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Research paper

An integrated risk assessment framework for fire accidents on passenger ships

Shanshan Fu [a,b], Zhan Sun [a], Chailu Jiang [a], Yunhan Hao [c], Wengang Mao [b,*]

[a] College of Transport & Communications, Shanghai Maritime University, Shanghai, China
[b] Department of Mechanics and Maritime Sciences, Chalmers University of Technology, Gothenburg, Sweden
[c] College of Foreign Languages, Shanghai Maritime University, Shanghai, China

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ABSTRACT

Passenger ships offer high capacity and comfort, but fires pose a serious risk of severe casualties. This paper proposes a framework for risk assessment of fire accidents on passenger ships by integrating failure mode and effects analysis (FMEA), risk matrix (RM) and hybrid causal logic (HCL) model. First, based on maritime accident investigation reports, identify the critical risk scenarios that cause fires on passenger ships by applying FMEA and RM. Then, an HCL model is proposed to analyze the risk process of passenger ship fire accidents. The model integrates event sequence diagrams and fault tree analysis to systematically examine the development paths and root causes of passenger ship fires, and quantifies the probabilities of fire progression scenarios. The results show that the highest fire risk stems from a sequence of events: it begins with fuel leakage in the engine room, followed by a failure to promptly address the faulty equipment, which leads to a fire. Due to delayed detection or ineffective fire extinguishing operations, the fire cannot be suppressed and spreads rapidly. Key factors are identified, along with proposed risk control options. The proposed framework can be used for quantitative risk assessment of fire accidents on passenger ships.

Nomenclature

BEs	Basic Events
BN	Bayesian Network
ESD	Event Sequence Diagram
ESs	End States
FMEA	Failure Mode and Effects Analysis
FSA	Formal Safety Assessment
FT	Fault Tree
FTA	Fault Tree Analysis
HCL	Hybrid Causal Logic
IMO	International Maritime Organization
MAIRs	Maritime Accident Investigation Reports
IEs	Intermediate Events
LLI	Lloyd's List Intelligence
PEs	Pivotal Events
PI	Probability Index
RCOs	Risk Control Options
RI	Risk Index
RM	Risk Matrix
RLs	Risk Levels
CI	Consequence Index

1. Introduction

Passenger ship transportation is widely recognized for its unparalleled advantages over other modes of passenger transportation, including the ability to accommodate large numbers of people, offer superior comfort, and provide spaces for entertainment. However, these benefits are accompanied by inherent risks. According to Luo and Shin (2019), fire accidents are among the most serious accidents affecting maritime transportation safety. The fire accident on the MS Scandinavian Star Ferry in 1990 resulted in severe casualties, with a total of 158 people killed (Blix et al., 2018). Weng and Yang (2015) reported that marine fires caused 2.32 times as many deaths as other types of marine accidents. This risk is particularly acute on passenger ships, where the large number of passengers introduces additional uncertainty. Passengers may trigger fire through unsafe behaviors. Facilities like restaurants and entertainment venues also increase the potential risk of fire. When a fire breaks out on a passenger ship, if the crew is unable to carry out effective operations, the fire can spread rapidly, potentially causing extensive damage to the ship, significant casualties, and environmental pollution (Wang et al., 2021a). Therefore, an in-depth study of the risk

* Corresponding author.
E-mail address: wengang.mao@chalmers.se (W. Mao).

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scenarios associated with passenger ship fires and an analysis of the fire progression can significantly enhance the effectiveness of fire prevention, control, and response measures, thereby improving maritime safety.

Many scholars have studied the fire risk of ships. Currently, fire dynamics (Zhang et al., 2022a; Callesen et al., 2021), accident probability analysis (Aydin et al., 2024; Bhardwaj et al., 2021; Fu et al., 2016a), and fuzzy comprehensive evaluation (Lutfi Tunçel et al., 2023; Zhang et al., 2023; Ji et al., 2020) are the main methods for analyzing the risk of fire accidents on ships. Wu et al. (2021) analyzed 132 electric vehicle fire accidents and proposed a data-driven Bayesian network model for the safety management of electric vehicles transported on RoPax ships. The results showed that adjustment on the external temperature is an effective measure for consequence reduction. Aziz et al. (2019) proposed a structured bow-tie methodology for fire/explosion failure scenarios. Porterie et al. (2024) developed a performance-based simulation tool to quantify the effects of fire on people, vessels, and cargo on roll-on/roll-off ships. The tool incorporates a deterministic computational fluid dynamics model to assess the fire consequences on vehicle decks and open areas of the ship. Liu et al. (2024) used a quantitative risk assessment methodology to evaluate the risk of leakage fires in the nacelle of a ship, and the results showed that the probabilistic approach was more accurate than the threshold approach in risk quantification. In addition to the above methods, Munim et al. (2024) used historical data of maritime accidents in Norwegian coastal waters and used machine learning methods to predict the risk of ship fire/explosion accidents. At the same time, the study showed that the three factors that have the greatest impact on the risk of accidents are category of navigation waters, phase of operation, and gross tonnage of the ship.

The single-method research mentioned above cannot fully capture the dynamics and uncertainty of fire risk. To address this, researchers combine methods better to reveal the complex characteristics of ship fire risk. Sezer and Akyuz (2024) proposed a conceptual risk modeling method for chemical tanker cargo hold fire/explosion accidents based on evidence reasoning and the success likelihood index method. This method combines Bayesian network (BN) to provide a practical tool for assessing and managing related risks. Bairami-Khankandi et al. (2025) used association rule mining and predictive Bayesian trend analysis to identify the causes of maritime accidents and observed differences between passenger ships and cargo ships and between shipboard fires and navigation accidents. Wang et al. (2021b) combined grounded theory, FTA, and BN to identify key risk factors in ship fires, highlighting timely cabin closure, effective ventilation, and rapid emergency response as crucial factors. Sarıalioğlu et al. (2020) proposed a hybrid method that combines human factors analysis, a classification system, and fuzzy fault tree analysis to analyze fire accidents in ships' engine rooms. Li et al. (2022) proposed an expert comprehensive evaluation combined with a fuzzy fault tree analysis method to assess the risk of a ship's power system under fire conditions, which eliminates the influence of incomplete statistics in the risk assessment process. Ma et al. (2024) developed a comprehensive quantitative risk analysis method based on bow-tie and fuzzy Bayesian network to assess the risk progression from cause to consequence of fire in a ship's cabin.

Another combined methodology includes the hybrid causal logic (HCL) model, which enables multi-level causal analysis in complex systems. The HCL model has been applied to risk assessment in various fields, including aviation systems (Groth et al., 2010), ship collisions (Wang et al., 2020; Wu et al., 2020), autonomous vehicles (Thomas and Groth, 2023), oil and gas industry (Abílio Ramos et al., 2020; Chalgham et al., 2020), and offshore platforms (Wang et al., 2015; Røed et al., 2009). Mohaghegh et al. (2009) proposed a hybrid approach that integrates system dynamics, BN, event sequence diagram (ESD), and fault tree (FT), integrates deterministic and probabilistic modeling perspectives, and demonstrated how to use the hybrid approach to analyze the dynamic impact of organizational factors on system risk. Zhang et al. (2022b) introduced the HCL method into the study of maritime autonomous surface ships, identifying critical influencing factors and determining event chains that lead to accidents. Similarly, Xu and Kim (2023) used the HCL model to analyze collisions between icebreakers and vessels during escort operations, proposing risk control measures based on the model's qualitative and sensitivity analysis.

The application of the HCL model offers an innovative approach for assessing fire risks on ships. The HCL model can systematically integrate various risk factors, potential failure modes, safety measures, and emergency response scenarios to provide a comprehensive assessment of risk. Moreover, the HCL model enables quantitative analysis to evaluate the contribution of individual factors in critical risk scenarios and to identify potential intervention points. This approach bridges the gap between existing methods in describing dynamic processes and modeling complex causal relationships, providing a more comprehensive framework for risk management.

In summary, significant progress has been made in ship fire risk research, with several studies specifically addressing passenger ships. For instance, Liu et al. (2021) developed an improved expert weighting and risk coefficient model to address fire risks in cruise ship bilge systems, while Bao et al. (2023) used the BN approach to prioritize fire causal chains in ro-ro passenger ships. Except for a few studies on the fire risks of passenger ships, existing research on the impact of fires on passenger ship safety mainly focuses on evacuation performance and evacuation routes, as well as the inherent fire safety levels in ship design. Liu et al. (2023) proposed an improved artificial fish swarm algorithm to provide optimal evacuation routes for evacuees during fire on passenger ships. Xie et al. (2022) proposed a quantitative method that combines fire data derived from computational fluid dynamics and AnyLogic evacuation simulations to evaluate the evacuation performance of passengers under fire accidents. Spyrou and Koromila (2020) proposed a risk model for evaluating the fire safety of passenger ships in the design stage, which can be used to assess the inherent level of fire safety for ship design.

However, due to their high passenger density and complex compartment structures, passenger ships face unique fire risk challenges. Addressing these challenges remains critical with the rising global demand for such vessels. In the domain of passenger ship fire risk assessment, existing methods often focus on static analyses of subsystems, single-factor evaluation, or evacuation simulation, while there is relatively little exploration of the complex causal mechanisms of fire development and the interactions among multiple influencing factors. To address these shortcomings, this paper proposes a risk assessment framework for fire accidents on passenger ships by integrating failure mode and effects analysis (FMEA), risk matrix (RM), and the HCL model. The FMEA and RM are applied to identify key passenger ship fire risks systematically. Then, an HCL model is proposed for analyzing fire accident process based on ESD and FT methods to comprehensively examine the progression of fire and the intricate interaction among influencing factors. Compared with existing approaches, the framework more comprehensively integrates multiple risk sources, reveals how risk factors interact across different stages and shape scenario evolution, delineates the fire's progression pathways, and on this basis, provides quantitative decision support.

The remainder of this study is organized as follows. Section 2 describes the proposed framework and associated methods. Section 3 introduces the data used in the study. Section 4 presents a case study of a framework for assessing the risk of fire accidents on passenger ships. Section 5 discusses the results from fire risk scenarios and proposes risk control options (RCOs). Finally, section 6 concludes the research.

