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Research paper

Risk analysis of human evacuation aboard passenger ships based on fuzzy DEMATEL-ISM-BN

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ABSTRACT

Accidents involving passenger ships present unique and considerable challenges for evacuation and rescue, posing significant risks to life and property. However, existing studies rarely analyse the risk influential factors (RIFs) affecting the evacuation process of passenger ships and the interconnections among these RIFs. To address these gaps, this study proposes a risk analysis framework for the emergency evacuation of passenger ships, aiming to dissect and quantify the interdependencies of RIFs within the context of Human Evacuation from Passenger Ships (HEPS). Firstly, this study conducts a comprehensive review of existing literatures and extensive investigations into passenger ship accidents in order to identify the RIFs of HEPS. Secondly, combining fuzzy language rating data on the relationships between RIFs, the Fuzzy Decision-making trial and evaluation laboratory (DEMATEL) and Interpretative Structural Modeling (ISM) methods are employed to build a hierarchical network model. Thirdly, the hierarchical network model is mapped to a Bayesian Network (BN), facilitating a detailed investigation into the RIFs influencing HEPS. Finally, forward causal reasoning is employed to determine the probabilities of various RIFs occurring and reverse diagnostic reasoning is used to deduce the probability changes of RIFs under different accident severities. This study is of significant importance for enhancing the emergency evacuation capabilities of passenger ships and ensuring public safety.

1. Introduction

According to the World Maritime Review 2022 released by the United Nations Conference on Trade and Development (UNCTAD), more than 80% of global commodity trades are conducted through maritime transport (Aydin et al., 2024; Jiang et al., 2024). Maritime transport has become an integral component of the world economy and transportation network (Feng et al., 2024c; Huang et al., 2023). Due to the increasing demand for maritime trade, the size of ships continues to grow, posing new challenges to the safety of maritime transportation (Cao et al., 2023b; Feng et al., 2024a).

With the increasing number of tourists choosing water-based sightseeing, passenger ship is ranked as the fourth-largest passenger transportation mode, following buses, railways, and aviation (Fang et al., 2023a; Wang et al., 2022b). Although modern passenger ships are equipped with advanced accident prevention systems and devices to ensure safety, accidents like the capsizing of the "Sewol" in 2014 and the sinking of the "Eastern Star" in 2015 have still occurred, resulting in enormous loss of life, property, and environmental damage (Fang et al., 2024a; Wang et al., 2023). In the event of a severe accident on a passenger ship, the evacuation of personnel is a crucial means of minimizing the consequences of the accident (Wang et al., 2021a). Therefore, as the emergency evacuation of passenger ships is closely related to maritime safety and human safety, it is attracting attentions from the International Maritime Organization (IMO), shipping companies, and researchers (Xiao et al., 2024; Zhang et al., 2025).

The Maritime Safety Committee (MSC) of the IMO, during the MSC 92 to MSC 107 meetings, discussed passenger ship safety and domestic ferry safety, approving a series of evacuation analysis guidelines for existing and new passenger ships (Valcalda et al., 2023; Wang et al., 2021c). In the guidelines MSC.1/Circ.1533 (International Maritime Organization and Organisation, 2016), the process of Human Evacuation from Passenger Ships (HEPS) is divided into three stages, these are the assembly stage, abandonment stage, and search and rescue stage

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(Wang et al., 2023). HEPS is a complex process, where the ability of personnel to evacuate in a timely, rapid, and safe manner is influenced by many factors such as the human factors (e.g., captain, crew, passengers), ship equipment, environmental factors, and organization factors (Fang et al., 2022). Firstly, the captain needs to promptly assess the danger of the accident, make assembly and abandonment decisions, conduct personnel communication and action arrangements, and issue alarms and distress signals. Secondly, the crew needs to respond to the captain's instructions, deal with the danger of the accident, evacuate passengers promptly, manage the crowd, and proficiently release life-saving appliances (LSA). Thirdly, passengers need to wear life jackets, quickly gather at assembly stations, and enter lifeboats, rafts, and other life-saving devices. During this process, adverse weather conditions, ship rolling, panic and other factors all affect the efficiency of personnel evacuation. Meanwhile, these factors can also mutually influence each other, ultimately making it more difficult for personnel to evacuate in a timely, rapid, and safe manner, resulting in significant loss of life and property (Ventikos et al., 2023). Therefore, analysing the risk influential factors (RIFs) and their interrelationships of the evacuation process is of great significance to improve the efficiency of passenger ship evacuation and reduce the severity of accidents.

Currently, research on HEPS mainly focuses on the safety awareness and evacuation behaviour of evacuees (Wang et al., 2020, 2021c), the movement characteristics of evacuees (Fang et al., 2023a; Wang et al., 2021a, 2021b), modeling of passenger ship evacuation (Fang et al., 2024a; Wang et al., 2022b), etc. However, there is few research discussing the impact of different RIFs on the evacuation process from the perspective of risk analysis, including the coupling relationships among these RIFs. Therefore, to supplement research in this area, this study draws on existing literatures and passenger ship accident investigation reports to identify RIFs in the HEPS process. Based on the structural characteristics and hazards of passenger ships, the Fuzzy Decision-making trial and evaluation laboratory (DEMATEL)-Interpretative Structural Modeling (ISM) models are employed to conduct a hierarchical analysis of these RIFs, analysing superficial causes, transitional causes, and root causes. Combining the Bayesian Network (BN) model to examine the accident causation chain, this study achieves the identification, quantification, and ranking of RIFs in the process of HEPS. This study provides a comprehensive and systematic risk analysis method for HEPS, reducing the loss of life and property caused by evacuation errors or inefficiencies, and improving the safety management level of emergency evacuation for passenger ships.

The following sections are organized as follows, in the second section, a literature review is conducted and contributions to the current research on HEPS are summarized. The third section introduces the Fuzzy DEMATEL, ISM, and BN methods. The fourth section presents the application results of the Fuzzy DEMATEL-ISM-BN methods in HEPS, sensitivity analysis is conducted, and measures and recommendations are provided. Finally, in the fifth section, this paper presents conclusions, identifies research limitations, and suggests future research directions.

2. Literature review

Evacuation of individuals is a hot topic in reliability and safety research (Wang et al., 2023). In comparison to the extensive literature on land-based evacuation, there is limited attention given to HEPS during emergencies. In the limited research on the unique aspects of HEPS, researchers have primarily conducted a series of studies on evacuees' safety awareness, wayfinding tools, and the movement characteristics of evacuees.

