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Evaluation of fire and explosion accident risk from bulk cargoes

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ABSTRACT

Dry bulk cargoes are generally transported for industrial production purposes without being placed in any packed. Many of these cargoes have different risks due to their nature. Therefore, developing measures to minimise or eliminate the heavy losses that may occur due to these risks is essential. This article analyses the risk of fire and explosion accidents caused by cargoes within the scope of International Maritime Solid Bulk Cargoes (IMSBC) code group B. In this context, 31 accident reports were examined, and the nonconformities were classified qualitatively through the Human Factors Analysis and Classification System (HFACS) method. Accident occurrence probabilities and consequences were calculated quantitatively using the fuzzy bow tie method. As a result of the study, it has been determined that the nature of the cargo and the factors caused by procedural violations play an essential role in accidents.

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KEYWORDS
IMSBC code; fire; bulk carrier; bow-tie method; HFACS

1. Introduction

The global economy is based on maritime transport because 80% of international cargo is transported by ships. Maritime transport, vital for world trade, has various risks due to its nature. These risks can be grouped as the human factor, environmental conditions, the institutional and operational environment (Dominguez-Péry et al. 2021; H. Wang et al. 2021). The risks of each ship type (tanker, container, ro-ro, general cargo, bulk carrier, etc.) cargo-related operational environment differ. In this context, the International Maritime Organisation has published Cargo Stowage and Securing (CSS) Code, International Grain Code, The International Maritime Dangerous Goods (IMDG) Code, The International Bulk Chemical Code (IBC Code), International Gas Carrier Code (IGC Code) etc. for the prevention of cargo-related risks in different ship types.

Bulk carriers, the largest in number in the World's maritime fleet, carry 42.7% of international cargo (UNCTAD 2021). Bulk carriers are vessels carrying dry cargo in bulk forms, such as unpacked ore, metals, scrap, and cereals. Some cargoes are classified as 'dangerous goods' because they require special attention during loading, transportation and discharging operations. Hazards arising from cargo can be generally classified as shifting of cargo, dusting, liquefaction of the cargo, deterioration and causing fire (Morska et al. 2011). The sustainable transport of dry bulk cargoes depends on creating safe operational conditions during navigation and port operations. To ensure these conditions, the IMSBC code has been published by the International Maritime Organisation (IMO 2020).

The primary goals of the IMSBC code are to make it easier for individuals to stow and transport these goods securely by defining the necessary precautions and to inform all maritime stakeholders about the risks involved in handling specific types of solid bulk cargoes. Solid bulk cargoes are divided into three groups by the IMSBC code.

Group A Cargoes: This group includes solid bulk cargoes that are likely to liquefy during transportation. These cargoes release the moisture they contain under normal transport conditions and can destabilizse the ship (nickel ore, mineral concentrates, etc.).

Group B Cargoes: This group involves cargoes containing chemical hazards (direct reduced iron, ammonium nitrate-based fertilizsers, coal, etc.).

Group C Cargoes: Cargoes in this group do not contain liquefaction tendencies and chemical hazards. Apart from these, it has dangers (sand and fine particulate cargoes, cement) (IMO 2020).

Despite various codes, conventions, and protocols by IMO and Baltic, the International Maritime Council (BIMCO), International Association of Dry Cargo Shipowners (INTERCARGO), fire and explosion accidents continue to occur on bulk carriers for various reasons. IMO's study, which analysed the accidents with serious consequences on bulk carriers between 1999 and 2018, stated that 140 accidents occurred. Fire and explosion made up 33 of these accidents. When fire and explosion accidents were examined, it was stated that 28 of 33 fire and explosion accidents were caused by cargo in ship holds (IMO 2019). According to the Swedish Club, when the causes of cargo damages between 2007 and 2016 are analysed numerically, it is stated that fire and explosion accidents ranked twenty-sixth and the total rate was only 0.76%. However, the same report states that the ratio to the total cargo damage cost is in the first place at 28% (Swedish club 2017). In case of fire and explosion accidents caused by solid bulk cargoes on bulk carriers, operational costs increase and affect sustainable trade. Therefore, preventing such accidents will contribute to significant savings for all transportation parties.

With this motivation, the study analyzed the causes and consequences of cargo-related fire and explosion accidents on bulk carriers using a hybrid of HFACS, expert opinion-based fuzzy logic and bow-tie methods. The structure of the article is as follows. This section includes the current situation in bulk cargo transportation and the purpose of the article. Section 2 consists of a literature review. In Section 3, the methodology used in the article is introduced and explained. Section 4 presents a thorough qualitative-quantitative risk analysis of fire and explosion accidents to illustrate how the suggested approach might be used. The study ends in the final section with recommendations for additional research and potential comments on the topic.

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2. Literature review

Over 26,000 maritime shipping incidents have been reported in maritime shipping in the last ten years (AGCS 2021). The high rate of occurrence of maritime incidents and their relatively severe consequences have led many studies to focus on incident prevention. The topics of some studies examining the risks in maritime transport in the literature are as follows: LNG bunkering (Carboni et al. 2022), liquefaction of solid bulk cargoes (W. Wu et al. 2022), cargo handling operation (Gao 2022), collision (R. W. Liu et al. 2022), container fire (K. Wang et al. 2023), and engine room fires (Ikeagwuani and John 2013) etc. Different risk assessment methods were used in the studies. In general, risk analysis methods can be evaluated in three categories. These are hazard identification, risk process analysis, and risk estimation (Akyildiz and Mentes 2017). Identifying hazards is a crucial step in risk assessment. If any danger is ignored or not noticed, the resulting risks cannot be determined or analysed, and no preventive measures can be taken. The consequences of this situation can be very dire. Typical risk identification methods include HFACS (Y. Li et al. 2022), The decision- making trial and evaluation laboratory (DAMATEL) (Ma et al. 2024), the Cognitive reliability and error analysis method (CREAM) (Pei et al. 2024), and Hazard operability study HAZOP (Johnson 2010). Analysis of the risk process is the process of determining the correlations of dangerous events using qualitative analysis methods such as STAMP (Hu et al. 2022) and Accimap (Underwood and Waterson 2014). Finally, in risk estimation studies, the estimation of the risk of the event and the situations that increase the probability are quantitatively analysed through methods such as Fault tree analysis (FTA) (Shang et al. 2021), Bayesian networks, (Babaleye and Kurt 2020) etc.

As a result of the literature review conducted within the scope of the study, many studies analysing operational and accident risks on bulk carriers were identified. Some of them are an environmental threat (Grote et al. 2016), poisoning due to cargo (Loddé et al. 2015), energy efficiency (Tran 2019), collision (Campanile et al. 2018), bending moment calculations in case of rough sea conditions (Vásquez et al. 2016), and fuel consumption (Yan et al. 2020). Studies on IMSBC and fire are concentrated and categorised. The first category is on IMSBC Code group A cargoes. Akyuz et al. (2020) made a comprehensive quantitative risk analysis regarding liquefaction caused by IMSBC Code Group A cargoes. They used bow-tie analysis in a fuzzy environment as a method. As a result of the study, they recommended that the operating procedures (checklist, plan, etc.), including the reasons causing the liquefaction of the cargo should be required by the maritime authorities (flag state, port state, etc.) (Akyuz et al. 2020). In another bulk cargo liquefaction risk study, researchers examined the ship accident reports about listing or total loss due to the liquefaction of 25 cargoes between 1986 and 2019. They used interpretive structure modelling (ISM) to create the hierarchy of the relationship of risk factors obtained from accident reports and the fuzzy Bayesian networks model to find the effect level of the factors. As a result of their study, it was stated that factors caused by human error (short shipment) (29%), not paying attention to the cargo (27%), and insufficient information (22%) were the important factors causing the liquefaction of the cargo (Sakar et al. 2020). Munro and Mohajerani (2017) stated in their study that the combination of cyclic loading, fine particles, and moisture caused ships to capsize. In this context, they developed the Modified proctor/fagerberg test (MPFT) apparatus and conducted experiments to determine the Transportable moisture limit (TML) value of the Iron ore fines (IOF) cargo. The experiments stated that liquefaction occurred even for cargoes below the legal TML value. Thus, they concluded that the cargo was liquefiable at the TML limit value determined in the IMSBC code for the IOF cargo. In another study which was conducted by Munro and Mohajerani (2016), the causes of excessive moisture contained in bulk cargoes were investigated. Within the scope of their studies, they examined 18 accidents caused by the liquefaction of cargo between the years 1988 and 2015. They recommended the establishment of sampling and testing techniques that may be essential to reduce the potential for such accidents (Munro and Mohajerani 2016).