2. Methodology

2.1. Framework

A framework for risk assessment of passenger ship fire accidents is proposed, as illustrated in Fig. 1, based on the principles of ISO 31000

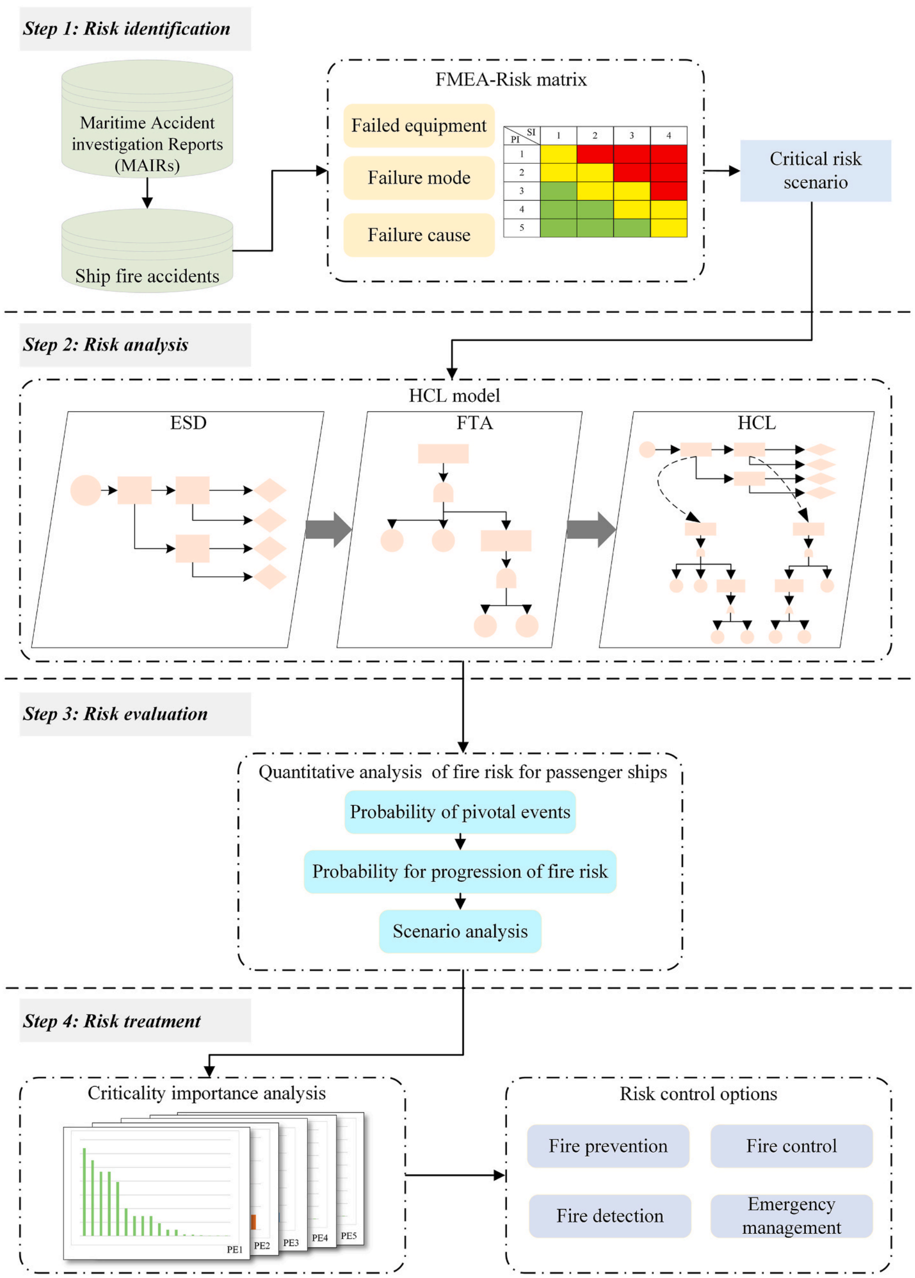


Fig. 1. Framework for risk assessment of passenger ship fire accidents.

(The International Organization for Standardization, 2018), which ensures a systematic and comprehensive approach to managing risks associated with fire accidents on passenger ships.

The framework consists of the following four main steps:

Step 1: Risk identification. Using FMEA and RM, critical risk scenarios of fire accidents on passenger ships are identified through detailed analysis of Marine Accident Investigation Reports (MAIRs) collected by maritime investigation agencies.

Step 2: Risk analysis. Based on the results of Step 1, an HCL model for fire accidents on passenger ships is proposed. Using ESD and FT, the progression of fire from ignition to gradual spread and escalation is determined, and the fundamental factors influencing the fire progression process, along with the causal relationships between these factors, are identified.

Step 3: Risk evaluation. Quantitative risk assessment is conducted on the HCL model for the critical risk scenario of passenger ship fires to calculate the probabilities of different fire progression scenarios. The model is validated and analyzed through historical data.

Step 4: Risk treatment. Scenario analysis is conducted across four dimensions: fire prevention, detection, control, and emergency management. The critical importance of each basic event is evaluated to identify the key factors influencing the progression of passenger ship fires. Based on these findings, targeted RCOs are proposed to effectively enhance fire safety on passenger ships.

2.2. Risk identification

At the risk identification stage, a hybrid approach combining FMEA and RM methods was employed to systematically identify critical risk scenarios associated with fire accidents on passenger ships.

FMEA is a widely used risk assessment method in engineering practice. It can systematically analyze causes, consequences, and severity to identify key risk points, and has been successfully applied across various fields for accident risk assessment (Chen et al., 2023; Kang et al., 2022). The method focuses on proactively predicting and analyzing failure modes, enabling effective control of risk factors before they escalate. FMEA also supports the efficient allocation of resources based on risk levels, reducing resource waste, and minimizing the likelihood of accidents. It is particularly applicable to the risk assessment of accidents such as ship fires.

The RM is a widely used semi-quantitative risk assessment tool that is applied across various industries, including aluminum (Gul and Guneri, 2016), marine, space processing (Lengyel and Mazzuchi, 2018; Zhang et al., 2017), and transportation (Benekos and Diamantidis, 2017). It's typically employed to determine risk levels (RLs) based on a combination of probability and consequence (Duijm, 2015). According to different RLs, RM is divided into different zones with different colors.

The risk can be viewed as a combination of various risk scenarios. In the maritime sector, the International Maritime Organization (IMO) formal safety assessment (FSA) (IMO, 2018) provide a RM for conventional ships, the risk can be expressed as:

$$Risk = Probability \times Consequence. \tag{1}$$

To facilitate the ranking and validation of ranking, consequence and probability indices are usually defined on a logarithmic scale. The log probability index and log consequence index are defined as PI and CI, respectively. Therefore, the risk index (RI) can be expressed as:

$$RI = log(Probability) + log(Consequence) = PI + CI. \tag{2}$$

The FSA classifies consequences into four levels: minor, significant, severe, and catastrophic. Bolbot et al. (2022) proposed an enhanced RM for both conventional and autonomous ships, incorporating five frequency classes and applying individual and societal risk acceptance criteria to determine risk ratings. Based on the FSA (IMO, 2018) and studies by Bolbot et al. (2022) and Hong et al. (2020), as well as the characteristics of passenger ship fire accidents, the logarithmic probability index was determined and the RM is developed, as shown in Table 1. Based on the FSA (IMO, 2018), an example of the logarithmic consequence index is presented in Table 2. The RM comprises 5 × 4 cells, including six intolerable risks (high risk), eight tolerable risks (medium risk), and six negligible risks (low risk), represented in red, yellow, and green, respectively.

Since the probability in Table 1 are continuous values while the Probability Index (PI) is categorized as 5 levels, the PI can be derived from,

$$PI_i = 6 + \text{round}(\log_{10} p_i), PI_i \epsilon [1, 2, 3, 4, 5], \tag{3}$$

where i represents the risk scenario, $i = 1, 2, \cdots, n$. PI_i represents the logarithmic probability index of the risk scenario, p_i represents the probability of the risk scenario occurring.

Table 1
Risk matrix.

Probability index (PI)		Probability (per ship year)	Consequence index (CI)			
			1	2	3	4
			Minor	Significant	Severe	Catastrophic
5	Frequent	10^{-1}	6	7	8	9
4	Likely	10^{-2}	5	6	7	8
3	Occasional	10^{-3}	4	5	6	7
2	Unlikely	10^{-4}	3	4	5	6
1	Rare	10^{-5}	2	3	4	5

Table 2
Logarithmic consequence index.

Scale	Consequence	Effects on human safety	Effects on ship	S (Equivalent fatalities)
1	Minor	Single or minor injuries	Minor equipment damage	0.01
2	Significant	Multiple or severe injuries	Non-severe ship damage	0.1
3	Severe	Single fatality or multiple severe injuries	Severe damage	1
4	Catastrophic	Multiple fatalities	Total loss	10

2.3. Risk analysis

The HCL model is an analytical framework that integrates multiple causal modeling approaches to describe and quantify relationships in complex systems. The HCL model generally has a structure of three layers, including ESD, FTA, and BN (Groen et al., 2006). It can be used to model each part using the most appropriate method for more complex scenarios. Given the statistical data from MAIRs can directly provide probability values for human and organizational factors, as well as the need to simplify the model to reduce its complexity and computational burden, this paper simplifies and omits the BN part in the HCL model and focuses on ESD and FTA.

ESD is a graphical method used to visualize sequences of related events (Zhou et al., 2016). It clearly illustrates the progression of events from the initial event to the end states (ESs), facilitating the identification and construction of event sequences and aiding in understanding the scenario (Stamatelatos et al., 2011). The response following the identified initial events is called the pivotal events (PEs) in ESD. ESD provides a visual analytical framework to help explain how different factors cause a hazard or accident. And it quantitatively estimates the likelihood of accidents.

FTA is a widely used tool for assessing the safety and reliability of systems (Ferdous et al., 2007). After construction, the model can calculate the probability of the top events occurring. The main constituent elements of FTA include the top events, intermediate events (IEs), basic events (BEs), and AND and OR gates. The core of FTA is to construct a logic tree rooted at the top event, which systematically traces back and graphically represents all the possible causes that lead to the events. This analysis not only helps reveal and understand potential fault paths in complex systems but also enables a qualitative and quantitative assessment of the probability of fault occurrence, providing a scientific basis for improving system design and enhancing reliability and safety.

In the FT model, M_j is used to represent the corresponding IEs, and X_i is used to represent the BEs. Under the assumption that probability is equivalent to occurrence frequency, the probability of influencing factors in the progression of a ship fire accident can be expressed as $P(X_i)$. The specific formula is:

$$P(X_i) = N_i / N, \tag{4}$$

where, N_i is the number of occurrences of the corresponding BEs, N is the total number of fires caused by fuel leakage in the engine room.

The framework of the HCL model developed in this paper is shown in Fig. 2. In the HCL framework, the PEs of ESD is the top event of FT. First, ESD is used to analyze the progression paths of passenger ship fire risks. Then, FTA is applied to examine the failure modes identified in the ESD. Finally, the two methods are integrated to construct the HCL model, which is then used for quantitative analysis.

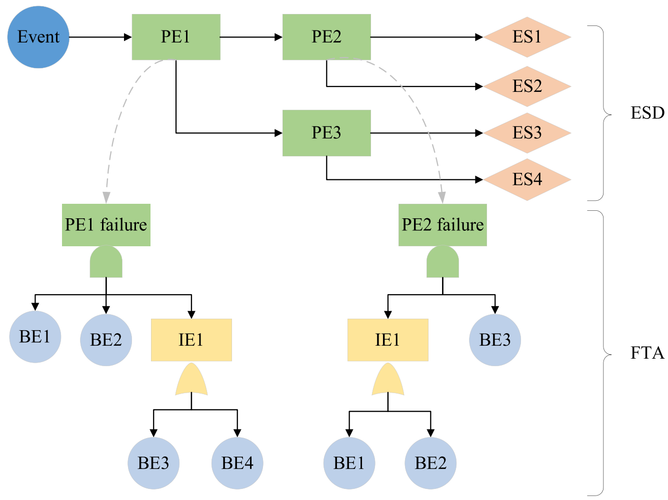


Fig. 2. Diagram of HCL model.