2.1. Safety awareness and wayfinding tools during emergency evacuation

Individual safety awareness and behaviour are pivotal in managing evacuation safety, drawing significant attention in safety research (Gao et al., 2024). In evacuation activities, improving personal safety awareness can reduce unsafe behaviour, thereby contributing to the safety management of evacuees. Therefore, researchers (Wang et al., 2020, 2021c) have investigated the dimensions of individuals' safety awareness during emergency evacuation, including their perception of wayfinding tools, and individuals' wayfinding behaviour during emergency evacuation. The influence of these risk factors on the evacuation process has been analysed.

The concept of safety awareness originates from situational awareness. It is the perception of potential hazards in a specific environment at a particular time, along with the prediction of their future states (Wang et al., 2021c). To demonstrate the level of passenger safety awareness, Wang et al. (2021c) conducted a questionnaire survey and statistical analysis on 1373 passengers aboard a Roll on-Roll off ship on the Yantai-Dalian route. The results revealed demographic differences among passengers in terms of safety awareness and perception of emergency wayfinding tools. Lu et al. (2018) conducted a survey of 316 ferry passengers, employing structural equation modeling to investigate the influence of safety marketing stimuli on passengers' safety awareness. However, the study did not clarify the directional impact of these factors on evacuation process.

Wayfinding tools are essential for guiding evacuees during emergencies. They not only raise individuals' awareness of the evacuation process but also quickly direct individuals towards safety zones efficiently. Ronchi et al. (2016) examined the design of variable message signs as wayfinding aids for emergency evacuation in road tunnels, evaluating the effectiveness of VMS in such scenarios. Regarding the time needed to make wayfinding decisions, Galea et al. (2014) highlighted the limited noticeability of traditional emergency signs in unfamiliar settings, with only 38% of individuals recognizing them. To address this issue, Galea et al. (2017) designed innovative dynamic signs, which significantly improved compliance and guidance, with a 77% follow rate in evacuation scenarios. Despite these advancements, the research on HEPS still present unique data collection challenges. Research on the impact of wayfinding tools on the evacuation process is primarily concentrated in the field of terrestrial buildings, with few studies related to HEPS.

2.2. Movement characteristics during emergency evacuation

Unlike situations on land-based evacuation, passengers on ships have to evacuate from inclined or moving ships in emergency situations (Fang et al., 2024b). This makes it much more challenging for individuals to move compared to typical circumstances, significantly decreasing individual's walking speed and thus increasing the total evacuation time (Fang et al., 2023a). In order to incorporate the influence of ship list and motion on the evacuation model, researchers conducted studies based on three aspects: simulated corridor experiments in ship environments, shipboard observations, and modeling simulations.

In simulated corridor experiments, Bles et al. (2001) conducted walking experiments in a container model installed on a hydraulic system. The study found that dynamic ship motion reduced individuals' walking speed by 15%. Zhang et al. (2017) considered the impact of wind and waves on individuals' navigation and decision-making abilities. They conducted walking experiments with a single pedestrian under different roll angles, using a six-degree-of-freedom platform based on a maritime rescue simulation system. Their study gathered data on adaptive movements and walking pauses, analysing the influence of roll angles on individuals' walking patterns. However, the study did not consider the influence of walk upstairs and downstairs on individual's speed, limiting the evacuation model's applicability.

In shipboard observations, Walter et al. (2017, 2019) separately studied the walking capabilities of individual along different walking directions (transverse and longitudinal) under two ship motion modes (roll > pitch, pitch > roll). The results showed that when roll exceeded pitch, walking along the short axis or transverse axis of the vessel within the specified path should allow a greater maximum walking distance than walking along the long axis or fore-and-aft axis of the vessel. Conversely, when pitch exceeded roll, this relationship reversed. Hwang (2013) conducted an experimental study on the individual's walking speed on a roll-on/roll-off passenger ship to enhance the safety of passengers unfamiliar with onboard living conditions during ship evacuation. The influence of ship motion on individual's walking speed was analysed separately during berthing and sailing states. The results revealed that the speeds of individuals during berthing and sailing were 2.02 m/s and 1.42 m/s, respectively. The research findings serve as a reference for shipping companies in formulating evacuation decisions.

In modeling and simulation studies, researchers utilize mathematical models and computer simulation techniques to investigate the impact of ship motion on individuals' walking gaits, walking speeds, or evacuation times. Balakhontceva et al. (2016) established a multi-agent system for human evacuation in a ship inclined situation under wind and wave conditions, studying evacuation times under specific wave intensity and ship speed scenarios. Chen et al. (2016) analysed the characteristics of ship sway and the characteristics of individual's walking, establishing a mathematical model for individual's walking under the influence of ship sway. The research results showed that the inertial force of ship sway motion, acting as a parallel component in the direction of personnel movement, affects the walking speed, showing an initial acceleration followed by deceleration. However, as mentioned by the researchers in the limitations of their study, the modeling and simulation analysis of walking speed are often based on theoretical assumptions, lacking practical validation.

2.3. Research gaps and contributions

While there are numerous studies conducting the analysis of HEPS, the afore-mentioned studies primarily focuses on evacuation analysis during the ship design phase, modelling of personnel movement during evacuation, with few attentions to activities during abandonment and rescue phases. Moreover, there is few studies from the perspective of risk analysis on the RIFs influencing the HEPS process. Existing maritime accident reports often emphasize the captain's evacuation instructions, crew's abandonment operations, and the organization of rescue forces by maritime authorities. This has resulted in gaps between current research on HEPS and the content of maritime accident investigation reports. Meanwhile, in recent years, there has been in-creasing attention to the reliability issues of passenger ships, such as operational vulnerabilities and accident susceptibility, as well as the development of a fire risk assessment model during the design phase. These are the most critical concerns for stakeholders during the operation of passenger ships. Therefore, it is essential to study the reliability and risk analysis of HEPS from the perspective of emergency response practices. This study aims to make the following contributions:

(1) A framework for hazard identification and risk assessment in the HEPS process is developed to identify, quantify and rank RIFs in the HEPS process.
(2) Through an extensive literature review and analysis of passenger ship accident reports, a comprehensive set of RIFs for HEPS is constructed.
(3) Addressing the limitations of research data, fuzzy language is used to address the uncertainty of expert knowledge, and the advantages of DEAMTEL, ISM, and BN are utilized comprehensively to propose an integrated risk assessment model.
(4) The framework's applicability is illustrated through a case study of a specific passenger ship sinking accident, and counter measures for the reduction of passenger ship casualties are proposed from the perspectives of risk control.