The second group of studies investigates fire and explosion accidents in bulk carriers. Yazir (2022) examined cargo-induced explosion, flashing and other safety risks of bulk carriers. He compared five quantitative evaluation criteria of the fixed and fire extinguishing systems and five fixed extinguishing systems in pairs with the expert opinion IF-TOPSIS method. As a result of the study, it was determined that an ideal system to be applied on ships was the fixed carbon dioxide fire system. In another study, accidents that occurred on bulk carriers between 1980 and 2010 and resulted in death were analysed. As a result of their research, they found that 19% of accidents were caused by fire and that the number of accidents was strongly related to flag status, cargo, location of the casualty, weather conditions and tonnage (Roberts et al. 2013). Navas de Maya and Kurt (2020) used the fuzzy cognitive maps (MALFCMS) method for fire and explosion accidents on bulk carriers between 2000 and 2011. It ranked the sub-causes contributing to maritime accident learning according to their final weights. In this context, the most critical sub-reasons were procedural deficiencies, inadequate equipment maintenance, competence, inappropriate equipment, and identified as a lack of situational awareness.

It was found that there is no study evaluating the fire accident risks caused by IMSBC code group B cargoes. A hybrid method consisting of HFACS and the Bow-tie method was used to eliminate this gap in the literature. Ship fires have a complex structure. Classifying the factors causing accidents using the HFACS method reveals the apparent causes and hidden factors contributing to the accident. However, HFACS is insufficient for quantitative analysis of accidents. In this study, the logical relationship between the accident factors and the numerical analysis of the logical relationship was performed using the Fuzzy Bow-tie method for quantitative analysis. In this respect, an effective hybrid risk assessment method for analysing fire accidents has been introduced to the literature.

3. Methodology

3.1. Research structure

As fires and explosions caused by IMSBC Code Group B cargoes on bulk carriers continue to occur despite the precautions taken, the study was initiated to determine the causes and consequences of these accidents. Then, a comprehensive literature review was carried out and the gap in the literature in the relevant field was identified. Accident reports published by 35 accident investigation organisations (Table 1) were reviewed to identify the causes of fire and explosion accidents and their consequences. As a result, 31 accident reports related to the study were reached between 1999 and 2022. Obtained accident reports were demographically classified according to the tonnage of bulk carriers and the cargo type (Table 2).

The accident reports were examined in detail, and the factors causing fire and explosion accidents were determined. The detected accident factors were classified under the HFACS structure, and their frequencies were calculated according to the

Table 1. List of organisations conducting maritime accident investigations.

Name of the Organization	Abbreviation	Country(s)
Accident Investigation Board Norway	AIBN	Norway
American Bureau of Shipping	ABS	USA
Australian Transport Safety Bureau	ATSB	Australia
Bahamas Maritime Authority	BMA	Bahamas
Federal Bureau of Maritime Casualty Investigation	BSU	Germany
Bureau d'enquêtessur les événements de mer	BEAMER	France
Confidential Hazardous Incident Reporting Programme	CHIRP	United Kingdom
Countryman & McDaniel	C& M	USA
Danish Maritime Accident Investigation Board	DMAIB	Denmark
Department of Marine Services and Merchant Shipping	ADOMS	Ancient and Barbuda
Dutch Safety Board	DSB	Holland
European Maritime Safety Agency	EMSA	Portugal
Global Integrated Shipping Information System	GISIS	United Kingdom
International Transportation Safety Association	ITSA	USA, Canada, Sweden,
Isle of Man Ship Registry	IOMSR	Holland
Japan Transport Safety Board	JTSB	United Kingdom
Transport Safety Investigation Center	UEIM	Japan
Marine Accident Investigation Branch	MAIB	Türkiye
Marine Accident Investigation Committee Cyprus	MAIC	United Kingdom
Marine Accident Investigators' International Forum	MAIF	Cyprus
Marine Casualty Investigation Board	MCIB	United Kingdom
Marine Department-Hong Kong	MARDEP	China
Maritime Safety Administration of People's Republic of China	MSA	China
National Transportation Safety Committee	NTSC	Indonesia
Marine Accident Investigation Department	DIAM	Panama
Philippine Coast Guard	PCG	Philippines
Safety Investigation Authority	SIA	Finland
Swedish Accident Investigation Board	SHK	Sweden
Swedish Transport Agency	STA	Sweden
The Nautical Institute	MARS	United Kingdom
Transport Accident and Incident Investigation Bureau	TAIIB	Latvia
Transport Accident Investigation Commission	TAIC	New Zeland
Transportation Safety Board of Canada	TSB	Canada
United States Coast Guard (Homeport)	USCG	USA
United States National Transportation Safety Board	NTSB	USA

Table 2. Vessel type and IMSBC code group B cargoes where fire and explosion accidents occur.

	Vessel type				
Cargo	General cargo/ Multi-purpose	Handysize bulk carriers	Handymax bulk carriers	Panamax bulk carriers	Post-Panamax bulk carrier
Wood Products		2	1		
Ferrous Metal Borings			1		
Direct Reduced Iron	1	3			
Zinc Ashes	1				
Zinc Oxide Enriched Flue Dust	2				
Coal	1	1	3	3	2
Ammonium Nitrate Based Fertilizer	1	1	1		
Wood Pellets	1	1			
Petroleum Coke				1	
Incinerator Bottom Ash [U-IBA]	1				
Nut Shells		1			
Aluminium Silicon Powder	1	1			
Total	9	10	6	4	2

HFCAS levels. The logical relationship (tree error) and results (event tree) between the data obtained from this classification and the factors were established. The primary application steps of the Bow-tie (FTA-ETA) methodology were introduced to the experts participating in the study, and the final version of the bow-tie diagram was created by consulting their views on the structure. Thus, the qualitative part of the study was completed. Knowing the BE and IE probability values is necessary to evaluate the study quantitatively. In this context, two main approaches have been adopted in the literature while calculating probability values. These are statistical data and expert judgment (Brownstein et al. 2019). Since the data obtained in this study are unsuitable for calculating probabilities, BE and IE probabilities were determined using expert judgment.

The experts involved in this study were chosen from people related to the subject. Experts may come from various backgrounds, professions, and experiences (Badida et al. 2019). Therefore, assessing the experts' viewpoints would be highly accurate considering their expertise and familiarity with cargoes falling under IMSBC group B. Expert opinions were weighted in this study based on professional position, years of professional experience, and IMSBC group B cargo experience. The subsequent sections of the study provide descriptive data regarding the experts. In the quantitative approach, minimum cut sets (accident combinations) were defined, and the probability of flammable/explosive gas generation combinations was assessed. Finally, the results were compared to relevant studies and interpreted. The flowchart shown in Figure 1 provides an overview of the steps of the study.

3.2. Background

3.2.1. HFACS

The Human Factors Analysis and Classification System (HFACS) is a classification tool developed for identifying and qualitatively analysing contributing factors to accidents (Shappell and Wiegmann 2000). The HFACS model examines accident factors at four levels and 19 sub-levels (Figure 2). These levels are as follows: Organizsational influences, Unsafe supervision, Pre-conditions for unsafe acts, and Unsafe acts (Shappell and Wiegmann 2000). According to this model, errors at each level affect the other, and an accident occurs.

The first use of the HFACS method began with the investigation of aviation accidents. Later, it was used in accident analyses in many areas, such as maritime transport (Kandemir and Celik 2021), applied training (Z. Li et al. 2022), construction industry (Ye et al. 2018), mining industry (R. Liu et al. 2019), nuclear control room (Karthick et al. 2020), healthcare (Zheng et al. 2023), chemical industry (Jing Wang et al. 2020), rail transport (C. Li et al. 2019) etc. The most important feature distinguishing HFACS from other methods for investigating accident causes is that it can define the role of administrative and organisational factors in accident occurrences. Another advantage of the HFACS hierarchical structure is that it enables human error-related factors in accidents to be accurately identified and correlated. In addition, the HFACS method does not require expert opinion on classifying causes and causal