3. Data

3.1. Lloyd's list intelligence database

The Lloyd's List Intelligence (LLI) database mainly includes vessel details and accident details, as shown in Table 3. Based on the LLI database, 2049 accident data of passenger ships are collected from 1980 to 2022 in global waters, including 230 fire/explosion accidents on passenger ships.

According to the IMO Casualty Investigation Code (Resolution MSC.255(84)), a serious marine casualty is defined as an accident involving loss of life, serious injury, the loss of a ship, or severe damage to the ship, the environment, or property. Such accidents are subject to a mandatory safety investigation by the flag state, as shown in Table 2. In contrast, non-serious accidents typically do not require a full investigation and do not have the MAIRs. Fig. 3 illustrates the distribution of passenger ship accident types. Among all accident types involving passenger ships, fire/explosion account for the second-highest percentage of accidents, making up 11.2 % of all accidents, followed by machinery damage (28.3 %) and closely followed by groundings (11.3 %). The data indicate that from 1980 to 2022, there were 543 serious accidents on passenger ships, representing 26.5 % of the total accidents. Among these serious accidents, there were 99 cases of fire/explosion, making it second only to machinery damage and grounding. Fires on passenger ships often result in more severe injuries and greater property losses than other types of accidents.

Between 1980 and 2022, the overall number of passenger ship accidents exhibits a rising trend year by year, as shown in Fig. 4(a). Although accidents fell after 2013, the share of fire/explosion incidents continued to rise. Additionally, as shown in Fig. 4(b), the proportion of serious fire/explosion accidents exceeds 30 % across four distinct periods, peaking at 100 % between 1980 and 1990. The proportion of fires/explosions declined relative to the previous decade from 1991 to 2001, before rising again to 40.7 % in the most recent decade.

From 1980 to 2022, passenger-ship accidents generally increased. Although accidents fell after 2013, the share of fire/explosion incidents continued to rise.

Table 3
Details of LLI database.

Details	Variable
Vessel	IMO Number, Name, Loading Condition, Gross Tonnage, Dead Weight Tonnage, Flag State, Ship Type, Registered Owner
Accident	Date, Location, Pollution Indicator, Serious Indicator, Loss Type

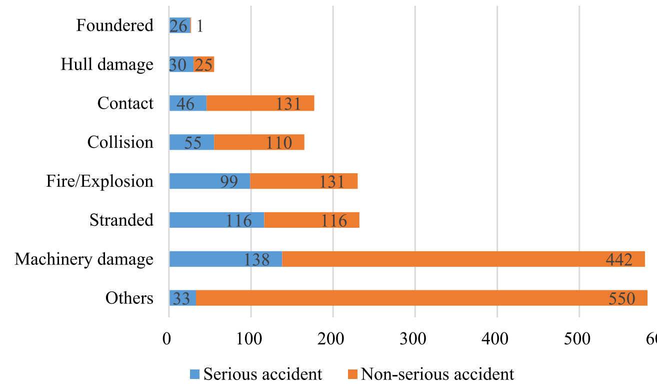


Fig. 3. Distribution of types in passenger ship accidents.

The spatial distribution of passenger ship fire accidents from 1980 to 2022, as shown in Fig. 5, are mapped based on collected location data. Red markers indicate the locations of serious passenger ship fire accidents, while green markers represent non-serious fire accidents. Evidently, the number of serious fire accidents significantly exceeds that of non-serious ones. Spatially, passenger ship fire accidents are mainly concentrated in the North Sea, the English Channel, the northeastern Mediterranean, the eastern and western coasts of the United States, and the Gulf of Mexico.

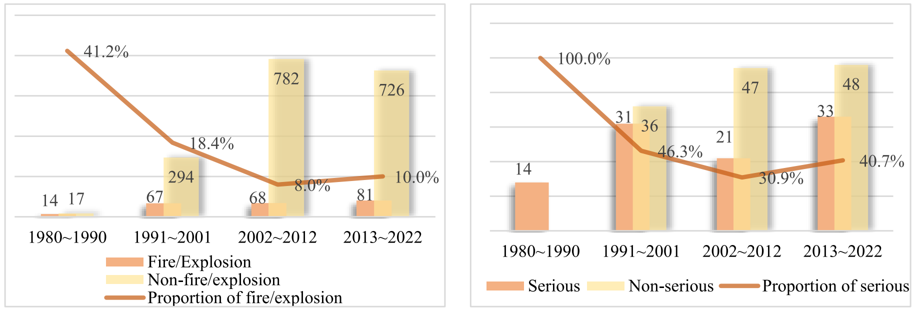
3.2. Maritime accident investigation report

MAIRs are a crucial data source for maritime safety analysis, as they contain details of all ships involved in accidents, including accident details and the detailed causes of the accidents. By searching various maritime databases, this paper compiled 62 MAIRs on fires of passenger ships from 11 maritime investigation agencies between 1996 and 2023. The data sources of the 62 MAIRs are listed in Table 4. These original data are used in the first step of the methodology, which involves risk identification. Based on this foundation, further steps including risk analysis, risk evaluation, and risk treatment, are conducted, providing data support for subsequent quantitative analysis and the development of RCOs.

According to the FSA proposed by IMO, the severity of accident consequences is divided into four levels. The temporal distribution of different accident consequence levels is shown in Fig. 6.

The MAIRs provide a wealth of information. Extracted information from MAIRs published by national maritime investigation agencies of various countries can typically be categorized into three main sections: vessel, navigation, and accident. The specific content of each section is shown in Table 5.

A further analysis of 62 passenger ship fire accidents is conducted to identify the ignition sources and fire sites. Hot surfaces are the leading ignition source, responsible for 54.65 % of cases; electrical heating is another major source. Additionally, mechanical heat and open flames contribute to numerous accidents, as illustrated in Fig. 7(a). Passenger ships typically include several types of compartments, such as the engine room, vehicle deck, passenger cabins, and service spaces, including the galley and sauna room. As shown in Fig. 7(b), the engine room is the most common site of fire, accounting for 72.58 % of the cases. This is followed by the vehicle deck at 11.29 %. Fire accidents are also reported in passenger cabins and service spaces, each accounting for 8.06 % of the total incidents.



(a) Annual distribution of passenger ship accidents.

(b) Annual distribution of passenger ship fires/explosions.

Fig. 4. Time distribution of passenger ship accidents.

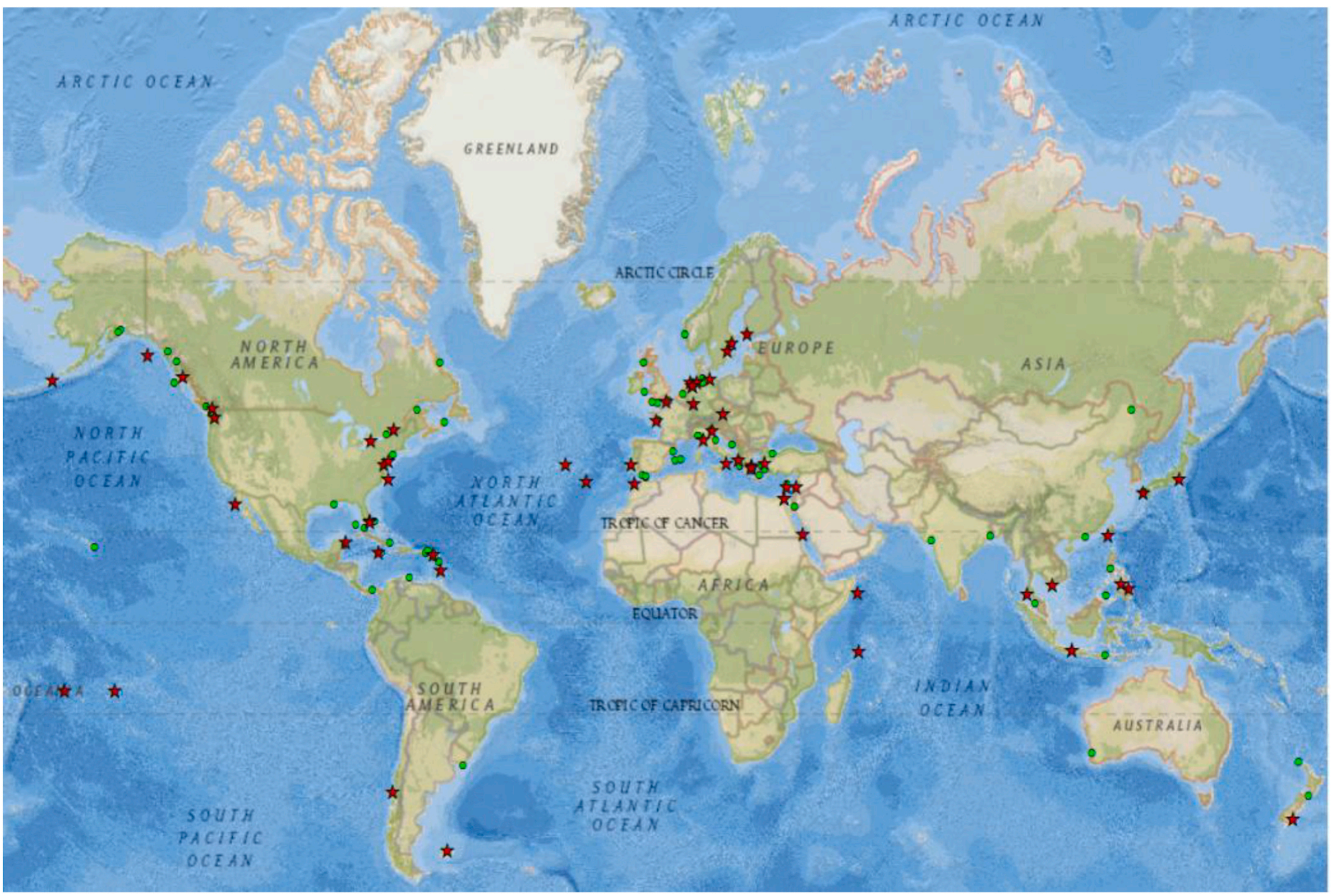


Fig. 5. Spatial distribution of passenger ship fire accidents.

4. Risk estimation

4.1. Identifying critical risk scenarios

Using the FMEA method, 62 cases of fire on a passenger ship are analyzed. Then, further analysis is conducted on the location of fires, the specific equipment and failure modes that lead to the occurrence of fires, the causes of failure, and the resulting casualties. The impacts caused by each fire accident are also recorded for subsequent assessment of accident consequences. Partial results of the analysis are shown in Table 6 as an example.