3. Methodology

Owing to the interaction among diverse RIFs, the emergency evacuation system for passenger ships has already become a complex system (Wang et al., 2023). To better analyse the mutual influence and hierarchical relationship among RIFs, this study integrated the advantages of the Fuzzy DE-AMTEL, ISM, and BN methods to quantify the RIFs in the evacuation process of passenger ships, as depicted in Fig. 1. The significance influence of each RIF is obtained through the fuzzy DEAMATEL method, and the sensitive RIF is identified by ISM and BN. Compared with traditional DEMATEL, the model constructed in this study can better comprehend the causality and hierarchy in complex systems, while handling uncertainties in complex systems, and is more robust and reliable when confronted with fuzzy data. As shown in Fig. 1, the methodology of this study is divided into four stages, and explanations for each stage are provided in the flowchart below. First, the RIFs are identified initially through an extensive literature review and analysis of investigation reports on passenger ship accidents. Second, the results from the expert's judgement are defuzzified using triangular fuzzy numbers. These defuzzified results are then utilized to establish the interrelationships among RIFs through DEAMTEL and to determine the importance level of each RIF. Third, employing the ISM method, the RIFs are categorized into different levels to build a multilevel network model. Final, based on the multilevel network model, the BN model is established in conjunction with passenger ship accident data. This combination facilitated diagnostic reasoning and sensitivity analysis to identify the most sensitive RIFs.

3.1. Identification of the risk factors

Accidents typically result from unsafe human behaviour, inadequate conditions of objects, and management deficiencies. In the maritime sector, accidents arise from a combination of human, equipment, environmental, and organizational factors (Feng et al., 2024b). It's noteworthy that 80 percent of maritime accidents are related to human factors (Cao et al., 2023b; Uflaz et al., 2023). The emphasis in emergency response to accidents should be on understanding and addressing these complex human factors (Elidolu et al., 2023; Liu et al., 2022; Uflaz et al., 2023). Thus, this study specifically addresses the characteristics of passenger ships and analyses human factors in three aspects: captain (Ca), crew (Cr), and passengers (Pa). In this study, RIFs are initially identified through an exhaustive literature review and a detailed analysis of passenger ship accident reports. Subsequently, five experts and professors specializing in passenger ship safety are engaged to pinpoint the final RIFs in the evacuation process, drawing on their knowledge and experience, as illustrated in Table 1. In Table 1, both the explanation and source of each RIF are provided. It's crucial to note that in the column detailing the sources of RIFs, only a representative portion is listed for this study.

3.2. Fuzzy DEMATEL

The DEMATEL method grounded in the principles of graph theory and matrix theory, enables the identification of key factors among numerous elements through expert scoring of inter-factor relationships (Shi et al., 2024). This method has a wide range of applications in analysing the emergency management of ships (Tac et al., 2020). Due to the complex relationships among RIFs influencing HEPS, it presents a significant challenge for experts attempting to assign precise influence values during the questionnaire scoring process. To address this issue, fuzzy language is employed as a scoring criterion by experts completing the survey questionnaire.

Fuzzy logic proves to be a valuable tool in handling the uncertainties and intricacies inherent in expert judgment and decision-making. When faced with uncertain issues, experts tend to express their opinions using fuzzy language rather than a specific value (Aydin, 2023). Fuzzy sets

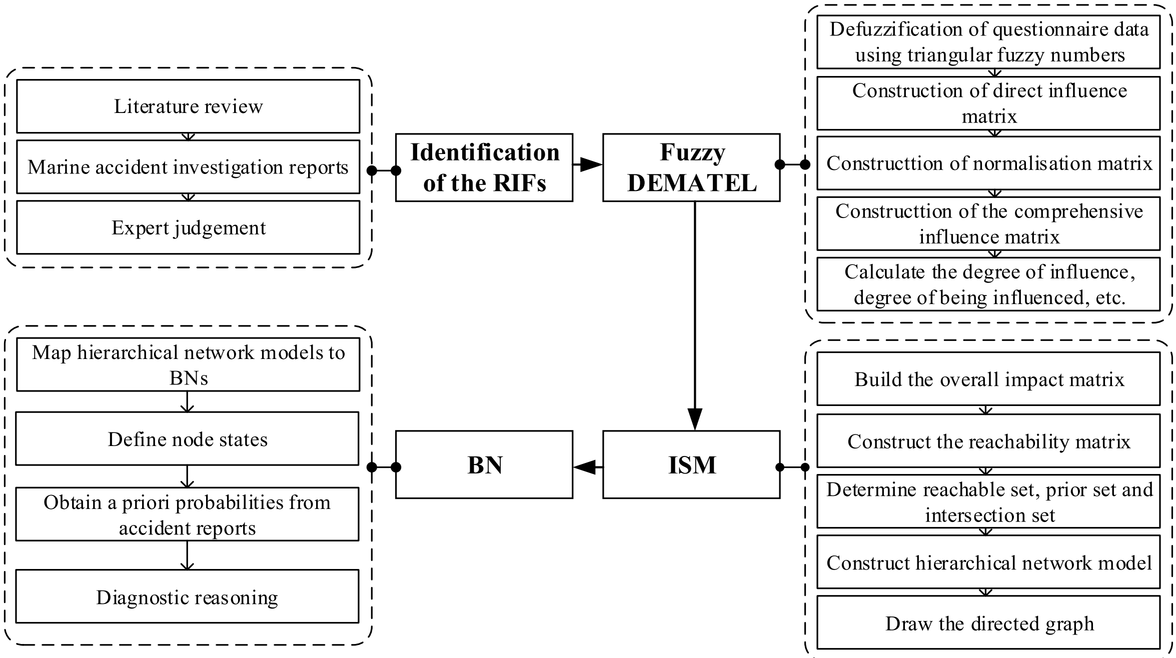

Fig. 1. Flowchart of research methodology.

convert linguistic terms into fuzzy numbers, representing experts' uncertain judgments and capturing the fuzziness of parameters. Commonly, prior research (Wan et al., 2024a) transforms experts' viewpoints into triangular and trapezoidal fuzzy numbers. This study, however, opts for the use of triangular fuzzy numbers due to their simplicity and efficiency. The fuzzy language in the survey questionnaire and its corresponding triangular fuzzy numbers are presented in Table 2.

Based on the principles of DEMATEL, the calculation process of Fuzzy DEMATEL in this study consists of the following three steps.

Step 1: Constructing the direct influence matrix.