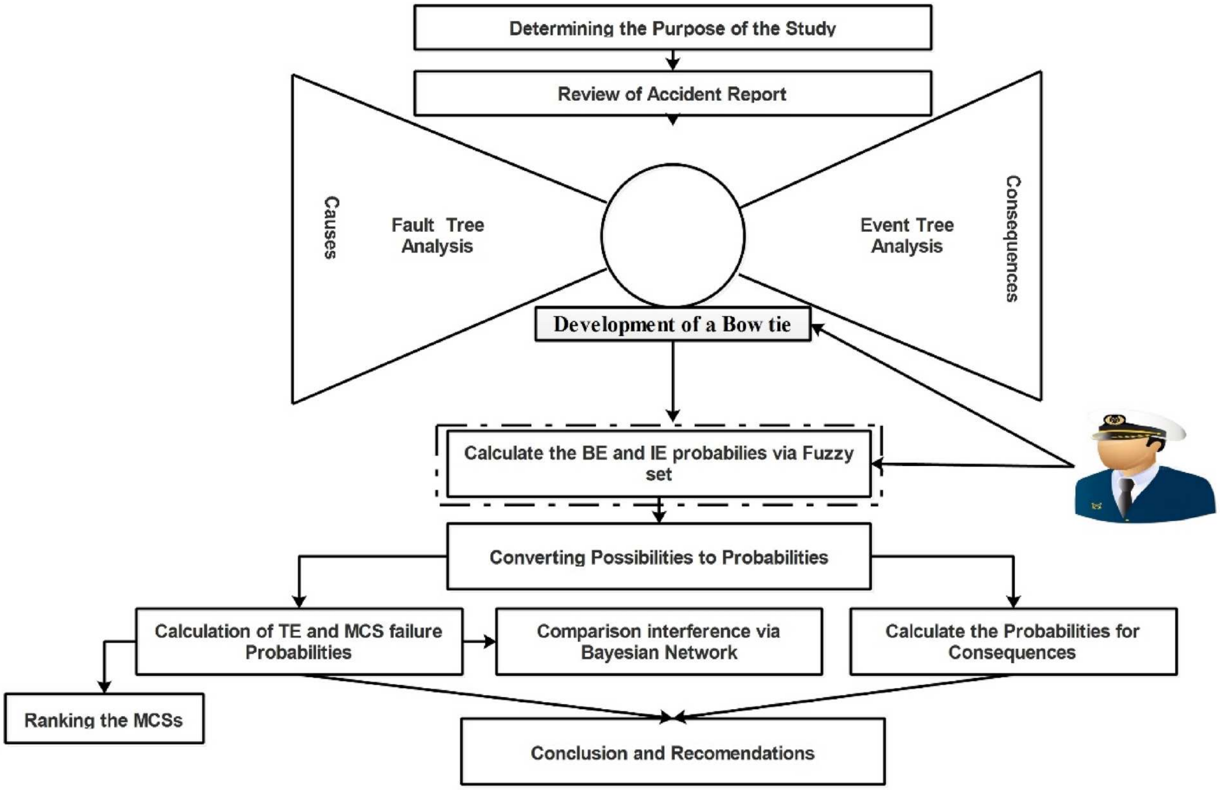

Figure 1. Flow chart of the methodology. (This figure is available in colour online.)

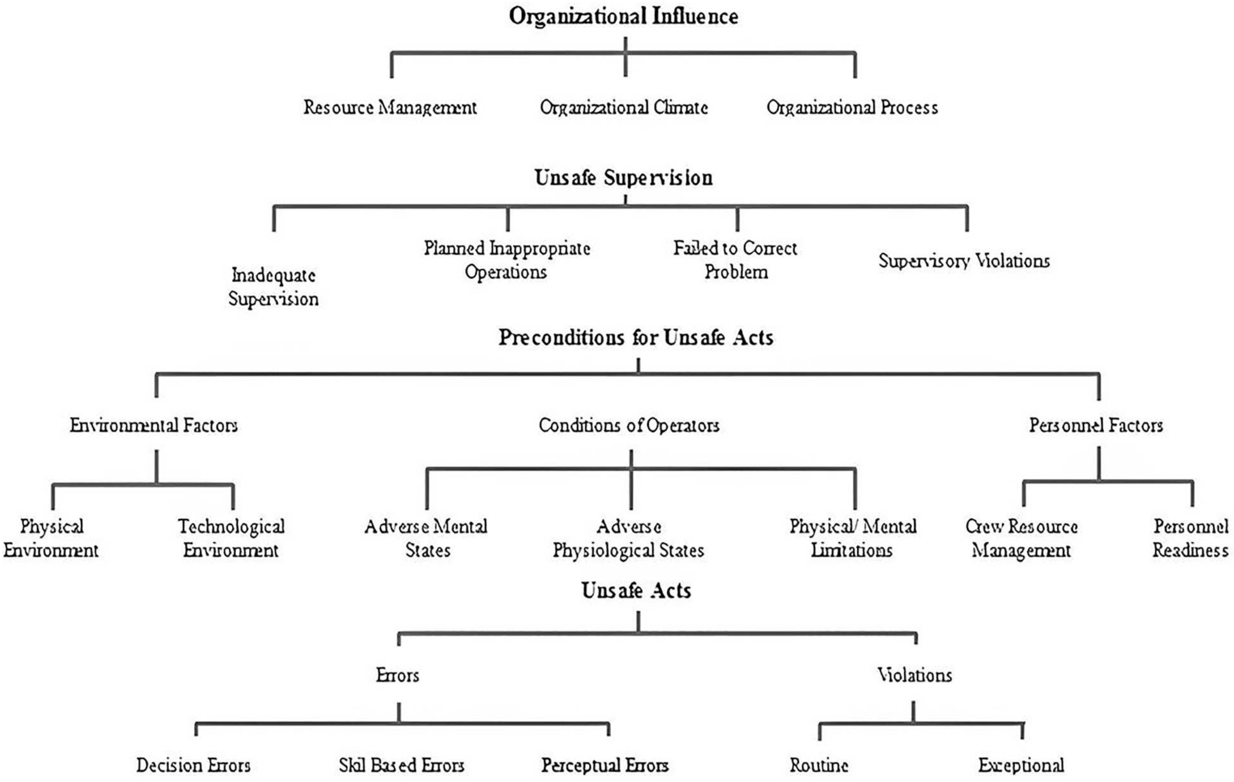

Figure 2. Human factor analysis and classification system (HFACS) (Shappell & Wiegmann, 2000). (This figure is available in colour online.)

factors. For this reason, researchers who have mastered the main structure and infrastructure can gradually reveal the occurrence of accidents (Kaptan et al. 2021).

3.2.2. Fuzzy bow-tie analysis

Bow-tie analysis is one of the linear chain accident models. The model is easy to understand and provides powerful control to its users (de

Ruijter and Guldenmund 2015). It can graphically reveal the factors affecting the accident, and quantitative risk assessment is easy. It is the most critical step in accident prevention that none of the accident causal factors are omitted while constructing the bow-tie diagram. In this study, the bow-tie diagram was obtained by classifying the accident factors obtained from accident reports according to the HFACS method. On the other hand, bow-tie is a static model. Due to this structure, it is insufficient to detect changes that may occur in sudden or unexpected operational processes (Khakzad et al. 2012).

The model has been widely applied in risk analysis in different areas such as maritime inspection (Sotiralis et al. 2019), anchor handling (Kaptan 2021b), STS operation (Arici et al. 2020), liquefaction of cargo (Akyuz et al. 2020). The model consists of an FT (Fault tree) describing possible causative events and an event tree (ET) on the right that shows possible consequences of the critical event. Figure 3 shows the basic structure of a bow tie model. Basic Event (BE), Mediator Event (ME), and Top Event (TE) are the base, intermediate, and top events of the fault tree, respectively. Intermediate events (IE) and Conclusion (C) represent intermediate event and accident result, respectively. In the traditional Bow-tie method, the probabilities of occurrence of BE-IE events are numerical values. BE-IE is unlikely to occur due to high uncertainties and insufficient data (Shahriar et al. 2012). Fuzzy logic is a mathematical tool used to model the uncertainty of human thought in the real world (Darbra et al. 2008). Each BE-IE probability value in a Bow tie model with a fuzzy approximation is represented by a fuzzy number (Lu et al. 2015). Expert opinions are given with fuzzy numbers. Fuzzy numbers obtained from expert opinions constitute BE-IE probability values (Elidolu et al. 2022).

3.2.2.1. Probability calculation according to expert judgment.

Experts give their opinions for each (BE) and (IE), referring to the starting points of the chain of events. However, beliefs in the underlying causes of an occurrence may vary between experts. Thus, evaluations are influenced by the significance of each expert from various perspectives. Different perceptions and decisions regarding the top events result from experts in a heterogeneous group with varying experience and knowledge levels. Past studies have used a weighting factor to represent the relative quality of the opinions of various experts (Y. Liu et al. 2020). Various justification weights, from 1 to 5, can be assigned to each expert to reflect differences in the impact of their assessment.

