several authoritative databases and investigation bodies, including the IMO's GISIS system, the UK Marine Accident Investigation Branch (MAIB), and the European Maritime Safety Agency (EMSA). Using multiple official sources enhances the reliability and validity of the dataset and reduces the likelihood of bias or incomplete reporting. The integration of these data into CPTs within the BN further allows quantitative modelling of causal relationships between identified risk factors.

The research also demonstrates a clear methodological contribution by combining the HFACS-PV human-factor classification system with BN modelling. While HFACS-PV provides a systematic framework for identifying accident causes, the BN translates these findings into a dynamic probabilistic model capable of predicting accident likelihood under varying operational conditions. This transition from retrospective accident analysis to predictive risk modelling represents an important advancement in maritime safety research. Similarly, the presented analysis of the BN satisfies the three benchmark axioms outlined in Section 2.1.1. This adds further verification and confidence in the behaviour of the dynamic BN model.

Finally, the conclusions are directly supported by the analytical results and validated through detailed case studies of grounding and collision incidents. By demonstrating how identified factors influence accident probabilities in real operational scenarios, the study establishes a clear connection between the data analysis, the discussion, and the final safety recommendations. Consequently, the research provides both empirical evidence and practical insights for improving navigational safety in high-risk waterways.

Future work will focus on refining and validating the model through applications in other constrained maritime environments, such as the Bosporus and Singapore Strait, demonstrating its adaptability and potential for broader use in global maritime safety and proactive risk management (Yildiz et al., 2022a, 2024).

CRediT authorship contribution statement

Sean Loughney: Writing – original draft, Validation, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Serdar Yildiz:** Writing – original draft, Validation, Methodology, Investigation, Data curation. **Özkan Uğurlu:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Christos Kontovas:** Writing – review & editing, Validation, Investigation. **Jin Wang:** Writing – review & editing, Validation, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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