The direct influence matrix serves to depict the immediate connections among different factors. Drawing on expert knowledge, specialists conduct pairwise comparisons of identified RIFs to establish the direct influence relationships and their respective magnitudes. Assuming the invitation of p experts for evaluation, experts use the fuzzy language in Table 2, filling out the survey questionnaire based on their experience and knowledge. Later, let $\widetilde{z}_{ij}^k = \left(a_{ij}^k, b_{ij}^k, c_{ij}^k\right)$ represent the triangular fuzzy number indicating the influence of factor i on factor j given by the k^{th} expert. Then, the triangular fuzzy direct influence matrix $\widetilde{Z}^k$ for each expert regarding various factors on other RIFs is defined as per Equation (1).

$$\widetilde{Z}^k = \begin{bmatrix} 0 & \widetilde{z}_{12}^k & \dots & \widetilde{z}_{1j}^k \\ \widetilde{z}_{21}^k & 0 & \dots & \widetilde{z}_{2j}^k \\ \dots & \dots & \dots & \dots \\ \widetilde{z}_{i1}^k & \widetilde{z}_{i2}^k & \dots & 0 \end{bmatrix} \quad k = 1, 2, ..., p; i = 1, 2, ..., n; j = 1, 2, ..., n. \tag{1}$$

To simplify fuzzy data into precise values, this study utilizes the Converting Fuzzy Data into Crisp Scores (CFCS) method (Opricovic and Tzeng, 2003) to complete this calculation process, the specific calculation steps are as follows:

Firstly, standardize the triangular fuzzy numbers, as shown in Equation (2):

$$\begin{cases} l_{ij}^k = \left(a_{ij}^k - \min a_{ij}^k\right) \Big/ \Delta_{\min}^{\max} \\ m_{ij}^k = \left(b_{ij}^k - \min b_{ij}^k\right) \Big/ \Delta_{\min}^{\max} \\ r_{ij}^k = \left(c_{ij}^k - \min c_{ij}^k\right) \Big/ \Delta_{\min}^{\max} \\ \Delta_{\min}^{\max} = \max c_{ij}^k - \min a_{ij}^k \end{cases} \tag{2}$$

where $l_{ij}^k, m_{ij}^k, r_{ij}^k$ represents the standardized left, middle, and right triangular fuzzy values; $a_{ij}^k, b_{ij}^k, c_{ij}^k$ represents the left, middle, and right triangular fuzzy values from the initial expert evaluations; $\Delta_{\min}^{\max}$ represents the difference between the maximum and minimum values.

Secondly, calculate the left and right normalized values u_{ij}^k and n_{ij}^k, as shown in Equation (3):

$$\begin{cases} u_{ij}^k = m_{ij}^k \Big/ \left(1 + m_{ij}^k - l_{ij}^k\right) \\ n_{ij}^k = r_{ij}^k \Big/ \left(1 + r_{ij}^k - m_{ij}^k\right) \end{cases} \tag{3}$$

where u_{ij}^k and n_{ij}^k are the left and right normalized values, respectively.

Finally, calculate the precise value of the triangular fuzzy number according to Equation (4):

$$z_{ij}^k = \min a_{ij}^k + \frac{\Delta_{\min}^{\max}\left[u_{ij}^k\left(1 - u_{ij}^k\right) + n_{ij}^k n_{ij}^k\right]}{\left[1 - u_{ij}^k + n_{ij}^k\right]} \tag{4}$$

Utilizing Equations (2)–(4), calculate the standardized crisp values after each expert's evaluation to obtain the direct influence matrix Z, as shown in Equation (5).

$$\begin{cases} z_{ij} = \left(z_{ij}^1 + z_{ij}^2 + ... + z_{ij}^p\right) \Big/ p \\ Z = \begin{bmatrix} 0 & z_{12} & \cdots & z_{1j} \\ z_{21} & 0 & \cdots & z_{2j} \\ \vdots & \vdots & \vdots & \vdots \\ z_{i1} & z_{i2} & \cdots & 0 \end{bmatrix} \end{cases} \tag{5}$$

where z_{ij}^p represents the standardized precise values after the evaluation

Table 1
Hazard identification of human evacuation from passenger ships.