3.2.2.2. Fuzzification.

Triangle and trapezoidal fuzzy sets are generally used to calculate probability values for basic events (Tanaka et al. 1983; Cheng and Mon 1993; Rajakarunakaran et al. 2015). This study used a triangular fuzzy number set (TFN). The fuzzy probability values are represented as (a_1, a_2, a_3) in the triangular fuzzy set of numbers. The set of fuzzy numbers A is in the range R→ [0,1], and it is the membership function of the set of fuzzy numbers $\mu_{\tilde{A}}(X)$ A, with X ∈A. Considering that the set A is in the range $[a_1, a_3]$, the membership $\mu_{\tilde{A}}(X)$ is calculated as follows (Kosko 1994).

$$\mu_{\tilde{A}}(\mathrm{x}) = \left\{ \begin{array}{ll} 0 & ; x \leq a_1 \\ (x - a_1)/(a_2 - a_1) & ;\ a_1 \leq x \leq a_2 \\ (a_3 - x)/(a_3 - a_2) & ;\ a_2 \leq x \leq a_3 \\ 0 & ; x \geq a_3 \end{array} \right\} \tag{1}$$

3.2.2.3. Aggregation.

Since the experts have different academic and work experiences (heterogeneous), it is encountered that they make other decisions in the same case. For this reason, it is essential to reconcile the difference between the decisions obtained because of expert evaluation. The following steps are applied to consolidate the opinions obtained by heterogeneous expert groups (Hsu and Chen 1996):

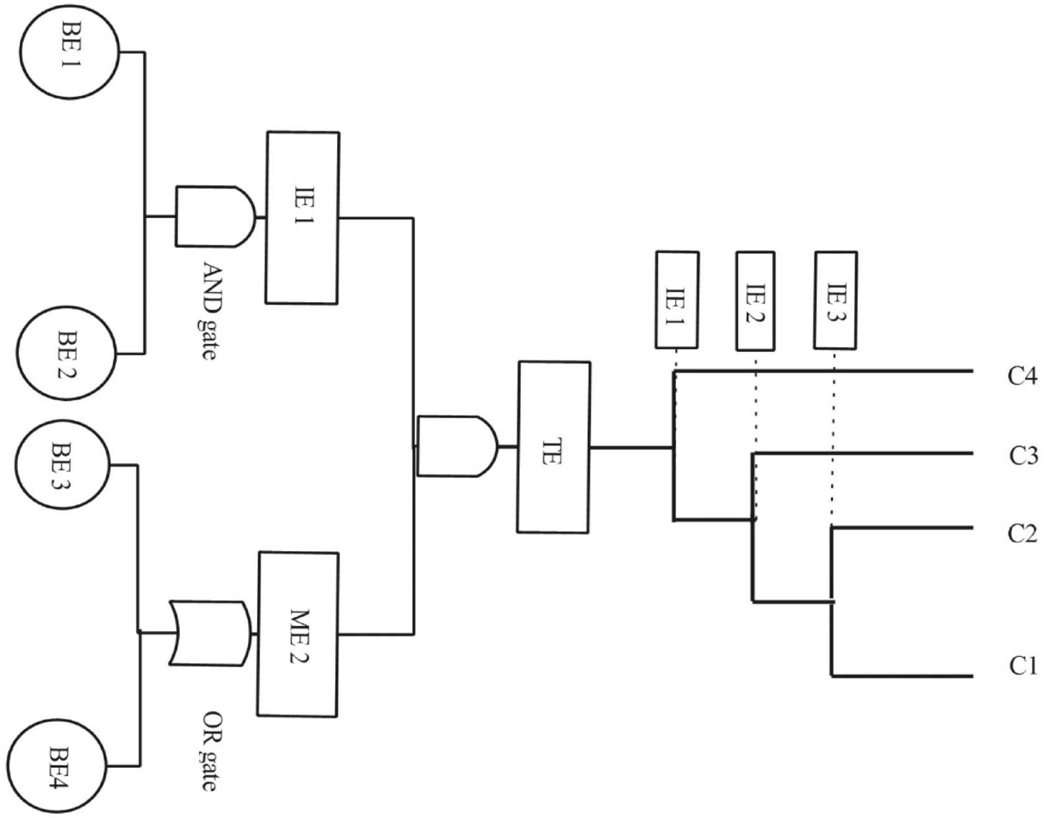

Figure 3. Generic bowtie. (This figure is available in colour online.)

$\widetilde{R1}$, $\widetilde{R2}$: Different expert opinions,
$S_{UV}(\widetilde{R1}, \widetilde{R2})$: Degree of agreement of different expert opinions,
$S(\tilde{A}_1, \tilde{A}_2)$: The degree of similarity between fuzzy sets of numbers,
$AA(E_u)$: Average degree of agreement of opinion,
$RA(E_u)$: Relative degree of agreement of opinions,
CC (E_u): Degree of consensus coefficient,
$\tilde{R}_{AG}$: Aggregated result of their opinions.

Step (i): Determine the degree of agreement S_{UV} $(\widetilde{R1}, \widetilde{R2})$ of the opinions $\widetilde{R1}$ and $\widetilde{R2}$ of a pair of experts E_U (u = 1 to M).

Accordingly, $\tilde{A}_1 = (a_{11}, a_{12}, a_{13})$ and $\tilde{A}_2 = (a_{21}, a_{22}, a_{23})$ form two triangular fuzzy sets of numbers. The degree of similarity between these two sets of fuzzy numbers is obtained by Equation (2).

$$S(\tilde{A}_1, \tilde{A}_2) = 1 - \left(\frac{1}{3}\right)\sum_{i=1}^{3} |a_{1i} - a_{2i}| \tag{2}$$

Step(ii): The Expert's average degree of agreement is calculated using Equation (3).

$$AA(E_u) = \frac{1}{M - 1\sum_{\substack{U \neq V \\ V=1}}^{M} S(\tilde{A}_1, \tilde{A}_2)} \tag{3}$$

Step(iii): The Relative agreement of M experts is calculated using Equation (4).

$$RA(E_u)\frac{A(E_U)}{\sum_1^M A(E_U)} \tag{4}$$

Step(iv): The degree of the expert's consensus coefficient is calculated using Equation (5).

$$CC(E_U) = \beta.w(E_U) + (1 - \beta).RA(E_U) \tag{5}$$

Step(v): Aggregated result $(\tilde{R}_{AG})$ of expert opinions is calculated using Equation (6).

$$\tilde{R}_{AG} = CC(E_1) \times \tilde{R}_1 + CC(E_2) \times \tilde{R}_2 + \ldots + CC(E_M) \times \tilde{R}_M \tag{6}$$

3.2.2.4. Defuzzification. The defuzzification process is performed to obtain measurable results in fuzzy logic. The conversion of fuzzy numbers into a crisp score, fuzzy possibility score (FPS), is significant for making decisions on uncertain issues (Sarıalioğlu et al. 2020). The FPS number of significant events is obtained from the final membership function computed in the expert opinion aggregation stage. The most popular FPS method in the literature, clarification according to the centre of gravity, was adopted in this investigation (Sugeno 1999). Equation (7) is used for this step. In the Equation, X^* is the fuzzy probability, $\mu_{\tilde{I}}(x)$ is the aggregated membership function, and X is the output variable.

$$X^* = \frac{\int \mu_{\tilde{I}}(X)dx}{\int \mu_{\tilde{I}}(X)} \tag{7}$$

3.2.2.5. Occurrence probability generation. Due to uncertain data, estimating the probability of failure is occasionally impossible. This problem can be solved by converting the net probability of failure (CFP) to the probability of failure (FP) form (Aydin et al. 2021). In this study, it was used in the conversion function Equation (8) of the CFP (crisp failure possibility) to FP (failure probability) form proposed by (Onisawa 1990).

$$FP = \begin{cases} \frac{1}{10^K}, CFP \neq 0 \\ 0, CFP = 0 \end{cases}, \quad K = \left[\left(\frac{1 - CFP}{CFP}\right)\right]^{\frac{1}{3}} \times 2.301 \tag{8}$$

3.2.2.6. Calculation of MCS and TE error probability. It is called the minimum number of combinations of basic events (minimum cut sets MCS) sufficient for the TE. Each top event has a distinct number of minimum shear sets. The significance value of MCS is frequently determined using the FV-I (Fussel Vessely Importance Measure) approach (Shafiee et al. 2019). Therefore, the FV-I methodology was employed in this study. Equation (9) represents this approach.

$$I_I^{FV}(t) = \frac{Q_I(t)}{Q_S(t)} \tag{9}$$

When $I_I^{FV}(t)$ defines the size of MC$_i$, the probability of failure to occur represented by the cut set i of $Q_I(t)$ and $Q_s(t)$ gives the probability of failure of TE to occur in the entire MCS.

3.2.2.7. Calculate probabilities for ETA results. Probabilities are determined in this stage using a fuzzy set environment for each possible result. First, language evaluation is translated into numerical value using expert opinion. Next, Equation (8), explained earlier, converts possibilities into probabilities. Finally, the traditional event tree equation is applied to calculate the probabilities of each outcome (Ferdous et al. 2011).

4. Case study

This section classified the causes of fire and explosion accidents caused by cargoes within the scope of IMSBC code Group B cargoes using the HFACS method. Then, a quantitative risk analysis was made by creating a bow tie to cover the causes and consequences of the accident.