The PI and CI in this paper are calculated based on the 62 MAIRs collected. The estimation of CI is based on Table 2, while the PI is derived by first calculating the average annual failure frequency of each type of failed equipment during the accident data coverage period and then estimating PI using Eq. (3). Finally, the RI of the failed equipment is obtained using Eq. (2), as shown in Table 7.

Based on the FMEA analysis of each reported passenger ship fire accident, it is determined that the main locations for these accidents were the engine room, passenger cabin, vehicle deck, and service space. On passenger ships, there are 4 pieces of equipment are associated with a high fire risk, 14 with a medium risk, and 11 with a low risk. The engine room presents a high fire risk, with 2 pieces of equipment contributing to this risk. The primary failure modes include rupture, fracture, and electrical failure, which can result in severe consequences, such as fuel leakage, short circuits, and overheating. The electrical equipment on the

Table 4
Data source of the 62 MAIRs.

Maritime accident investigation agency	Counts
Marine Accident Investigation Branch (MAIB)	15
Transportation Safety Board of Canada (TSB)	3
Australian Transport Safety Bureau (ATSB)	1
Investigation Commission Transport Accident (TAIC)	3
National Transportation Safety Board (NTSB)	14
Maritime Safety Administration China (MSA)	2
Danish Maritime Accident Investigation Board (DMAIB)	2
Accident Investigation Board Norway (AIBN)	2
Global Integrated Shipping Information System (GISIS)	11
Marine Safety Investigation Unit (MSIU)	5
Federal Bureau of Maritime Casualty Investigation (BSU)	4
Total	62

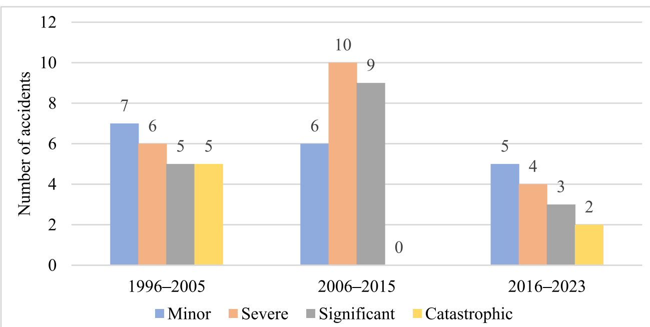


Fig. 6. Temporal distribution of the consequence of passenger ship fire accidents.

Table 5
Accident information provided by the MAIRs.

Details	Variable
Vessel	Name, IMO Number, Flag State, Ship Type, Year of Build, Gross Tonnage, Length Overall
Navigation	Port of Departure, Destination Port, Voyage segment, Loading Cargo, Number of Crew, Environmental Conditions, Operating Conditions
Accident	Time and Date, Location, Injuries/Fatalities, Analysis, Conclusions, Recommendations

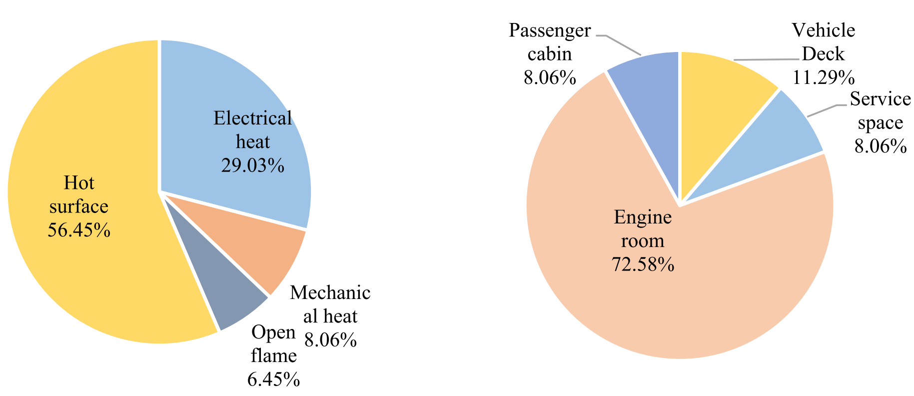
shipborne vehicle deck is classified as medium-risk equipment. Its main failure modes include overheating, short circuit and arcing, which are particularly dangerous in a closed environment. There is a high-risk electrical appliance in the passenger cabin, which is an illegal item. Overall, the failure modes in the passenger cabin are all electrical. Although potential fire sources are frequent, this area is typically equipped with a comprehensive fire detection and automatic fire extinguishing system, which can detect and suppress initial fires in a timely manner, thereby making the overall fire risk relatively controllable. The service space mostly involves high-power heating or mechanical equipment, and common failure modes include overheating, short circuits, and misoperation. The service space includes one high-risk equipment. This is typically due to the relatively low fire protection standards in this area and the limited availability of detection and fire extinguishing facilities. Additionally, the equipment that catches fire in this area is often random and accidental.

The data shows that the engine room is the most common area for fires on passenger ships, and the risk of fires caused by equipment failure in this area is very high. As a key component of a passenger ship, the engine room contains numerous important systems, including electrical equipment and a large number of flammable materials, such as high-

Table 6
Part of the FMEA analysis for passenger ship fire accidents.

No.	Location	Failed equipment	Failure mode	Failure cause	Injuries/ Fatalities
1	Engine Room	Thermal oil Heater	Coil cracks	Material defect	3 Injuries
2	Engine Room	Pressure regulating valve	Actuator diaphragm rupture	Material defect	No fatalities
3	Engine Room	Crankcase	Penetration	Mechanical failure	No fatalities
4	Engine Room	Oil return pipe	Rupture	Back pressure valve stuck	No fatalities
5	Vehicle Deck	Battery of shipborne vehicle	Electrical system short circuit	Poor technical condition	Passengers with minor scratches
6	Vehicle Deck	Battery of shipborne vehicle	Chemical reaction with seawater	Battery leakage	1 Injury
7	Passenger Cabin	Air conditioner	Electrical failure	Lack of regular maintenance	1 Injury
8	Galley	Heat oil frying pan	Circuit breaker not activated	Misoperation	No fatalities
9	Shop	Fridge power lead	Short circuit	Mechanical load	4 Injuries
10	Sauna Room	Heating element	Overheating	Lack of device management	No fatalities

According to the FMEA results, 29 pieces of equipment identified as causing ship fire accidents were analyzed, and the risk level of the failed equipment was determined using the FMEA-RM method.



(a) Distribution of ignition source. (b) Distribution of fire sites.

Fig. 7. Distribution of passenger ship fire accidents.

pressure fuel pipes. These components generate a significant amount of heat during operation, and once a failure occurs, the likelihood of fire increases substantially. When a fire occurs in the engine room, its location in the lower, critical part of the hull, combined with confined spaces and a complex internal structure, can lead to rapid fire spread. Moreover, a fire in this area can easily compromise the vessel's power and navigation systems, posing a significant risk to passenger safety.

As shown in Table 7, 12 out of the 21 identified failure modes of engine room equipment are related to fuel leakage. These failure modes mainly involve fracture, rupture, and wear. For example, key components such as fuel pipelines, oil return pipes, and flanges can fail due to fractures, installation defects, or improper maintenance. Once failure occurs, fuel may leak under high temperatures and pressure, coming into contact with ignition sources such as hot surfaces or electric arcs, which can easily lead to a fire.

Additionally, although coolant pumps, hoses, and other components do not directly transport fuel, they can still contribute to fuel system failures. Through mechanisms such as thermal damage, mechanical impact, and structural loosening, they may trigger or exacerbate fuel leakage, significantly increasing the risk of fire. According to the RI, 10 of the fuel leakage related failure modes fall into the medium to high-risk category, and the two identified high-risk equipment in the engine room are both related to fuel leakage, indicating that such events warrant close attention due to both their likelihood of occurrence and the severity of their consequences. These findings suggest that fuel leakage in the engine room is a typical trigger of passenger ship fires, characterized by both high probability and severe consequences. The identification results are compared with similar studies on ship fire accidents (Sarıalioğlu et al., 2020; Guan et al., 2025), and the results show that they are consistent, further indicating that the identification results of this study have a certain realistic basis and representativeness.

This paper identifies fire caused by fuel leakage in the engine room as a critical risk scenario. This scenario poses a significant safety hazard that necessitates thorough identification and evaluation through a comprehensive risk assessment framework, accompanied by the development of effective mitigation strategies.

4.2. ESD for the critical risk scenarios

The progression of a fire typically involves four key stages: incipient, growth, fully developed, and decay (Suh, 2025). In the incipient stage, the fire is still small and presents the best opportunity for control. During the growth stage, the fire rapidly expands from the ignition source, and fixed firefighting systems alone are often insufficient prompt intervention by the crew is essential. In the fully developed stage, the fire has burned long enough to exceed the bulkhead's fire-resistance limit, allowing it to spread beyond the compartment into the surrounding fire zone. At this point, it can only be contained through effective fire isolation measures. In the decay stage, the fire subsides as fuel is exhausted or isolated, though the risk of reignition may remain.

- The occurrence of fuel leakage in the engine room serves as a trigger for the potential subsequent fire. Whether fuel leakage becomes a fire depends on effective precautions in the engine room and timely crew action. Based on historical accident data and the typical stages of fire progression, this paper assumes fuel leakage in the engine room as the initial event of ESD, denoted by Event A, and then refines the PEs. For the PE1, when a fire occurs on passenger ships, timely precautions taken by the crew in the engine room represent effective intervention in the initial spill.
- For the PE2, in the initial phase of fire progression, the ability to detect a fire on time is crucial to prevent it from spreading. The PE2 highlights the role of early detection and alarm systems, as well as the crew's rapid response to initial fires.
- For the PE3, during the fire growth phase of fire progression, the crew's ability to perform active and effective fire extinguishing

Table 7
Risk assessment results of failed equipment.