RIFs	Description	Sources	Definition of states
Accident hazard risk assessment (Ca1)	In the event of an accident, the captain shall organize the crew to investigate the disaster and make a hazard assessment.	Literatures (Joustra, 2018); Accid-ent report (Al Salam Boccaccio 98, 2006)	Lack of timely and reasonable assessment (yes); Timely and reasonable assessment (no).
Decision-making for assembly, evacuation and abandonment of ships (Ca2)	If the danger escalates, the captain needs to order an evacuation and decide to abandon the ship.	Accident report (Sewol, 2014)	Failure to make timely and reasonable decisions (yes); Timely and rational decision-making (no).
Personnel communication and action arrangements (Ca3)	Communicate with the crew and direct them to probe the disaster; organize the evacuation of passengers to the muster station.	Accident report (Costa Concordia, 2012)	Failure to communicate with the crew and organize actions in a timely manner (yes); Communicated with the crew and arranged actions in a timely manner (no).
Activate alarms and transmit distress signals (Ca4)	The captain issues an evacuation alert through the public broadcast system and sends a distress signal to maritime authorities and the shipping company.	Literature (Akyuz, 2016); Accident report (Lisco Gloria, 2010)	Failed to activate alarms and issue distress signals promptly (yes); Activated alarms and issued distress signals promptly (no).
Accident hazard disposal (Cr1)	Crew handle accident hazards according to the captain's instructions.	Accident report (Princess Ashika, 2009)	Improper handling or operational errors (yes); Proper handling and normal operations (no).
Crowd management (Cr2)	Before departure, the crew demonstrates to passengers how to use life-saving equipment. In the event of an accident, they organize passengers for an orderly evacuation, and so on.	Literature (Wang et al., 2021c); Accident report (Costa Concordia, 2012)	No instruction on Life-Saving Appliances (LSA) or lacking proper management actions (yes); Conducting LSA instruction and organizing orderly and reasonable crowd evacuation (no).
Proficiency in LSA operations (Cr3)	Crew are proficient in releasing lifeboats, rafts, and other devices related to maritime evacuation systems (LSA in this context means lifeboats, rafts, etc.).	Accident report (Princess of The Stars, 2008)	Crew are not proficient in LSA operations (yes); Crew are proficient in LSA operations (no).
Passenger panic and herd mentality (Pa1)	In the event of an accident, passengers may exhibit panic behaviour and conform to herd mentality.	Literature (Li et al., 2022); Accident report (Taimareho 1, 2020)	Severe panic and herd mentality among passengers (yes); Passengers may experience some level of panic and herd mentality, but their impact on the evacuation process is minimal (no).
Passenger turning-back behaviour (Pa2)	Occurs when passengers return to cabins to retrieve belongings.	Literature (Ni et al., 2018); Accident report (Costa Concordia, 2012)	Turning-back behaviour exists (yes); No turning-back behaviour exists (no).
Passenger mobility (Pa3)	Factors affecting passengers' mobility include age, gender, body size, and mobility, as well as considerations for seasickness and other relevant factors.	Accident report (Ivolga, 2015; Cavalo Marinho I, 2017)	Weak passenger mobility poses challenges for timely evacuation (yes); Passengers with sufficient mobility can be evacuated in time (no).
Competitive behaviour of passengers (Pa4)	Competitive behaviours during evacuation, including crowding, trampling, jumping directly into the water, and grabbing life jackets.	Literature (Kvamme, 2017); Accident report (Kim Nirvana-B, 2015)	Existence of competitive behaviour (yes); No competitive behaviour (no).
Passengers not wearing or incorrectly wearing LSA (Pa5)	The passengers are not wearing lifejackets or are improperly wearing lifejackets (the LSA here refers primarily to lifejackets).	Literatures (Ni et al., 2018; Stamou et al., 2023); Accident report (Boramar,2018)	No or improper wearing of LSA (yes); Properly wearing LSA (no).
Seaworthiness of ships (Sh1)	Vessel has good seaworthiness.	Accident report (Boramar, 2018; KM Lestari Maju, 2018)	The ship is unseaworthy due to factors such as overloading, structural damage, poor stability, undermanning, etc (yes); This ship is seaworthy (no).
Evacuation routes for ships (Sh2)	Rationalisation of ship evacuation route design.	Literature (Xu et al., 2010)	Evacuation routes are inadequately designed and congested or blocked (yes); Evacuation routes are well-designed, wide, and free of obstacles (no).
Availability of LSA for ships (Sh3)	LSAs are adequately maintained, tested and inspected to ensure the reliability of such equipment (this LSA is the same as the equipment referred to at Cr3).	Literature (Joustra, 2018); Accident report (Captain Ribeiro, 2017)	Equipment such as life rafts cannot be safely released and used during an evacuation (yes); Equipment such as life rafts can be safely released and used during an evacuation (no).
Ship's wayfinding support system (Sh4)	Implement a comprehensive wayfinding support system, including but not limited to emergency route signage, wayfinding tools, etc.	Literatures (Casareale et al., 2017; Wang et al., 2021c)	The ship's wayfinding equipment or marking is inadequate (yes); The ship is well equipped or labelled for wayfinding (no).
Ship alarm system (Sh5)	Alarm systems are in a state of readiness, such as fire, smoke and other onboard alarm devices, but also include EPIRB, SART, etc.	Accident report (Peejay V, 2016; Cavalo Marinho I, 2017)	Fire, smoke or public alarm system not working, public announcement language not comprehensive, lack of emergency alarm equipment such as EPIRB (yes); Fire, smoke or public alarm system is fully operational, public announcement language is comprehensive, and emergency equipment is available (no).
The sea conditions during the accident (En1)	Severe sea conditions, including fog, high winds, and waves.	Accident report (Dashun,1999; Skagit, 2012)	Poor sea conditions, including high winds, waves, and poor visibility (yes); Moderate sea conditions (no).
Nighttime environment (En2)	Ships navigating at night.	Accident report (ECO LUX, 2021)	If the accident occurred at night (yes); If the accident occurred during the day (no).
The rolling and heeling of ships (En3)	The ship is in a rolling or heeling position.	Literature (Fang et al., 2023b)	The ship is rolling or heeling (yes); The ship is not rolling or heeling (no).
Ship fire hazard (En4)	Fire hazard on board ship.	Accident report (New Jerusalem, 2015)	Ship has fire hazard (yes); Ship has no fire hazard (no).

(*continued on next page*)

Table 1 (*continued*)

RIFs	Description	Sources	Definition of states
Ship emergency response plan (Or1)	Vessels have comprehensive emergency plans covering collisions, groundings, fires, and other hazardous situations.	Accident report (Mutiara Sentosa I, 2017)	There is no reasonably sound contingency plan (yes); There are reasonable and comprehensive contingency plans in place (no).
Shore-based decision support (Or2)	In the event of an accident, the shore-based is able to provide the necessary decision support to the ship.	Literature (Bartolucci et al., 2021)	Failure to make timely decisions or operational arrangements with neighbouring SAR agencies, vessels (yes); Reasonable decision-making and joint operations with SAR organisations (no).
Search and rescue (SAR) response capabilities of neighbouring States or ships (Or3)	Neighbouring ships or neighbouring States have good search and rescue response capabilities.	Literature (Wang et al., 2023); Accident report (UEAN TE RAOI II, 2009)	Poor SAR response capability, due to factors such as lack of good joint communication between the company or flag State and neighbouring States or poor sea conditions (yes); Excellence SAR response capability (no).
Safety management plans for ships (Or4)	The ship has a good safety management system, including but not limited to the ship's crew training, the ship's emergency evacuation drill supervision, safety management supervision, ship inspection, etc.	Literature (Wang et al., 2023); Accident report (Princess Ashika, 2009)	Safety management system is inadequate or problematic (yes); Safety management system is developed (no).

of the p^{th} expert, and Z represents the direct influence matrix after the evaluation by the p^{th} expert.

Step 2: Calculating the normalized influence matrix and the combined influence matrix.

The interactions between RIFs are multifaceted, involving both direct and indirect relationships. The direct influence matrix cannot reveal the indirect relationships among factors (Wang et al., 2018). Hence, it becomes imperative to generate a comprehensive influence matrix that takes into account both the direct and indirect influences of all other factors. The calculation steps for the standardized influence matrix and the direct influence matrix are outlined in Equation (6).

$$\begin{cases} D = Z/S \\ T = D(I-D)^{-1} \end{cases} \tag{6}$$

where $S = \max\left\{\max_{1\le i\le n}\sum_{j=1}^{n} z_{ij}, \max_{1\le j\le n}\sum_{i=1}^{n} z_{ij}\right\}$, $D = (D_{ij})_{n\times n}$; $T = (T_{ij})_{n\times n}$, D represent the standardized impact matrices, T represents the comprehensive influence matrix, and I represents the n-order identity matrix.

Step 3: Calculating the influencing degree, influenced degree, centrality and causality.