4.1. HFACS implementation

Analysing bulk ships' fire/explosion accident reports with IMSBC code group B cargoes identified 323 accident factors. The average number of accident-related factors that result in accidents is 10.4. The distribution of accident factors according to HFACS levels is as follows:

Organizsational Influences: This level categorises organizsational-related nonconformities (Unqualified crew, Lack of information about the cargo, etc.) that increase the risk of accidents. The classification revealed that 30 distinct nonconformities were observed 85 times (Table 3).

Unsafe Supervision: At this level, nonconformities related to issues such as failure to perform routine tests and controls, implementation of a planned maintenance system, improperly planned operations, and failure to correct predetermined problems are classified under unsafe supervision. It was determined that 13 different nonconformities were seen 46 times by classification (Table 4).

Pre-conditions for Unsafe Acts: The level at which the accident factors prepare the ground for the apparent causes of the accidents is classified. It includes situations and factors that negatively affect the decision-making abilities of operators, such as environmental conditions, personal situations, and team management. As a result of the classification, it was determined that 29 different nonconformities were seen 72 times (Table 5).

Unsafe Acts: At this level, non-compliances related to wrong or erroneous behaviour conducted intentionally or unknowingly by the personnel are classified. It was determined that 27 different nonconformities were seen 120 times by classification (Table 6).

Table 3. Accident causes and frequency of occurrence at the level of organizational influences.

Sub-level	Nonconformities	Frequency
Resource Management		
	Cargo characteristics	7
	Ventilation system in the cargo hold	5
	Lack of information about fumigation application	2
	Compliance of gas sampling equipment operability and maintenance	4
	Lack of familiarity with the IMSBC's special requirements for the carriage of cargo.	7
	Lack of information about the cargo	8
	Crew unfamiliar with cargo	3
	Minimum crew manning	1
	Unqualified crew (master, 1st officer, 2nd officer, etc.)	10
	Lower ladder access inside the hatch	1
	Improper firefighting equipment	2
	Vessel's design and construction	1
	Electrical system	2
	Location of CO2 holes in the hold	1
	Hatch cover opening/closing time	1
	Hatch cover tightness	2
Organizational Climate		
	Working procedure and working habit	1
	Lack of management	1
	Poor safety culture of crew	2
Organizational Process		
	Share information on effective firefighting methods	2
	Proper Planning	3
	Gas detection procedures	4
	Hot work permits	2
	Risk mitigation measures	3
	Loading risk assessment	2
	Transportation risk assessment	1
	Ignored risk assessment	2
	Incorrect expression in SMS	1
	Planned maintenance	3
	Awareness safety level	1

Table 4. Accident causes and frequency of occurrence at the level of Unsafe Supervision.

Sub-level	Nonconformities	Frequency
Inadequate supervision	Temperature tracking inside the cargo hold	13
	Failure to effectively monitor fumigation application	2
	Lack of supervision from the responsible Officer.	10
	Lack of supervising from stevedore	4
	Owners/management not internal auditing/following	1
	Improper hold cleaning	3
Planned Inappropriate operations		
	Hot work	2
	Rest and working hours	2
	Lookout – Hold watch	4
Failed to correct Problem		
	SMS Manual dont provided guidance for cargo	2
	Cargo is not listed in IMSBC code	1
Supervisory violations		
	FFA not serviced/audited	1
	No actual real drills (fire/abandon ship) were conducted	1

4.2. Fuzzy bow-tie implementation

The likelihood of a fire depends on the presence of fuel, heat, and oxygen. When constructing the fault tree, oxygen was not considered because it may be present in all environments, including ship holds. On the other hand, fire depends on the formation of flammable-explosive gas when the cargo within the scope of IMSBC code B is exposed to a heat source or reacts. If gas formation does not occur, fire and explosion do not happen. For this reason, the top event of the fault tree has been determined as the formation of flammable, explosive gas. Root causes, HFACS structure, and expert opinions obtained from the 31 accident reports examined were considered in determining the events that led to the top event. FT diagram consists of 11, the primary event (BE), 6 Mediation and Event (ME), which effectively realises the top event and its results (Table 7). The ET diagram consists of three

Table 5. Accident causes and frequency of occurrence at the level of pre-conditions for unsafe acts.

Sub-level	Nonconformities	Frequency
Environmental Factors	Physical Environment	
	Rain	4
	Open light	3
	Moisture build-up in the cargo hold	4
	Water inlet to the cargo hold	2
	Rough seas	2
	Technological Environment	
	Sprayed water was blocked	1
	Incorrect positioning of the blower	1
	Short circuit	1
	Electric leakage in blower	1
	Foreign matters in cargo hold	3
	Electric charge	1
	Light or another electrical component	2
	Ignition source	18
	The gas tight integrity of the cargo hold was breached	1
Conditions of Operators	Adverse Mental States	
	Lack of awareness	6
	Overconfidence	2
	Lack of attention	3
	Adverse Physiological states	
	Physical fatigue	3
	Physical /Mental Limitations	
	Excessive workload due to lack of crew members	2
Personnel Factors	Crew Resource Management	
	Provide information on firefighting equipment aboard their vessel to the firefighting organisation.	1
	Good communication	1
	Failure to follow safety procedures	2
	Loosing communication with rescue centres	1
	Failure in management of emergency situations – Fire	2
	Chief officer's error of guidance – feedback	1
	Master's lack of authority	2
	Personnel Readiness	
	Drug	1
	Alcohol	1

Table 6. Accident causes and frequency of occurrence at the level of unsafe acts.

Sub-level	Nonconformities	Frequency
Errors	Decision Errors	
	Hot work	2
	The ship was not evacuated, although the smoke was poisonous.	1
	Improper ventilation	5
	Inappropriate firefighting operation	6
	Skill Based Errors	
	Improper cargo handling	5
	Improper hatch cover closure	3
	Cargo planning	2
	Gas detection	3
	Securing of cargo hold access hatches	1
	Using an improper fire extinguisher	2
	Failure to properly maintain the access hatch seal	1
	Improperly using a passive gas detection device	1
	Perceptual Errors	
	Spontaneous combustion	2
	High level carbon monoxide	4
	Local temperature rise	6
	Mixture of methane and coal dust	2
	Emit methane	8
	Moisture content inside the cargo hold.	3
	Cargo was excessively slack within the hold, creating an increased volume of air over the cargo surface.	1
	Unaware of the requirements of the IMSBC Code.	4
	Failure to measure gas level in holds	2
Violations	Routine	
	IMSBC code requirements did not been followed	25
	Failure to prepare ship and the terminal checklists	4
	Lack of daily gas measurements	13
	Lack of daily temperature measurements	9
	Exceptional	
	Improper fumigation	2
	Smoking taking place inside the hold	3

Table 7. Failures for fire and explosion accidents caused by Group B cargo.

Event	Event description
TE	Formation of flammable explosive gas
ME1	Unsafe acts
ME2	Operational conditions
ME3	Violations
ME4	Decision error
ME5	Detection error
ME6	Ship structural defects
BE1	Regulatory violations
BE2	Violation of procedures
BE3	Improper ventilation process
BE4	Improper handling
BE5	Improper cargo separation/planning
BE6	Implementation of ımproper extinguishing treatment
BE7	Inability to detect foreign matters in the cargo hold
BE8	Improper temperature and gas monitoring
BE9	Inappropriate cargo hold equipment
BE10	Improper extinguishing equipment
BE11	Cargo unsuitable for transportation

Table 8. The codes for intermediate events used in the event tree.

Event	Intermediate event
IE1	Fire and explosion local
IE2	Damage to the ship
IE3	Sinking of ship

intermediate events (IE) in the initial state, where disruptions result in flammable, explosive gas (Table 8). Explanatory information about the basic events is given below.

Regulatory violations (BE1): It is violation of the rules and procedures (IMSBC Code, Company ISM forms and port statutes, etc.) to be followed during loading and unloading. Rule violations include accidental factors, including wilful negligence or non-enforcement of regulations issued by IMO, flag states or competent authorities.

Violation of procedures (BE2): This refers to the accident factors caused by the violation of the procedures, such as testing, inspection, and fumigation, that should be done after or before the cargo is loaded.

Improper ventilation process (BE3): It covers accident factors caused by lack of ventilation, insufficient ventilation in cargoes that need ventilation, or no ventilation.

Improper handling (BE4) refers to the damage caused to the cargo and the ship's body by the handling tools such as cranes, conveyors and bulldozers used during unloading and loading. For example, suppose the cargo is not evenly distributed in the cargo hold because of improper handling. In that case, stresses may occur in the tank top and frames, and heating may occur due to excessive clustering in the cargo. Therefore, it covers the accident factors caused by the stated operational deficiency.

Improper cargo separation/planning (BE5): While preparing the cargo plan and distributing the cargo to the cargo hold, it should be kept away from possible heat sources. Otherwise, heating may occur at the border areas of the engine room. The contact of the cargo with places that may cause such heating should be prevented or minimised. It covers accident factors caused by a heat source.