Location	Failed equipment	Failure mode	Failure cause	PI	CI	RI
Engine Room	Heat transfer oil heater	Rupture	Stress fracture and unsuitable welding materials	2	2	4
	Fuel pipeline	Microswitch failure, fracture, bolt loosening, wear	Improper installation, design defect, lack of maintenance, debris in the pipe	4	2	6
	Thermal oil pump	Wear, leakage	Bearing failure, dislocation	3	2	5
	Cooling water pump	Friction overheating	Misoperation and lack of maintenance	2	4	6
	Valve	Bulkhead fracture	Material defects pressure	2	3	5
	Oil return pipe	Rupture	Lack of maintenance, abnormal pipeline pressure	3	3	6
	Exhaust pipe	Burst	Lack of coolant and lack of maintenance	3	3	6
	Hose	Fracture, coolant leakage	Material defects, improper installation	4	3	7
	Bolt	Fracture	Lack of early warning and examination	4	3	7
	Connecting rod	Overload	Gasket failure	2	3	5
	Testing instrument	Short circuit	Misoperation	2	4	6
	Main circuit breaker	Short circuit	Shell rupture	2	1	3
	Cable	Electrical failure	Electrical component defects	2	2	4
	Connector	Rupture	Improper installation	2	1	3
	Remote sensing box	Coolant leakage	Non-standardized operation of equipment	2	1	3
	Main switchboard	Electric arc	Lack of maintenance	2	3	5
	Junction box	Loose junction box	Lack of maintenance	2	3	5
	Flange	Fracture	Lack of maintenance, material defects, fatigue, or shift	4	2	6
	Filter	Electrical failure, leakage	Line insulation destruction, lack of maintenance	3	2	5
	O-rings	Wear	Shift	2	1	3
	Clutch	Friction overheating	Lack of maintenance	2	2	4
Vehicle Deck	Electrical equipment of shipborne vehicle	Overheating, short-circuit, electric arc	Poor circuit connection, insulation destroyed, seawater corrosion, technical flaw	4	2	6
Passenger Cabin	Illegal appliance	Electrical failure	Use of illegal appliances	3	4	7

(*continued on next page*)

Table 7 (*continued*)

Location	Failed equipment	Failure mode	Failure cause	PI	CI	RI
	Air conditioner	Electrical failure	Poor circuit connection	3	1	4
	Power plug	Appliances not turned off	Unsupervised use	2	2	4
Service Space	Hot oil fryer	Circuit breaker not activated	Misoperation and overheating failure	2	2	4
	Refrigerator	Short circuit	Mechanical load	2	2	4
	Drum dryer	Equipment overheating	Lack of maintenance	3	4	7
	Heater	Equipment overheating	Inadequate monitoring and test	3	3	6

operations will directly impact the fire's containment. The PE3 highlights the importance of crew firefighting skills.

- For the PE4, the effective evacuation of crew and passengers is essential to avoid significant loss of life before the fire reaches full scale. The PE4 emphasizes the efficiency of implementing evacuation plans and organizational coordination.
- For the PE5, in the third stage of fire progression, the effective measures taken by the crew to prevent the further spread of the fire are crucial in avoiding the total loss of the ship. The PE5 reflects a comprehensive fire response strategy and emergency management capability.

Based on the analysis of multiple possible scenarios of fire caused by fuel leakage in the engine room, different progression paths of the fire from the initial event to the ESs are obtained. Further, the ESD of fire caused by fuel leakage in the engine room as shown in Fig. 8. The detailed description of events is presented in Table 8.

A total of 7 progression scenarios are obtained, where 0 indicates normal and 1 indicates failure:

Scenario 1: Event A→PE1(0)→ES1. This scenario indicates that the fire precautions effectively prevented the fire caused by fuel leakage in the engine room.

Scenario 2: Event A→PE1(1)→PE2(0)→PE3(0)→PE4(0)→ES2. This scenario represents a situation where fire precautions failed, resulting in a fire. However, since the fire was promptly detected at the incipient stage, effective fire extinguishing operations and evacuation measures successfully minimized the losses and prevented any casualties.

Scenario 3: Event A→PE1(1)→PE2(0)→PE3(0)→PE4(1)→ES3. This scenario is similar to the Scenario 2, except that the evacuation failed, resulting in casualties.

Scenario 4: Event A→PE1(1)→PE2(0)→PE3(1)→PE5(0)→PE4(0)→ES4 or Event A→PE1(1)→PE2(1)→PE5(0)→PE4(0)→ES4. This scenario includes two paths, indicating that the fire was not effectively extinguished during the incipient and growth stages due to delayed detection or failure of fire extinguishing operations. Nevertheless, subsequent fire containment successfully confined the fire within the engine room, avoiding casualties.

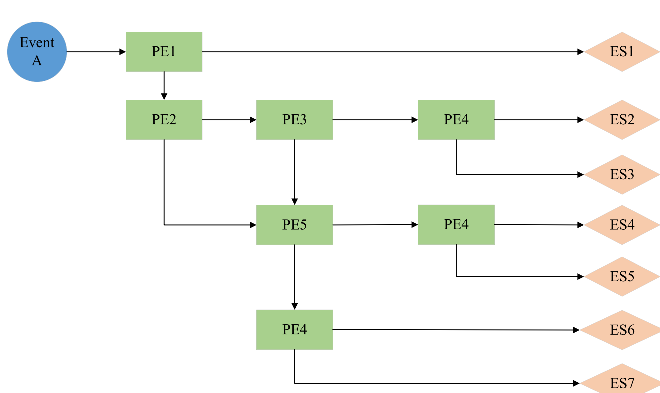


Fig. 8. ESD of fire caused by fuel leakage in the engine room.

Table 8
Description of ESD.

Events	Description
Event A	Fuel leakage in the engine room
PE1	Effective fire precautions
PE2	Timely fire detection
PE3	Effective fire extinguishing operations
PE4	Successful evacuation
PE5	Fire containment
ES1	No fire
ES2	Fire occurrence, Minor damage, No casualties
ES3	Fire occurrence, Minor damage, Casualties involved
ES4	Fire occurrence, Severe damage to the affected cabin, No casualties
ES5	Fire occurrence, Severe damage to the affected cabin, Casualties involved
ES6	Fire occurrence, Total ship damage, No casualties
ES7	Fire occurrence, Total ship damage, Casualties involved

Scenario 5: Event A→PE1(1)→PE2(0)→PE3(1)→PE5(0)→PE4(1)→ES5 or Event A→PE1(1)→PE2(1)→PE5(0)→PE4(1)→ES5. This scenario includes two paths, similar to Scenario 4. The difference lies in the failure of evacuation. Although the fire was contained within the engine room, casualties still occurred.

Scenario 6: Event A→PE1(1)→PE2(0)→PE3(1)→PE5(1)→PE4(0)→ES6 or Event A→PE1(1)→PE2(1)→PE5(1)→PE4(0)→ES6. This scenario includes two paths, indicating that the fire was not effectively suppressed during the incipient and growth stages due to delayed detection or failure of fire extinguishing operations. As fire containment also failed, the fire escalated into a fully developed stage and spread throughout the entire ship. Although the evacuation was successful, the ship still sustained severe damage.

Scenario 7: Event A→PE1(1)→PE2(0)→PE3(1)→PE5(1)→PE4(1)→ES7 or Event A→PE1(1)→PE2(1)→PE5(1)→PE4(1)→ES7. This scenario includes two paths and is similar to Scenario 6. The key difference lies in the failure of evacuation, which resulted not only in severe damage to the ship but also in casualties. It represents the most severe scenario.

4.3. FTA of pivotal events

The PEs identified in the ESD all represent successful and positive processes, outlining sequential development paths from the initial event to desired outcomes. To thoroughly analyze the potential risk factors behind these events, FTA is introduced, and the PEs in the ESD are transformed into their opposite concepts, which trace back from the undesired top events to the possible causes and conditions. In the FT model of this paper, PEs failure is used to denote the concepts opposite to PEs.

PE1 failure: Lack of effective fire precautions. The key initial factor in fuel leakage causing a fire in the engine room is the failure to detect the leakage in a timely manner. The primary initial factor contributing to fuel leakage in the engine room, which can cause a fire, is the lack of effective fire precautions. This is mainly due to the lack of safety precautions, the failure of the leakage alarm system, and the crew mishandling. The specific reasons for the failure of the leakage alarm system are the failure or lack of the pressure alarm device and the wear detector. After the fire occurs, the crew mishandling, such as the failure to quickly cut off the fuel supply and the failure to report it promptly, worsened the situation and increased the risk of fire. Additionally, the lack of proper leakage sleeves and insufficient adiabatic protection of equipment increase the possibility of fire occurrence.

PE2 failure: Delayed fire detection. Fire detection delays encompass various issues, including fire detection system failures, fire alarm malfunctions, and crews' inability to detect fires promptly. The failure of the fire detection system can be attributed to two main reasons. First, a malfunction of the fire detection equipment, and second, an insufficient number of fire detectors or improper installation, which prevents the detection of a fire even when it occurs. The primary reasons for alarm failure include malfunction, inadequate alarm equipment, and failure to issue timely warnings during critical moments. The delayed detection of fires by the crew is attributed to unattended cabins, non-standardized patrol procedures, and crew misjudgment.

PE3 failure: Fire extinguishing operations failure. The failure of fire extinguishing operations can be attributed to various factors. Inaccessible fire areas often lead to unsuccessful extinguishing efforts, even when fixed firefighting systems are activated, requiring manual intervention. The failure of the firefighting equipment further exacerbated the difficulties of extinguishing the fire. Equipment failures, such as an emergency fire pump failure, an insufficient number of fire extinguishers, difficulty in obtaining them, and the failure of fixed firefighting equipment, contributed to the rapid spread of the fire. In addition, improper firefighting operations by the crew, stemming from inadequate emergency procedures and unfamiliarity with the location of firefighting equipment, directly impact the effectiveness of firefighting.

PE4 failure: Evacuation failure. The reasons for the evacuation failure include the lack of emergency plans, weak passenger evacuation capability, poor evacuation conditions, insufficient crew training and drills, and inadequate rescue facilities. The main issue with emergency plans is the lack of clear emergency responsibility and inadequate emergency response plan. The unfamiliarity with escape routes and life-saving equipment reflects weak passenger evacuation capability. Poor evacuation conditions are primarily reflected in the improper placement of life-saving facilities and unreasonable escape routes, resulting in