Based on the obtained comprehensive influence matrix T, calculate the influence degree, influenced degree, centrality, and causality of each RIF, as shown in Equations (7)–(10).

$$R_i = \sum_{j=1}^{n} T_{ij} \tag{7}$$

$$C_j = \sum_{i=1}^{n} T_{ij} \tag{8}$$

$$f_i = R_i + C_j \tag{9}$$

$$e_i = R_i - C_j \tag{10}$$

Table 2
The utilization of fuzzy language and its triangular fuzzy numbers.

Fuzzy language	Triangular fuzzy numbers
Very low (VL)	(0, 0, 0.25)
Low (L)	(0, 0.25, 0.5)
Medium (M)	(0.25, 0.5, 0.75)
High (H)	(0.5, 0.75, 1)
Very high (VH)	(0.75, 1, 1)

where R_i is the sum of the rows of the comprehensive influence matrix T, representing the degree to which factor i affects other factors; C_j is the sum of the columns of the comprehensive influence matrix T, representing the degree to which other factors affect factor j (Akyuz and Celik, 2015); f_i represents the centrality of factor i, reflecting the importance of factor i in the entire system; e_i represents the causality of factor i, reflecting the impact of factor i on the entire system. If e_i is a positive value, it indicates that factor i has a significant impact on other factors and can be classified as a causal factor; if e_i is a negative value, it indicates that factor i is easily influenced by other factors and can be classified as an effect factor.

3.3. Interpretative structural modeling (ISM)

The ISM method is proposed in 1973, it constructs a clear and intuitive hierarchical structure model through block decomposition and hierarchical division of a complex system, sorting out the interrelationships among system factors (Cao et al., 2024). The advantage of the ISM method is that it is a simple and effective qualitative analysis method, which can classify the factors that are linked to each other hierarchically and analyse their evolutionary laws by constructing a structure matrix and a directed graph. Therefore, in this study, the ISM method is employed to investigate the causal relationship and propagation mechanism between the identified RIFs for the HEPS. The calculation steps of the ISM method are as follows.

Step 1: Constructing the overall influence matrix.

As shown in step 2 of Fuzzy DEMATEL, the integrated influence matrix reveals the direct and indirect effects of all other factors, but does not consider the effects of the factors on themselves (Kumar and Dixit, 2018). To account for the influence of the factors on themselves, a unit matrix is added to the integrated influence matrix, forming an overall influence matrix. The calculation steps are shown in Equation (11).

$$H = T + I \quad \left(\mathrm{H} = [\mathrm{h_{ij}}]_{n\times n}\right) \tag{11}$$

where I is the unit matrix.

Step 2: Constructing the accessibility matrix.

The accessibility matrix $K\left(K = [k_{ij}]_{n\times n}\right)$ can be used to describe the path relationships among factors in a complex system. Each element k_{ij} in the accessibility matrix K provides a link from one factor to another factor. In complex systems that contain many factors, to simplify the hierarchical structure of the system, it is necessary to introduce a threshold $\lambda, \lambda \in (0,1)$. If the influence of one factor on another exceeds the value λ, the corresponding element in the overall influence matrix is set to 1; otherwise, the corresponding element is set to 0, as shown in Equation (12).

$$k = \begin{cases} 1 & h_{ij} \geq \lambda \\ 0 & h_{ij} < \lambda \end{cases} \quad (i,j = 1,2,3,\cdots,n) \tag{12}$$

The key step in constructing the accessibility matrix is to determine the threshold λ, and there are mainly two methods for determining the threshold λ (Cao et al., 2024). One method involves assigning the threshold through expert knowledge and experience, while the other involves calculating the threshold using mathematical methods, where $\lambda = \alpha + \beta$, α, and β represent the mean and standard deviation of factors in the overall influence matrix. This study adopts the second method to determine the size of the threshold.

Step 3: Determine reachable set, prior set and intersection set and construct hierarchical network model.

Based on the accessibility matrix, K determines the accessibility set B_i, prior set P_i, and intersection set M_i for each factor. In the i row of the accessibility matrix, the set formed by factors corresponding to columns with elements equal to 1 is called the accessibility set B_i. The set formed by factors corresponding to rows with elements equal to 1 in the i column of the accessibility matrix is called the prior set P_i. The formula for calculating the intersection set M_i is shown in Equation (13).

$$M_i = B_i \cap P_i \tag{13}$$

When factor i satisfies Equation (13), it is assigned to the first layer. After determining the first layer, the process is repeated for the next layer, eliminating the corresponding row and column elements in the accessibility matrix. Then, these steps are iteratively repeated until all elements are assigned to their respective hierarchical levels. The iteration concludes to yield the final hierarchical structure distribution.

Step 4: Draw the directed graph.

Upon partitioning the factors at various levels of the system, an analysis is conducted on the accessibility matrix. If there are strongly connected factor pairs, one of the factors is chosen as the representative element to obtain a condensed accessibility matrix K'. Next, eliminate the transitive binary relations and self-reachable binary relations between elements in the accessibility matrix. The calculation method is shown in Equation (14) to obtain the skeleton matrix S'. Represent loops using directed acyclic graphs, calculate the general skeleton matrix S, analyse the causal relationships between factors, and then draw a multi-level hierarchical structure diagram for the RIFs of HEPS.

$$S' = K' - (K' - I)^2 - I \tag{14}$$

3.4. Bayesian Network model

BN is a graphical probability network based on probabilistic inference (Wan et al., 2024b; Wang et al., 2022a). The network topology of BN is composed of nodes, directed edges, prior probabilities, and Conditional Probability Tables (CPT), together forming a Directed Acyclic Graph (DAG). In the network, RIFs are used to represent nodes. Directed edges between nodes signify direct dependencies between preceding and following factors. These dependencies rely on the CPT (Cao et al., 2023a). The a priori probability of a node represents its initial probability, typically determined from historical data, expert experience, and knowledge. CPT involve combinations of probabilities for child nodes corresponding to parent nodes in various states (Wang and Wang, 2023). BN has several advantages, including insensitivity to missing data, the ability to learn causal relationships between nodes, and avoidance of overfitting. BN is used in this study to quantify the hierarchical structure obtained from ISM analysis. The ISM yields a multi-level structural mapping, offering an initial structure (directed hierarchical topology) for the BN model. The mapping is illustrated in Fig. 2. Specifically, in this study, each RIFs is mapped as each node in the BN, and based on the multilevel structure graph obtained from ISM, each node in the BN is connected and a directed network structure is constructed (Wang and Wang, 2023).