Implementation of improper extinguishing treatment (BE6): During loading, discharging, or navigation, heating or ignition may occur in the cargo. In cases where such cargo requires intervention, the chemical properties of the cargo should be known. For example, the intervention should be done with carbon dioxide in cargoes that can emit flammable and toxic gases when they are wet. In case of intervention with water, the risk of fire and explosion will increase. It covers accident factors caused by the lack of firefighting.

Inability to detect foreign matters in the cargo hold (BE7): Foreign materials can be mixed with the cargo through the handling equipment or the workers inside the hold, such as cigarette butts and oil falling from the handling equipment into the hold, fuel leaks or other foreign matter, including accident factors. It covers significant incidents involving accident factors caused by foreign materials.

Improper temperature and gas monitoring (BE8): The atmosphere inside the cargo hold should be controlled at regular intervals to prevent the atmosphere and cargo temperature in the cargo hold from causing undesirable situations such as ignition, explosion, and fire. It covers accident factors caused by the inability to monitor the concentration of flammable and explosive gases in the hold.

Inappropriate cargo hold equipment (BE9): The rubber of the hatch cover, the circuits inside the hatch, the tank top and the bilge well prevent the cargo from being damaged. This equipment should be maintained regularly. Otherwise, flammable and explosive gas formation may occur due to the contact of the cargo with water in the hold. It covers accident factors caused by cargo hold equipment.

Improper extinguishing equipment (BE10): In case of heating and ignition in the cargo, it is very important to intervene with the appropriate equipment to avoid turning it into a fire. It covers accident factors caused by a lack of first response.

Cargo unsuitable for transportation (BE11): In bulk carriers, according to SOLAS chapter VI rule 1–2, the shipper must inform the master about the cargo before loading as specified in IMSBC Code Rule 4. It is required for proper stowing and safe transport of cargo. It covers factors caused by improper notices or unsuitable cargo transported by bulk carriers.

4.3. Assessments from marine experts

This study was created based on the opinions of six experts, to prevent subjectivity in expert judgments. The expert group supporting the study is a heterogeneous group that includes the operations managers of companies operating bulk ships and the master and chief officer working on bulk carriers. Experts evaluating the effects of key events are people who have worked in the maritime industry for many years and are actively working in different positions in the industry. At this stage, the weighting process was carried out by considering the professional positions, qualifications, and experiences of the experts whose opinions were consulted. Each expert was given a score between 1 and 5 to reflect the differences in the weights of their opinions (Table 9). Equation (10) was used to calculate the weights of the experts. μ: symbol denotes the expert's rank in the group (Rajakarunakaran et al. 2015).

Table 9. Weighting rate of experts.

Constitution	Classification	Score
Professional position (PP)	Operation manager	5
	Master	4
	Chief Officer	3
Professional experience in years (PE)	Greater than 25 years	5
	20–25	4
	15–20	3
	10–15	2
	1–9	1
IMSBC group B cargo experience	Greater than 100 cargo operation	5
	80–100	4
	60–80	3
	40–60	2
	20–40	1

$$\begin{aligned} &\textit{Weighting factor of expert } (W_\mu) \\ &= \frac{\textit{Weighting score of the expert}}{\textit{In all weight score of experts}} \end{aligned} \tag{10}$$

Table 10 contains the data of the weighting calculations of the experts who made the evaluation.

4.4. Fuzzification stage

The numerical approach method was used to convert the linguistic phrases of marine professionals into fuzzy numbers. A seven-term language scale was used to obtain expert perspectives on fundamental occurrences with unknown error rates, as shown in Table 11.

The probability of each basic event was evaluated from lowest to highest. Table 12 presents the findings of the expert group's assessment of the prior incidents in the fault tree. The linguistic evaluation of each result in the event tree is shown in Table 13.

4.5. Aggregation stage

After recording the marine experts' decisions, the aggregation stage was created utilising the corresponding Equations (2–6). BE3 was selected for the display of the calculations. In this context, Table 14 provides similarity values and similarity functions BE3. Table 15 shows the average agreement (AA), the relative degree of agreement of each Expert (RA), and the consensus coefficient (CC).

4.6. Defuzzification stage

The defuzzification aims to produce quantifiable outcomes in fuzzy logic. Using the technique developed by Sugeno (1999), fuzzy numbers are converted into a crisp score called fuzzy possibility score (FPS). Values calculated using Equation (7) are listed in Table 16.

4.7. Occurrence probability of the BE-TE and MCS

The BE probabilities must be established to calculate the TE probability. The probabilities of all BEs were computed using Equation (8) (Table 17). According to this calculation, the root nodes with the highest risk in the occurrence of fire and explosion accident risks arising from solid bulk cargoes are as follows: (BE11) Cargo unsuitable for transportation, (BE2) violation of procedures, (BE6) Implementation of ımproper extinguishing treatment, (BE8) Improper temperature and gas monitoring. In the continuation of the calculation, BE values were placed in the TE, and the probability value was calculated. In this study, open FTA programme was used to calculate the probability value of TE. As a result of the calculation, the probability value of TE was found to be 3.59E-02. Then, the importance of each MCS in the fault tree was determined using Equation (9). A total of 24 'minimum cuts sets' were found for the top event. MCs B11-B2, B11-B6, B11-B8,

Table 10. Weight factors of experts assessing the risk of fire and explosion accident from IMSBC code Group B.

				Weight score				
Expert no.	Professional position	Professional experience in years	IMSBC group B cargo experience	Professional position (Score)	Professional experience in years (Score)	IMSBC group B cargo experience (Score)	Total score	Weight factor
1	Operation manager	35	250	5	5	5	15	0.238
2	Operation manager	23	150	5	4	5	14	0.222
3	Master	17	120	4	3	5	12	0.190
4	Master	20	120	4	4	5	13	0.206
5	Chf. officer	7	75	1	1	3	5	0.079
6	Chf officer	9	30	1	1	2	4	0.063

Table 11. Linguistic measurement scale.

	Triangular fuzzy number		
Measurement scale	a_1	a_2	a_3
Very low (VL)	0.00	0.04	0.08
Low (L)	0.07	0.13	0.19
Medium low (ML)	0.17	0.27	0.37
Medium (M)	0.35	0.50	0.65
Medium high (MH)	0.63	0.73	0.83
High (H)	0.81	0.87	0.93
Very high (VH)	0.92	0.96	1.00

Table 12. Linguistic evaluations of expert assessments of basic events.

Basic Event No	1. Exp.	2. Exp.	3. Exp.	4. Exp.	5. Exp.	6. Exp.
BE1	MH	M	VH	ML	H	H
BE2	H	H	VH	VH	MH	H
BE3	MH	M	ML	VH	H	H
BE4	M	ML	MH	H	M	ML
BE5	M	L	ML	VL	M	M
BE6	MH	H	H	VH	VH	H
BE7	L	ML	ML	VL	M	ML
BE8	H	MH	H	H	MH	M
BE9	ML	L	ML	L	ML	MH
BE10	ML	M	MH	ML	M	L
BE11	VH	H	VH	H	H	H

Table 13. Linguistic evaluations of expert assessments of each IE.

Intermediate Event No	1. Exp.	2. Exp.	3. Exp.	4. Exp.	5. Exp.	6. Exp.
IE1	H	VH	MH	MH	H	VH
IE2	M	MH	M	ML	ML	M
IE3	L	VL	ML	L	L	ML

B11-B3, and B11-B1 are significant errors that affect the probability of occurrence of TE. Table 18 shows the 10″ 'cuts set' with the highest-ranking values.

4.8. Probability calculations for ETA results

The ET diagram containing each result was created concerning the results of the examined accident reports, starting with the creation of the flammable and explosive gas (TE). Then, the likelihood of each result was determined based on the expert's linguistic evaluation. The FT and ET diagrams of each event are shown in Figure 4.

4.9. Comparison of results with the Bayesian network method

The TE probability findings of the bow tie method were compared using the Bayesian ties method. Bayesian networks facilitate the analysis and prediction of complex systems by visualising conditional dependence and independence relationships (Rohmer 2020). In the past, the Bayesian method was used in many studies evaluating fire and explosion risk. Some of them are offshore (Y. F. Wang et al. 2017), coal mines (M. Li et al. 2020), chemical plants (Zhu et al. 2019), LNG storage tanks (Zerouali and Hamaidi 2020), maritime transportation (B. Wu et al. 2021), lithium battery (J. Xie et al. 2023), hazardous chemical (X. Li et al. 2023).

The Bayesian network method consists of two parts: qualitative and quantitative learning. The structural learning part is the establishment of the network structure. The structural elements of the network are generally parent and child nodes and arrows directed from parent to child nodes. Quantitative learning is the calculation of the root nodes' prior or marginal probabilities, the child or intermediate nodes' conditional probabilities, and the result (leaf) node (Laitila and Virtanen 2022).