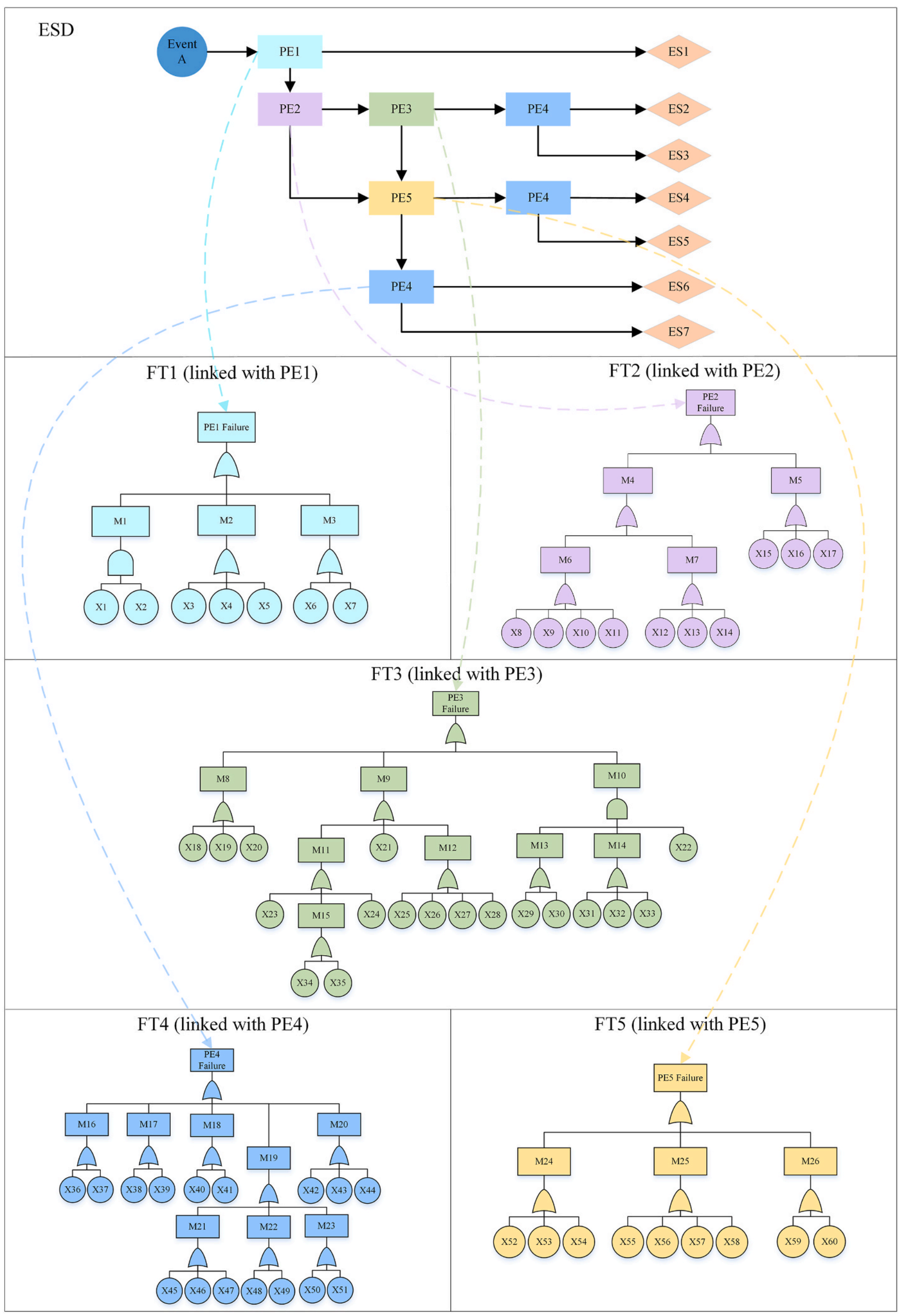


Fig. 9. HCL model for fire accidents on passenger ships.

congestion. Insufficient crew training and drills result in the crew being unfamiliar with life-saving equipment, unable to manage passengers in a timely and effective manner, and poorly communicating with the fire department and Coast Guard.

PE5 failure: Fire spread. The fire spread mechanism largely depends on two basic elements: sufficient fuel and oxygen. Under this condition, the presence of uncontrolled combustibles and the failure to isolate oxygen are the two key factors contributing to the spread of fire. Additionally, the lack of fire barriers is a significant factor in the fire spread, as evidenced by the absence of effective fire zones and inadequate insulation in the engine room bulkheads.

4.4. HCL modelling

An HCL model is constructed based on the ESD and FTA results. Firstly, the event progression paths in the ESD are mapped to the root causes identified in the FTA, establishing a direct link between events and their causes. Secondly, the model is further refined by determining the interactions and influences between these events and causes to reveal a more complex network of causal relationships. Finally, by integrating the sequential logic of the ESD with the causal logic of the FT model, an HCL model for fire accidents on passenger ships is developed, as shown in Fig. 9. Meanwhile, Table 9 provides descriptions of the IEs, while Table 10 details the BEs.

5. Results and discussion

5.1. Validation

Validation is an essential and indispensable step in the modeling process, as it helps confirm the accuracy of data analysis and the rationality of model construction. This paper conducts a comprehensive validation of the data and the proposed HCL model, which necessitates a careful review of both the data and the model itself.

The reliability of data is the basic guarantee for conducting rigorous risk assessment modeling research. This paper mainly uses the objective data source of MAIRs. Compared with subjective data such as expert judgment, objective data can more accurately reflect the evolution of accidents, help avoid potential interference of subjective factors on model results, and thus improve the scientificity and reliability of modeling analysis. To ensure the authenticity and integrity of the data, this paper collected a total of 62 MAIRs from multiple official investigation agencies. The use of official MAIRs not only enhances the reliability of the data source, but also provides solid data support for the research. This paper further emphasizes the importance of relying on standardized and systematic data collection and analysis methods in the risk assessment modeling process.

For modal validation, a framework for construct validity widely used in social science research (Goerlandt and Montewka, 2014) is employed, which is particularly applicable to modeling complex relationships in dynamic environmental systems and has been used in maritime risk analysis (Trochim and Donnely, 2008; Fu et al., 2016b). The framework encompasses several types of validity, some of which can be assessed quantitatively, while most require a qualitative judgment. In this study, the following qualitative scale is adopted to assess the validity of the HCL model:

- Solid supporting evidence that a model performs well: good;
- Some supporting evidence that a model performs well: moderate;
- Little or no supporting evidence that a model performs well: poor.

In the context of the HCL model, the adopted validation framework

Table 9
Description of the IEs.

IEs	Description	IEs	Description
M_1	Lack of safety precautions	M_{14}	Failure of fixed firefighting equipment
M_2	Failure of leakage alarm system	M_{15}	Failure to cut off fuel supply
M_3	Crew mishandling	M_{16}	Lack of emergency plan
M_4	Fire detection failure	M_{17}	Weak passenger evacuation capability
M_5	Crew failed to detect fire promptly	M_{18}	Poor evacuation conditions
M_6	Fire detection system failure	M_{19}	Insufficient crew training and drills
M_7	Fire alarm failure	M_{20}	Inadequate rescue facilities
M_8	Inaccessible fire area	M_{21}	Ineffective passenger management
M_9	Improper firefighting operations	M_{22}	Unfamiliar with life-saving equipment
M_{10}	Firefighting equipment failure	M_{23}	Poor communication
M_{11}	Non-compliant firefighting procedures	M_{24}	Uncontrolled combustibles
M_{12}	Unfamiliar with ship's fire system	M_{25}	Failure to isolate oxygen
M_{13}	Fire extinguisher failure	M_{26}	Lack of fire barriers

Table 10
Description of the BEs.

BEs	Description	BEs	Description
X_1	Lack of leakage sleeves	X_{31}	CO2 system failure/missing
X_2	Lack of adiabatic protection	X_{32}	High-pressure water mist system failure
X_3	High-pressure alarm failure/missing	X_{33}	Foam suppression system failure/missing
X_4	Wear detector failure/missing	X_{34}	Failure to close fuel valve promptly
X_5	Low-pressure alarm failure/missing	X_{35}	Pressure relief valve not opened
X_6	Failure to cut off fuel supply	X_{36}	Lack of clear emergency responsibility
X_7	Failure to report promptly	X_{37}	Inadequate emergency response plan
X_8	Smoke detector failure/missing	X_{38}	Passengers unfamiliar with escape routes
X_9	Improper smoke detector placement	X_{39}	Incorrect life jacket use by passengers
X_{10}	Heat detector failure/missing	X_{40}	Improper lifeboat placement
X_{11}	Failure to detect fire promptly	X_{41}	Poor escape route design
X_{12}	Fire alarm system failure/missing	X_{42}	Insufficient breathing apparatus
X_{13}	In manual mode	X_{43}	Lifeboats insufficient/faulty
X_{14}	Failure to alarm promptly	X_{44}	Insufficient life jackets
X_{15}	Unattended cabin	X_{45}	Delayed rescue coordination
X_{16}	Non-standardized patrol procedure	X_{46}	No guidance on life jacket use
X_{17}	Crew misjudgment	X_{47}	Delayed passenger evacuation notice
X_{18}	Poor ship structural design	X_{48}	Unsuccessful breathing apparatus use
X_{19}	Unclear fire zone naming	X_{49}	Failure to release lifeboats promptly
X_{20}	Smoke	X_{50}	No coordination with firefighting teams
X_{21}	Lack of effective emergency procedures	X_{51}	Delayed signal to coast guard
X_{22}	Emergency fire pump failure	X_{52}	Improper fuel storage
X_{23}	No risk assessment before firefighting	X_{53}	Engine room not keep clean
X_{24}	Failure to cut off power supply	X_{54}	Failure to cut off fuel supply promptly
X_{25}	Improper fire suppression system use	X_{55}	Failure to close ventilation ducts
X_{26}	Inadequate firefighting equipment use	X_{56}	Failure to close engine room doors
X_{27}	Unfamiliar with firefighting equipment locations	X_{57}	Failure to close fire dampers
X_{28}	Switched to manual	X_{58}	Watertight doors not closed
X_{29}	Insufficient fire extinguishers	X_{59}	Lack of fire zones
X_{30}	Difficulty accessing fire extinguishers	X_{60}	Bulkheads lack insulation

encompasses multiple types of validity, systematically evaluating the scientific soundness and applicability of the model from different perspectives. Specifically, face validity concerns the extent to which the model intuitively and reasonably represents the real-world phenomenon under study; content validity assesses whether the variables and structure of the model adequately reflect key elements of the actual system; predictive validity measures the model's ability to simulate or forecast future scenarios and system behavior; and concurrent validity emphasizes the consistency between the proposed model and existing studies or validated models.

In the application of the framework, this paper focuses on four primary types of validity: face, content, predictive, and concurrent. Each type is evaluated qualitatively, and the results are summarized in Table 11.

5.2. Quantitative analysis

According to the fire accident data in this paper, there are 34 fire accidents caused by fuel leakage in the engine room of passenger ships.

Table 11
Qualitative ratings of the validity types comprised in the validation framework.

Validity type	Qualitative rating	Explanation
Face	Moderate-good	The proposed HCL model reasonably reflects the progression of passenger ship fire accidents. The model structure is based on related works by Xu and Kim (Xu and Kim, 2023), Wang et al. (Wang et al., 2020), and Bao (Bao et al., 2023), and utilizes objective data from 62 maritime accident investigation reports (MAIRs) from official investigation agencies. Therefore, the HCL model has strong explanatory power in structure and its face validity can be rated as moderate to good.
Content	Moderate	The HCL model incorporates critical risk scenarios identified through the FMEA-RM method, including causal chains initiated by failed equipment, such as bolts, hoses, and fuel pipelines, leading to fuel leakage and subsequent fire events. These identified risks are consistent with findings from previous studies on ship fire accident risk (e.g., Sarıalioğlu et al., 2020; Guan et al., 2025), indicating that the model's risk identification has a realistic foundation and representativeness. Furthermore, the model accounts for five pivotal event nodes, covering multiple stages of passenger ship fire progression, including fire prevention, fire detection, initial response, fire suppression, and evacuation. Due to the incompleteness of MAIRs itself, the model still has certain shortcomings, so its content validity can be rated as medium.
Predictive	Good	The HCL model outputs seven potential fire progression scenarios, with Scenario 7 identified as the highest risk path based on probabilistic quantification. This outcome aligns with historical data, which show that over 30 % of real-world accident paths correspond to Scenario 7, thereby meeting the requirements of predictive validity.
Concurrent	Good	The risk assessment framework proposed in this study is built upon the ISO 31000 (The International Organization for Standardization, 2018) risk management standard, providing strong normative support. Moreover, the modeling techniques employed—event sequence diagram ESD and FTA are recommended by the IMO (IMO, 2018) for maritime risk assessment and have been applied in previous studies (Wang et al., 2020; Wu et al., 2020; Zhang et al., 2022b; Xu and Kim, 2023).