To construct a comprehensive BN model, one must calculate both a priori probabilities and conditional probabilities. A priori probabilities can be derived from historical accident data. The conditional probability of variable $X = (X_1, X_2, \cdots X_n)$ comprises both conditional independent probability and conditional joint probability, as illustrated in Equations (14) and (15).

$$P(X) = \prod_{i=1}^{n} P(x_i) \tag{15}$$

$$\mathrm{P}(X) = \prod_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{P}(x_i | parent(x_i)) \tag{16}$$

where x_i represents the network node, $P(x_i)$ signifies the probability of x_i, $parent(x_i)$ serves as the parent of x_i, $\mathrm{P}(x_i|parent(x_i))$ indicates the joint probability of each parent, and n denotes the number of nodes in the BN.

According to Bayesian theorem, BN can serve for both forward and backward inference. In forward inference, the prior probability of x_i can be determined using Equation (16). Backward inference, on the other hand, the prior probability can be updated based on new evidence or information regarding the variable E. The corresponding posterior probability can then be obtained using Equations (17) and (18).

$$P(X_i) = \sum_{X_i, j \neq i} P(X) \tag{17}$$

$$P(X \backslash E) = \frac{P(X,E)}{P(E)} = \frac{P(X,E)}{\sum_{X} P(X,E)} \tag{18}$$

Calculating the CPT becomes more challenging when a child node has multiple parent nodes. To address this issue, the Noisy-OR gate model can be employed to enhance the efficiency of CPT calculation (Zhang et al., 2025). Assuming that the child node C has n parents, denoted as $(Pa_1, Pa_2, \cdots Pa_i, \cdots Pa_n)$, each variable in the BN is a binary variable with states defined as "yes" and "no." Pa_i and $\overline{Pa_i}$ represent node occurrences and non-occurrences, respectively, and $i \in (1,\mathrm{n})$. $P(C \leftarrow Pa_i)$ denotes the probability of occurrence of child node C when only parent node Pa_i alone appears as shown in Equation (19).

$$P(C \leftarrow Pa_i) = P(C | \overline{Pa}_1, \overline{Pa}_2, \cdots, Pa_i, \cdots, \overline{Pa}_n) \tag{19}$$

The conditional probabilities of the child nodes can be computed using the Noisy-OR gate model, as outlined in Equation (20) (Oniśko et al., 2001).

$$P(C \leftarrow Pa) = 1 - \prod_{Pa_i \in Pa} (1 - P(C \leftarrow Pa_i)) \tag{20}$$

4. Results and discussion

Firstly, this study collected 67 complete accident investigation reports of passenger ship by searching data from 1990 to 2023 in the IMO-Global Integrated Shipping Information System. Through a combination of literature review, accident reports, and expert judgment, the RIFs of the HEPS are identified, as detailed in Table 1. Secondly, the questionnaire method is employed to gain the relevance of these RIFs and determine their direct impact on the degree of relevance. The DEMATEL-ISM model is employed to causally classify and hierarchically divide the RIFs, resulting in the generation of the final hierarchical structure diagram. This model is also used to analyse the coupling relationship between the system factors. Thirdly, based on the

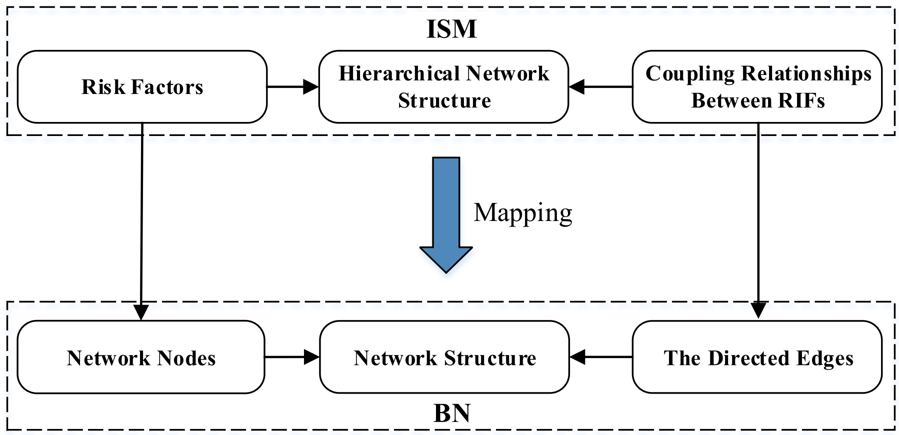

Fig. 2. Mapping from ISM model to BN model.

hierarchical analysis of RIFs mentioned above, the BN model is utilized to investigate the primary causes influencing the failure or inefficiency of evacuation actions for HEPS. The probability of RIFs occurring under various severity levels of accidents is deduced through reverse diagnosis.

4.1. The results of DEMATEL analysis

Utilizing the evaluative language in Table 2, this study evaluates the relationships between the RIFs influencing HEPS determined in this study, and collect subjective questionnaire data. The calculation of the direct influence matrix for HEPS using Equations (1)–(5) is shown in Table A1 of Appendix A. This study normalizes the direct influence matrix using Equation (6) to construct a comprehensive influence matrix, providing an interface for building the ISM model. Next, by calculating the influencing degree, influenced degree, centrality and causality of each RIF using Equations (7)–(10), the results are shown in Table 3. Based on the calculated results, the importance ranking and attributes of each RIF are determined, as illustrated in Figs. 3 and 4.

Based on Table 3, the causal relationship diagram of RIFs can be obtained, as shown in Fig. 3. Fig. 3 can intuitively display the causal relationships of the identified RIFs, providing valuable reference information for the decision-making process. As shown in Fig. 3, among the 25 RIFs, severe sea condition (En1), ship fire hazard (En4), ship safety management plans (Or4), nighttime environment (En2), ship emergency plan (Or1), and 11 other RIFs are considered as causal factors, while the remaining 14 RIFs are considered as resultant factors. It can be known from Fig. 3, particularly in the influencing ranking, severe sea condition (En1), ship fire hazard (En4), and ship safety management plans (Or4) can be identified as the top three RIFs. This indicates that these three RIFs are likely to have a significant impact on other RIFs during HEPS process. Existing studies and accident reports support this finding, for instance, Wang et al. (2023) highlighted that rough sea conditions and ship fire hazards not only affect the ship's navigability, but also significantly impact on other factors in the evacuation process. Moreover, according to the statistical accident investigation reports, most of the passenger ship accidents are caused by heavy sea conditions, such as the accidents of EASTERN STAR, AUNG TAKON 3, and SKAGIT. The analysis of the causes in these investigation reports points out that the lack of a comprehensive safety management plan on board the ship is one of the most important causes of the accidents. Therefore, En1, En4, and Or4 are also identified as the highest causal RIFs. By analysing the passenger ship accident investigation reports, it can be concluded that En1 and Or4 are the direct causal factors leading to most of the passenger ship accidents, which is consistent with the results of the analysis in this study. Crowd management (Cr2), panic and herd mentality (Pa1), assembly, evacuation, and abandon ship decision-making (Ca2) are the top three influenced ranking RIFs. This indicates that these three RIFs are easily influenced by other RIFs during HEPS process.