Conditional probabilities indicate the strength and type of causality between nodes, similar to the AND/OR transition in fault trees. To evaluate the conditional probabilities of nodes, we define the probability distribution of multiple nodes $U = \{x_1, x_2, x_3 \ldots\ldots\ldots, x_n\}$ as in Equation (11) (Jensen and Nielsen 2001).

$$P\ (U) = \prod_{i=1}^{n} P(x_i \backslash P_a(x_i)) \tag{11}$$

Table 14. BE3 similarity functions values calculations.

	Membership function								
Expert No	a_1	a_2	a_3	Similarity functions	Similarity functions value	Similarity functions	Similarity functions value	Similarity functions	Similarity functions value
E1	0.63	0.73	0.83	S(1.2)	0.770	S(2.3)	0.770	S(3.5)	0.400
E2	0.35	0.50	0.65	S(1.3)	0.636	S(2.4)	0.540	S(3.6)	0.400
E3	0.17	0.27	0.37	S(1.4)	0.770	S(2.5)	0.630	S(4.5)	0.910
E4	0.92	0.96	1.00	S(1.5)	0.860	S(2.6)	0.630	S(4.6)	0.910
E5	0.81	0.87	0.93	S(1.6)	0.860	S(3.4)	0.310	S(5.6)	0.100
E6	0.81	0.87	0.93						

Table 15. AA. RA and CC values expert for BE3.

Expert	AA	RA	CC
1	0.779	0.187	0.212
2	0.688	0.160	0.191
3	0.503	0.121	0.155
4	0.688	0.165	0.185
5	0.760	0.182	0.131
6	0.760	0.182	0.123

Table 16. Fuzzy possibility values for Bes.

	Aggregation results of basic events			
BE No	a_1	a_2	a_3	Fuzzy Possibility Score (FPS)
BE1	0.598	0.687	0.776	0.687
BE2	0.829	0.886	0.943	0.886
BE3	0.604	0.692	0.780	0.692
BE4	0.423	0.533	0.643	0.533
BE5	0.201	0.306	0.410	0.306
BE6	0.808	0.870	0.932	0.870
BE7	0.139	0.225	0.312	0.225
BE8	0.705	0.787	0.869	0.787
BE9	0.170	0.254	0.339	0.254
BE10	0.294	0.406	0.518	0.406
BE11	0.851	0.9038	0.956	0.903

Table 17. Fuzzy occurrence probability for BEs.

	Aggregated fuzzy numbers				
BE	a_1	a_2	a_3	Fuzzy occurrence Probability	Rank
BE1	0.598	0.687	0.776	1.70E-02	6
BE2	0.829	0.886	0.943	6.93E-02	2
BE3	0.604	0.692	0.780	1.76E-02	5
BE4	0.423	0.533	0.643	6.31E-03	7
BE5	0.201	0.306	0.410	9.50E-04	9
BE6	0.808	0.870	0.932	6.04E-02	3
BE7	0.139	0.225	0.312	3.38E-04	11
BE8	0.705	0.787	0.869	3.26E-02	4
BE9	0.170	0.254	0.339	5.11E-04	10
BE10	0.294	0.406	0.518	2.45E-03	8
BE11	0.851	0.9038	0.956	8.12E-02	1

The expression $P\ (U)$ is the conditional probability distribution of node U. $P_a\ (x_i),\ \ x_i$ is the parent set of x_i. Equation (12) is used to calculate the probability of x_i.

$$P(x_i) = \sum_{x_{i\,j \neq 1}} P(U) \tag{12}$$

Equation (13) is used to update the probabilities on the network in case of changes in the probabilities of the nodes in the Bayesian network.

$$P(U\backslash E) = \frac{P(U,E)}{P(E)} = \frac{P(U,E)}{\sum_u P(U,E)} \tag{13}$$

Basic events (BE), intermediate events (IE), and peak events (TE) in the bow tie method were transformed into root nodes and child and leaf nodes in Bayesian networks, respectively. The final network obtained as a result of the transformation is shown in Figure 5. In the Bayesian network marginal and conditional probability calculation, the expert opinions in Table 12 were considered using Genie software. The fuzzy Bayesian network probability calculation produced a leaf node value of 5.53E-02 (0.05%), almost identical to the fuzzy Bow-tie technique. As a result, the results obtained from the Bayesian network support the results of the Bow-tie approach.

Table 18. Calculations of the FV-I and fuzzy occurrence probabilities for MCs.

MCs	Fuzzy occurrence probability	FV-I measure index	Rank
BE11-BE2	5.620E-03	3.537E-01	1
BE11-BE6	4.906E-03	3.087E-01	2
BE11-BE8	2.650E-03	1.668E-01	3
BE11-BE3	1.420E-03	8.936E-02	4
BE11-BE1	1.389E-03	8.741E-02	5
BE11-BE4	5.120E-04	3.222E-02	6
BE10-BE2	1.690E-04	1.064E-02	7
BE10-BE6	1.490E-04	9.377E-03	8
BE10-BE8	7.999E-05	5.034E-03	9
BE11-BE5	7.717E-05	4.857E-03	10

5. Discussion and results

The study's scope included qualitative and quantitative analyses to determine the hazards of fire-explosion accidents brought on by cargoes with IMSBC code group B. Out of 31 accident reports analysed in the qualitative part of the study, 99 different accident factors were determined (Tables 3–6). The total frequency of accident factors was calculated as 323. Accident factors are classified according to the HFACS level. According to this classification, the percentage distribution of accident factors is as follows: unsafe acts (32.2%), organizsational influence (26.2%), pre-conditions for unsafe (22.2%), and unsafe supervision (14.2%). Accident factors are concentrated at the first and last levels of the HFACS.

BEs embracing 99 factors were developed for the quantitative risk evaluation of accident factors using the bow-tie approach. The most effective BEs in the event of a fire-explosion accident, according to Bow-tie results, are as follows: (BE11) unsuitable cargo for transportation, (BE2) procedural violations, (BE6) implementation of improper extinguishing treatment, and (BE8) improper monitoring of temperature and gas in the cargo hold. In this context, recommendations for eliminating high-probability BEs that most increase the probability of accident risk occurring are critical. Unsuitable cargo for transportation was found to be the most critical cause of such accidents (BE11) (Table 17). In ships carrying bulk cargo, the characteristics of the cargo to be transported must be notified in writing to the master or his representative in accordance with SOLAS Chapter 6 Rule 2 and Chapter 12 Rule 10 (IMSBC Code). Because the cargoes classified in this group are also classified as IMDG code Class 4 – (Flammable solids or substances) and Class 5: (Oxidizsing substances and organic peroxides), cargoes within the scope of Class 4 can start to burn caprice by spark friction (aluminium dust) and contact (water and air). Class 5 cargoes (Potassium chlorate) support combustion by emitting oxygen. Since they have different characteristics from the natural fire hazard, they should be carefully evaluated. Otherwise, after the cargo is accepted to the ship, in case of contact with ventilation or any foreign substance with chemical properties, the risk of heating, releasing explosive gas or burning may occur. Kaptan (2021a) studied the risks of shipping ammonium nitrate-based fertilizsers by sea. He determined that incorrect or incomplete declaration of the properties of the cargo by the shipper created a significant risk of fire and explosion accidents in parallel with the study. It is necessary to prevent this accident factor caused by the lack of communication. In this context, essential protocols should be made between the shipper and the company to determine whether the cargo is suitable for transportation. Furthermore, a legal structure that allows the master to confirm the correctness of the chemical and physical properties of the cargo in the protocols should be established.