In summary, as the evaluations of face, content, predictive, and concurrent validity in Table 11 are all rated moderate to good, the proposed model is considered to have moderate to good validity in assessing the risk of passenger ship fire accidents.

Based on the historical accident data, the probability of BEs is calculated according to Eq. (4). The number of occurrences of BEs in MAIRs and the calculated probability values are shown in Table 12.

The probability of BEs is used in the FT model as the input parameters of the underlying events to calculate the probability of PEs. By inputting the calculated probability of the BEs into the FT model and performing the calculations using FreeFTA software, the probability of PE1 failure is determined to be 5.33E-01. Using the same probability calculation method, the failure probabilities for the remaining 4 PEs are analyzed quantitatively. Since PEs and their failure are mutually exclusive, this paper further derives the probability of PEs. The final probability obtained for PEs is summarized in Table 13.

Following the BEs probability formula previously described, the probability of Event A is quantified as the ratio of the number of fire accidents caused by fuel leakage in the engine room of passenger ships to the total number of fire accidents of passenger ships. Accordingly, the probability of Event A is calculated to be 5.48E-01. Based on the probabilities of PEs quantitatively obtained from the FT, combined with the analytical framework of ESD, this paper further explores the probability of 7 scenarios of fire caused by fuel leakage in the engine room of passenger ships. The results of the progression of fire risk on passenger ships are presented in detail in Fig. 10.

The analysis results in Fig. 10 show that in the early stages of fuel leakage, the ship has a high probability of effectively preventing and promptly detecting the fire. This highlights the success of fire prevention measures. However, once the fire spreads, the chances of containing it and evacuating efficiently decrease, primarily due to delays in fire suppression and evacuation efforts. In the engine room, poor maintenance of firefighting equipment and failure to shut down ventilation systems worsen the difficulty of extinguishing the fire once it starts. Additionally, the multiple decks of passenger ships and their complex structural design complicate evacuation paths, and inadequate crew training, as well as a lack of firefighting knowledge among passengers, further hinder effective evacuation during fire emergencies.

5.3. Scenario analysis

The probabilities of various progression scenarios in passenger ship fires are compared and analyzed against the actual occurrence probabilities of accident scenarios to verify the model's accuracy and applicability. The ranked probability results of these progression scenarios are presented in Table 14.

The probability of timely discovery and control of fuel leakage in the engine room without causing a fire is 0.256, while the probability of fire occurrence is 0.744. This indicates that current measures to prevent and control fuel leakage in the engine room are insufficient. Among the progression paths following a fire, Scenario 7 has the highest probability of occurrence, 0.191, and is accompanied by the most severe consequences, which can be regarded as the scenario with the highest fire risk. The progression of scenario 7 begins with an untreated fuel leakage in the engine room causing a fire. Due to delayed detection or ineffective fire-fighting measures, the fire was not suppressed and spread rapidly. Ultimately, the failure to evacuate passengers and crew led to serious consequences including casualties. Eleven accidents, accounting for 32.4 % of the total, follow the progression path described in Scenario 7.

On January 14, 2018, the passenger vessel Island Lady caught fire on the Pithlachascotee River in Florida. The progression of this fire accident resembled that of Scenario 7. The fire was caused by overheating of the port engine. The failure of the cooling water pump caused the temperature to rise sharply, resulting in cracks in the engine cylinder. This led to abnormal pressure in the fuel system, fuel leakage to the high-temperature area, and ultimately ignited the exhaust pipe and surrounding structures. Due to the absence of a fire detection system in the lazarette, the fire was not detected in time. Additionally, the crew lacked sufficient fire response training and was unable to control the fire effectively in its early stages. The design flaws and inappropriate

Table 12
Probability of the BEs.

BEs	Counts	$P(X_i)$	BEs	Counts	$P(X_i)$	BEs	Counts	$P(X_i)$	BEs	Counts	$P(X_i)$
X_1	5	1.47E-01	X_{16}	1	2.94E-02	X_{31}	12	3.53E-01	X_{46}	4	1.18E-01
X_2	18	5.29E-01	X_{17}	5	1.47E-01	X_{32}	8	2.35E-01	X_{47}	5	1.47E-01
X_3	2	5.88E-02	X_{18}	3	8.82E-02	X_{33}	3	8.82E-02	X_{48}	4	1.18E-01
X_4	2	5.88E-02	X_{19}	1	2.94E-02	X_{34}	8	2.35E-01	X_{49}	6	1.76E-01
X_5	2	5.88E-02	X_{20}	9	2.65E-01	X_{35}	3	8.82E-02	X_{50}	2	5.88E-02
X_6	11	3.24E-01	X_{21}	11	3.24E-01	X_{36}	3	8.82E-02	X_{51}	4	1.18E-01
X_7	3	8.82E-02	X_{22}	3	8.82E-02	X_{37}	9	2.65E-01	X_{52}	1	2.94E-02
X_8	3	8.82E-02	X_{23}	4	1.18E-01	X_{38}	4	1.18E-01	X_{53}	1	2.94E-02
X_9	2	5.88E-02	X_{24}	3	8.82E-02	X_{39}	4	1.18E-01	X_{54}	6	1.76E-01
X_{10}	1	2.94E-02	X_{25}	8	2.35E-01	X_{40}	1	2.94E-02	X_{55}	16	4.71E-01
X_{11}	2	5.88E-02	X_{26}	9	2.65E-01	X_{41}	4	1.18E-01	X_{56}	4	1.18E-01
X_{12}	5	1.47E-01	X_{27}	2	5.88E-02	X_{42}	2	5.88E-02	X_{57}	6	1.76E-01
X_{13}	1	2.94E-02	X_{28}	3	8.82E-02	X_{43}	2	5.88E-02	X_{58}	3	8.82E-02
X_{14}	1	2.94E-02	X_{29}	4	1.18E-01	X_{44}	1	2.94E-02	X_{59}	2	5.88E-02
X_{15}	1	2.94E-02	X_{30}	1	2.94E-02	X_{45}	5	1.47E-01	X_{60}	9	2.65E-01

Table 13
Probability of the PEs.

PEs	Description	Probability
PE1	Effective fire precautions	4.67E-01
PE2	Timely fire detection	4.93E-01
PE3	Effective fire extinguishing operations	1.16E-01
PE4	Successful evacuation	1.47E-01
PE5	Fire containment	1.87E-01

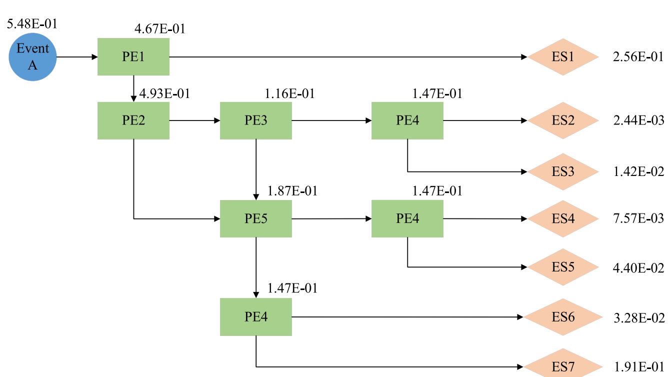


Fig. 10. Results of progression of fire risk on passenger ships.

Table 14
Ranking of probability for progression scenarios of fire risk on passenger ships.

Ranking	Progression Scenarios	Probability
1	Scenario 1: Event A→PE1(0)→ES1	2.56E-01
2	Scenario 7: Event A→PE1(1)→PE2(0)→PE3(1)→PE5(1)→PE4(1)→ES7 or Event A→PE1(1)→PE2(1)→PE5(1)→PE4(1)→ES7	1.91E-01
3	Scenario 5: Event A→PE1(1)→PE2(0)→PE3(1)→PE5(0)→PE4(1)→ES5 or Event A→PE1(1)→PE2(1)→PE5(0)→PE4(1)→ES5	4.40E-02
4	Scenario 6: Event A→PE1(1)→PE2(0)→PE3(1)→PE5(1)→PE4(0)→ES6 or Event A→PE1(1)→PE2(1)→PE5(1)→PE4(0)→ES6	3.28E-02
5	Scenario 3: Event A→PE1(1)→PE2(0)→PE3(0)→PE4(1)→ES3	1.42E-02
6	Scenario 4: Event A→PE1(1)→PE2(0)→PE3(1)→PE5(0)→PE4(0)→ES4 or Event A→PE1(1)→PE2(1)→PE5(0)→PE4(0)→ES4	7.57E-03
7	Scenario 2: Event A→PE1(1)→PE2(0)→PE3(0)→PE4(0)→ES2	2.44E-03

materials used in the fuel tank indication system contributed to the rapid spread of the fire throughout the vessel. During the evacuation, the crew failed to distribute life jackets in time, and the passengers jumped directly into the water to escape, resulting in injuries to the passengers. As a result, the fire became uncontrollable, completely destroying the vessel, causing one fatality and injuring 15 others.

Scenario 6 follows the same fire progression path as Scenario 7 but the scenario does not result in any injuries. Six accidents, or 17.6 % of the total, followed the path of Scenario 6. The highest probabilities of PE4 and PE5 failures during this progression are 0.853 and 0.813, respectively.

In Scenario 5, fuel leakage in the engine room caused a fire, but due to delayed detection or failure of fire extinguishing operations, the fire was not extinguished in time and the fire spread. Although the fire is eventually contained and further spread is prevented, the failure to implement effective evacuation measures results in injuries and fatalities. Scenario 5 has the third-highest progression probability of 0.044, but no casualties are reported in the MAIRs. In the MAIRs, the crew evacuates passengers promptly, thereby avoiding casualties. It's similar to the response observed in Scenario 4, which accounts for a higher proportion of actual passenger ship engine room fires caused by fuel leakage. In total, five accidents, or 14.7 %, follow the progression path of Scenario 4.

The fire accident involving the Oscar Wilde on February 2, 2010, in Falmouth Bay followed a progression path consistent with Scenario 4. The fire was initiated by a rupture in the actuator diaphragm of a pressure regulator valve, caused by material defects and inadequate maintenance. As a result, fuel was sprayed onto the hot surface of an adjacent auxiliary engine, igniting a fire. The fixed fire extinguishing system proved ineffective due to insufficient gas pressure and incomplete nozzle coverage, allowing the fire to escalate. Eventually, the crew manually activated the emergency fire pump. The fire-resistant structure of the auxiliary engine room successfully prevented the fire from spreading further, and personnel evacuation was completed without incident. The fire caused severe damage to the auxiliary engine room and adjacent areas but did not affect the rest of the vessel.