Another critical reason is (BE2) procedural violations identified. Such accident factors result from the company's 'Cargo Handling

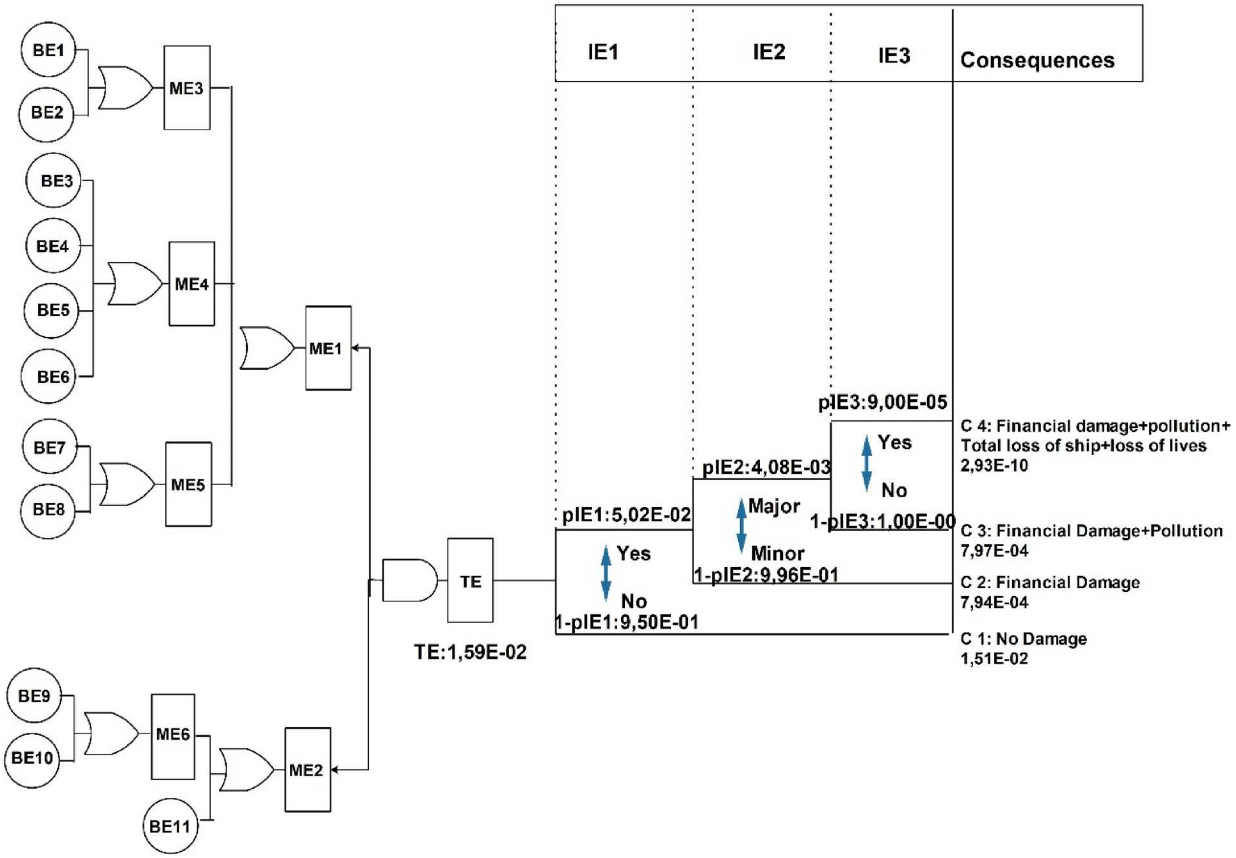

Figure 4. Bow-tie diagram for fire and explosion accident risk from bulk cargoes. (This figure is available in colour online.)

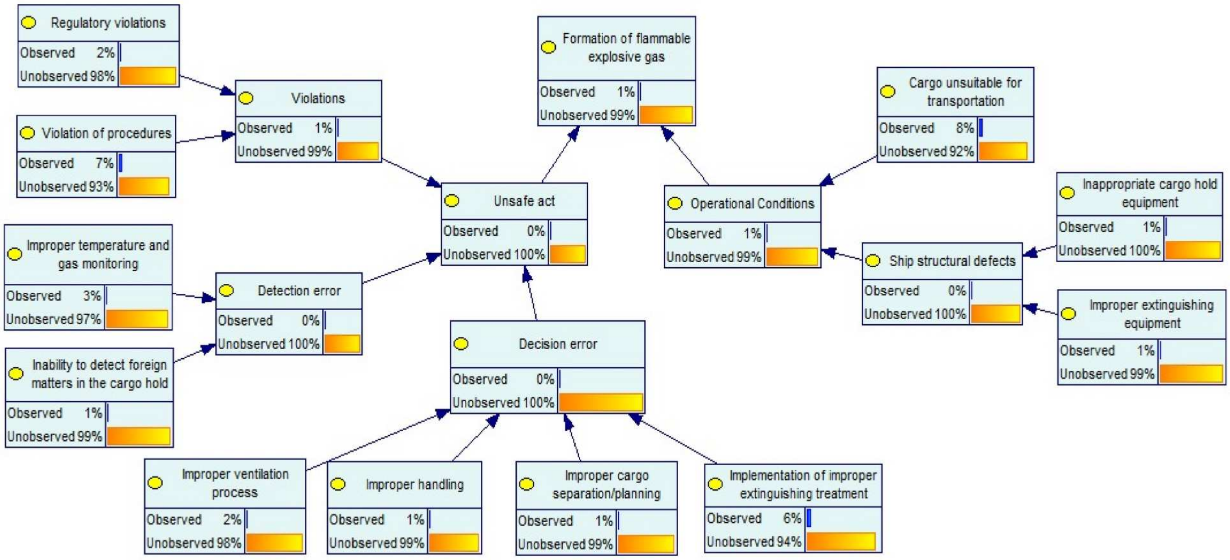

Figure 5. BN diagram for fire and explosion accident risk from bulk cargoes. (This figure is available in colour online.)

Manual' forms, the special provisions in the 'Charter Party', and the failure to follow the steps in the 'IMSBC Code' book after the cargo is accepted on board. For example, proper ventilation procedures should be applied for mineral cargoes such as coal and direct reduced iron (Kaptan 2022). On the other hand, in continuous ventilation, the cargo will come into contact with oxygen more depending on time, which will cause the cargo to heat itself and cause the risk of fire and explosion. In addition, explosive and toxic gases such as hydrogen, phosphine and arsine may occur due to the contact of the cargo with water, especially in cargoes such as Ferro silicon and Aluminium silicon powder (IMO 2016). On the other hand, hot work around the cargo and sparking material can be listed as critical procedural violations. Sarıalioğlu et al. (2020) stated that implementing improper procedural operations in the engine room significantly increased the risk of fire formation in their study examining the causes of fires in the engine room. Similarly, studies on ship fires stated that procedural non-compliances increased the risk of accident occurrence (Jinhui Wang et al. 2022; X. Xie et al. 2022). The prevention of this factor depends on whether the ship's personnel is well aware of the cargo-related procedures. Therefore, planning training at regular intervals for all bulk carrier crew should be made compulsory.

Another critical accident cause is implementation of improper extinguishing treatment (BE6). It is crucial to intervene quickly when cargoes (ammonium nitrate, etc.) start decomposing, heating up, and outgassing. It can be ensured that the event is concluded without damage by removing the deterioration in the cargo in the small area or by intervening with the fast correct fire extinguisher. Incorrect intervention is useless and may even encourage the event to turn into a fire/explosion or spread.

It plays a vital role in the occurrence of (BE8) improper temperature and gas monitoring in cargo hold fire. The accident reports examined stated that temperature increased and chemical gas releases were observed, especially before the fire and explosion accidents (Panama Maritime Authority 2009; BSU 2015; Isle of Man Ship Registry 2017). However, there were accidents where the ship's crew did not notice these signs due to improper follow-up, and there were total ship casualties due to late intervention. Therefore, technology should reduce the risk of human-induced accident factors (Wróbel 2021; Bicen and Celik 2022). Bulk carriers do not required fixed multi-purpose gas detectors in their holds. However, within the scope of IMSBC code group B, it is recommended to make it mandatory to position fixed multi-purpose gas detectors homogeneously inside the hold when cargo is transported.

Finally, only significant BEs were not detected in the study. Therefore, various accident combinations created by BEs were examined, and accident combinations that increased the accident risks were determined. It was determined that the variety of cargo unsuitable for transportation and violation of procedures, improper temperature and gas monitoring, extinguishing treatment, improper temperature and gas monitoring and improper ventilation process basic events increased the average accident probability by 3% (Table 18).

6. Conclusions

The study has devised and recommended a methodology for a realistic safety assessment of fire and explosion accidents brought on by IMSBC code group B cargoes. The proposed methodology consists of two parts. In the first part, depending on the accident reports, the factors causing the accidents were found and classified according to the HFACS method. Since the relative frequencies of the accident factors were insufficient for quantitative evaluation, fuzzy set theory was used to determine the probabilities. As such, a realistic and versatile risk assessment was carried out through the HFACS-Fuzzy Bow-tie method recommended for the quantitative analysis of risks. Since the methodology is adaptable and flexible, it can be used in risk analysis related to maritime transport.

As a result of the study, the probability of cargo-related accident risk was calculated as 3.59E-02. The most effective causes of accidents in the occurrence of accidents are as follows: (BE11) unsuitable cargo for transportation, (BE2) procedural violations, (BE6) Implementation of improper extinguishing treatment, and (BE8) improper monitoring of temperature and gas in the cargo hold. In addition, the most effective MCSs and combinations that caused the accident were determined as B11-B2, B11-B6, and B11-B8.

It has been concluded that preventing such accidents requires developing and standardising planning, effective shore-ship communication, and continuous in-service training activities. Thus, such accidents will be prevented, and safe transportation will be provided, benefiting all parties in the maritime industry. Furthermore, in future studies, researchers can obtain comprehensive findings within the scope of the subject thanks to the experimental environment they will establish in the ship environment.

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