On September 20, 2009, the passenger ferry Fire Island Belle, carrying 100 passengers, caught fire in the Great South Bay, New York. The accident followed the progression path of Scenario 2. The fire was triggered by the fatigue fracture of a pipe fitting on the secondary fuel filter of the central engine, causing fuel to spray onto the exhaust pipe of the port-side engine. The fuel ignited upon contact with gaps in the exhaust pipe, sparking the fire. The fire alarm system did not activate immediately, allowing the flames to spread initially. After the fire broke out, the crew used the onboard fixed Halon system to extinguish it. The fire was contained and extinguished shortly after detection. The captain promptly docked the vessel, safely evacuating all passengers and crew without any casualties. According to the MAIRs, there are eight accidents similar to the progression path of Scenario 2, accounting for 23.5 % of all accidents. However, no accidents follow a fire progression path of Scenario 3. This shows that the crew implements effective emergency measures after the fire occurs, successfully controls the flames, and safely evacuates all personnel in accordance with the emergency response manual.

5.4. Risk control options

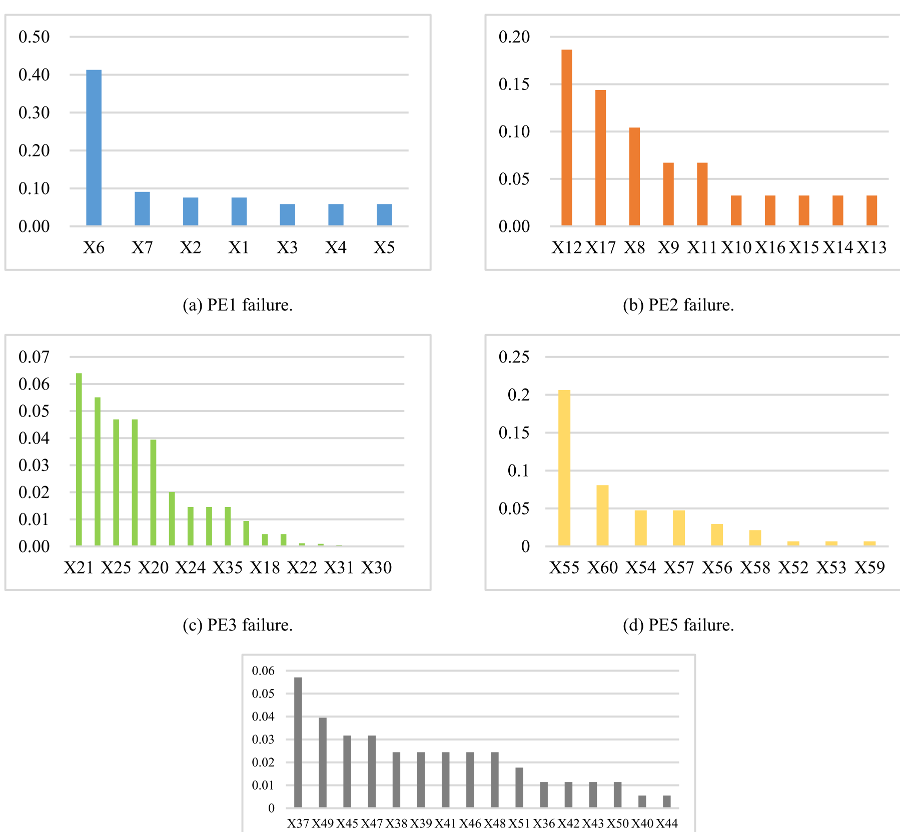
The RCOs are a critical component of risk management. They refer to feasible measures or strategies proposed during risk assessment to reduce risk levels and enhance system safety. In this paper, the concept of critical importance is introduced to support the identification and prioritization of RCOs. In the context of risk assessment, this indicator helps determine which basic events have the greatest impact on system safety, thereby guiding developing and prioritizing control measures. The critical importance is a quantitative metric used to evaluate the influence of basic events on the probability of the top event. It reflects the extent to which the occurrence of a basic event contributes to overall system risk.

By calculating the criticality importance of each basic event, key weaknesses with high risk and sensitivity can be identified, providing a scientific basis for targeted risk control. Based on this analysis, this paper proposes RCOs in four areas: fire prevention, fire detection, fire control, and emergency management, aiming to translate analytical results into actionable safety measures to reduce the likelihood or mitigate the consequences of hazardous events. The critical importance of basic events is calculated and ranked using FreeFTA software, as shown in Fig. 11.

5.4.1. Fire prevention

Based on the FMEA and RM methods, this paper identifies engine room fuel leakage as a critical risk scenario for passenger ship fires, representing a significant fire risk in the engine room. The related failure modes primarily include the fracture of high-risk components, such as hoses and bolts, as well as the rupture, fracture, and wear of medium-risk components, including fuel pipelines, oil return pipes, and flanges. When fuel leaks under high temperature and high-pressure conditions and comes into contact with hot surfaces or electrical arcs, it can easily trigger a fire. To address the above medium- and high-risk components, it is essential to strengthen leak prevention measures, with a focus on risk monitoring, regular inspections, and effective maintenance management. At the same time, thermal insulation protection should be installed on the hot surfaces of various high-temperature devices in the engine room, such as the exhaust pipe and heat transfer oil heater. Furthermore, the selection and structural design of insulation materials should be enhanced, and a comprehensive mechanism for periodic inspection, repair, and replacement should be established to ensure long-term effectiveness. These measures aim to improve the overall fire safety level of passenger ships.

Based on the criticality importance analysis of the PE1 failure FT in Fig. 11(a), it is found that X_6 (failure to cut off fuel supply) is the most significant event leading to the failure of the fire precautions. In a review of all cases of passenger ship fires triggered by fuel leakage in the engine room, 11 are due to delayed emergency actions by the crew in cutting off the fuel supply, which leads to further leakage and eventually causes the fire. To prevent similar accidents, it is essential to enhance the maintenance and inspection of fuel valves while improving the reliability of fuel equipment. Further causes of failure to cut off the fuel supply in a timely manner may stem from the crew not adhering to established procedures or inadequate emergency response protocols on board. To address these challenges, it is crucial to provide comprehensive training for the crew on emergency response and fuel spill management procedures. Such initiatives can enhance crew resilience and significantly



(a) PE1 failure. (b) PE2 failure. (c) PE3 failure. (d) PE5 failure. (e) PE4 failure.

Fig. 11. Criticality importance analysis of PEs failure.

reduce the risk of fires resulting from operational errors.

5.4.2. Fire detection

The criticality importance analysis in Fig. 11(b) highlights three BEs with the greatest impact on PE2 failure: X_{17} (crew misjudgment), X_{12} (fire alarm system failure/missing) and X_8 (smoke detector failure/missing). To address these risks, it is essential to prioritize the maintenance and inspection of fire detection systems during ship management processes, ensuring their reliability and operational integrity. Additionally, enhancing the crew's ability to interpret fire detection signals accurately is crucial. Historical accident reviews indicate that delayed fire detection is often caused by crew misinterpretation or neglect of fire alarms rather than system faults. Therefore, enhancing professional training for the crew, particularly in fire recognition and emergency response, is crucial to improving fire safety on board ships.

5.4.3. Fire control

The criticality importance analysis of Fig. 11(c) shows that X_{21} (lack of effective emergency procedures) has the highest criticality importance ranking under the case of PE3 failure. It indicates that ship management companies need to enhance their fire response capabilities by developing robust safety management systems, implementing effective emergency procedures, and improving crew training programs. Historical accident analyses reveal that a common cause of delayed fire control is the crew's lack of familiarity with or improper use of firefighting equipment. Therefore, ensuring that crew members are well-trained and proficient in the operation of firefighting equipment is critical to effectively managing and controlling fires.

If a fire escalates beyond the control of fixed firefighting systems, the crew must act swiftly to prevent its spread and contain it within the initial compartment. Key actions include promptly isolating combustible materials, cutting off the air supply, and implementing measures such as boundary cooling. The criticality importance analysis of PE5 failure in Fig. 11(d) identifies X_{55} (failure to close ventilation ducts) as the primary factor contributing to the fire's spread. This underscores the need to require ship ventilation systems to be equipped with automatic fire dampers that can shut down automatically in the event of a fire.

5.4.4. Emergency management of fire accidents

The criticality importance analysis of PE4 failure in Fig. 11(e) identifies X_{37} (inadequate emergency response plan) as the most significant factor contributing to evacuation failure. It is necessary to develop comprehensive, clear and practical emergency management procedures after a fire to ensure the availability and functionality of lifeboats and other emergency equipment during emergency circumstances. By optimizing emergency plans and improving the efficiency of emergency facilities, the risk of injury or loss of life during fires and other emergencies can be significantly reduced, thereby improving the overall safety management standards of the ship.

Additionally, timely communication between the ship and shore is vital in the aftermath of a fire. The MAIRs often reveal that captains are overconfident in their ability to control the fire and delay contacting shore firefighting forces, resulting in missed opportunities for effective rescue. To address this, emergency management procedures should explicitly include a mechanism for immediate communication with shore rescue teams, ensuring that necessary support is mobilized before the situation becomes critical.

6. Conclusion

This paper proposed a framework for risk assessment of fire accidents on passenger ships that integrates FMEA, RM, and the HCL model. This framework comprehensively analyzes the characteristics of passenger ship fires, effectively identifies key risk scenarios, and deeply explores the evolution of fire accident scenarios. The validity of the data and model is also verified. The probability of fire accident scenarios is then quantitatively analyzed, and risk control options are proposed.

The results show that fuel leakage in the engine room has been identified as the critical risk scenario leading to passenger ship fires. The progression path for Scenario 7 involves fuel leakage occurred in the engine room of the passenger vessel, and the malfunctioning equipment was not addressed in time, leading to the outbreak of a fire. Due to delayed detection or ineffective fire extinguishing operations, the fire was not suppressed and rapidly spread. As a result, the failure to evacuate passengers and crew led to serious consequences, including loss of life. This scenario represents the highest fire risk. Among all the pivotal events, fire extinguishing operations failure has the highest probability of occurrence. Three key factors contributing to this event are the lack of effective emergency procedures, smoke, and inadequate use of firefighting equipment. Additionally, in real accidents, Scenarios 3 and 5 do not occur. This indicates that when the fire is under control in real fire accidents, the crew has demonstrated exceptional skill in evacuating passengers.

The integrated risk assessment framework proposed in this paper systematically analyzes the progression of fire accidents on passenger ships. Compared with existing methods, it more comprehensively integrates multiple risk sources and reveals the interactions among risk factors across different stages. Moreover, it clearly delineates fire progression pathways and proposes practical RCOs based on quantitative analysis results, thereby offering a more guidance-oriented reference for fire risk prevention and emergency management on passenger ships. Moreover, the main data source used in this paper, maritime accident investigation reports, has certain subjectivity and limitations. If more reliable and detailed data become available in the future, further research will be conducted.

CRediT authorship contribution statement

Shanshan Fu: Writing – original draft, Methodology, Funding acquisition, Data curation, Conceptualization. **Zhan Sun:** Writing – original draft, Software, Methodology, Data curation. **Chailu Jiang:** Writing – original draft, Data curation. **Yunhan Hao:** Writing – review & editing. **Wengang Mao:** Writing – review & editing, Resources.

Declaration of competing interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled, 'An Integrated Risk Assessment Framework for Fire Accidents on Passenger Ships'.

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