As higher central values indicate greater importance of RIFs, to identify the primary RIFs during HEPS process, it is necessary to normalize the central values of Table 3 to obtain the importance levels of each RIF, as illustrated in Fig. 4. From Fig. 4, it can be observed that in terms of importance, crowd management (Cr2), assembly, evacuation, and abandon ship decision-making (Ca2), panic and herd mentality (Pa1), personnel communication and action arrangements (Ca3), and accident hazard disposal (Cr1) are the top five ranked RIFs. This finding is fully confirmed by the existing accident investigation reports, such as MV Al Salam Boccaccio 98. The ship captain underestimated the danger of the situation and failed to organize the evacuation in time and communicate with nearby ships, shipping company or maritime authorities, ultimately led to huge casualties. Furthermore, based on the analysis of accident reports and the investigations of domestic ferries, it was found that passengers did not receive professional evacuation training after boarding passenger ships.

Table 3
The results from the DEMATEL analysis.

Code	Influencing degree	Influenced degree	Centrality	Causality
Ca1	0.531	0.708	1.239	−0.177
Ca2	0.520	0.974	1.494	−0.455
Ca3	0.605	0.844	1.449	−0.240
Ca4	0.430	0.763	1.193	−0.332
Cr1	0.524	0.863	1.387	−0.339
Cr2	0.491	1.191	1.682	−0.700
Cr3	0.372	0.613	0.985	−0.241
Pa1	0.412	1.024	1.436	−0.612
Pa2	0.245	0.780	1.025	−0.534
Pa3	0.411	0.416	0.827	−0.006
Pa4	0.366	0.745	1.112	−0.379
Pa5	0.228	0.906	1.134	−0.678
Sh1	0.752	0.386	1.138	0.367
Sh2	0.383	0.543	0.927	−0.160
Sh3	0.631	0.567	1.197	0.064
Sh4	0.338	0.414	0.752	−0.076
Sh5	0.535	0.371	0.906	0.165
En1	0.954	0.081	1.036	0.873
En2	0.726	0.090	0.816	0.637
En3	0.764	0.252	1.016	0.512
En4	0.932	0.254	1.186	0.677
Or1	0.756	0.200	0.956	0.556
Or2	0.602	0.392	0.993	0.210
Or3	0.460	0.268	0.728	0.192
Or4	0.847	0.171	1.018	0.676

4.2. The results of ISM analysis

Based on the comprehensive influence matrix T established in DEMATEL, this study obtains the overall influence matrix H using Equation (11), as shown in Table A2 of Appendix A. Next, calculating the mean and standard deviation of H to obtain the threshold value $\lambda = 0.0399$. According to Equation (12), calculate the reachable matrix K, as shown in Table A3 of Appendix A. Based on the reachable matrix K, calculate the reachable set B_i, the antecedent set P_i. Then, use Equation (13) to calculate the intersection M_i, obtaining the specific stratification results, as shown in Table 4. Then, using Equation (14), to calculate the skeleton matrix S', represent loops using a daisy chain, construct the general skeleton matrix S, and based on this, create a multi-level hierarchical structure diagram for the evacuation RIFs of HEPS, as shown in Fig. 5.

ISM categorizes the RIFs of HEPS into 8 levels and divides the entire hierarchical structure into three parts: direct causes, intermediate causes, and root causes. As shown in Fig. 5, direct causes include passengers not wearing or improperly wearing LSA (Pa5), with the variation in this RIF having the most significant impact on HEPS. Intermediate causes include crowd management (Cr2), panic and herd mentality (Pa1), passenger mobility (Pa3), accident hazard disposal (Cr1), LSA safety availability (Sh3), Seaworthiness of ships (Sh1), ship safety management plans (Or4), and 15 other RIFs. They act on the upper-level RIFs, indirectly influencing HEPS. The root cause affecting HEPS is the sea condition at the time of the accident (En1). This RIF is the lowest level in HEPS and can easily influence other RIFs. Specifically, whether passengers correctly wear life jackets and other life-saving equipments during the evacuation process is the most direct RIF causing casualties. The sea condition at the time of the accident is the fundamental RIF causing casualties during the evacuation process, this conclusion is also well supported by the statistical results of the causes of passenger ship accidents. Other RIFs serve as indirect elements connecting the entire evacuation process. It should be noted that in Fig. 5, the RIFs in the L4 hierarchy are not linked to the other RIFs, this situation occurs due to the fact that the RIFs in the L4 hierarchy are weakly correlated with the factors in other hierarchies, and therefore there is no connectivity in the L4 hierarchy.

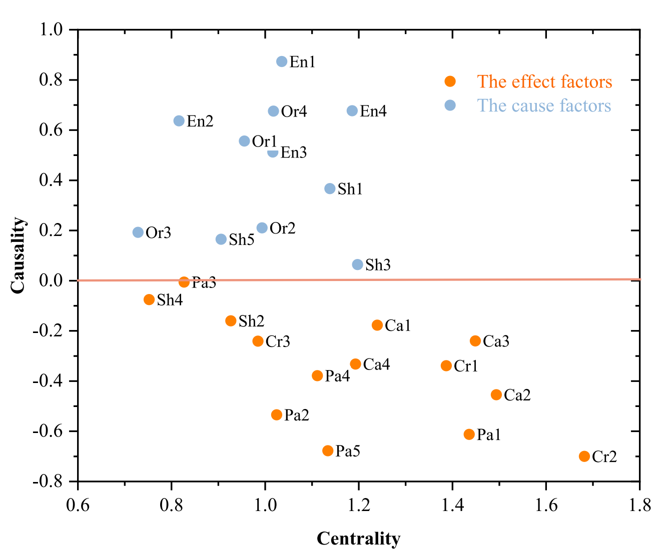

Fig. 3. The cause-effect relationship diagram depicting RIFs.

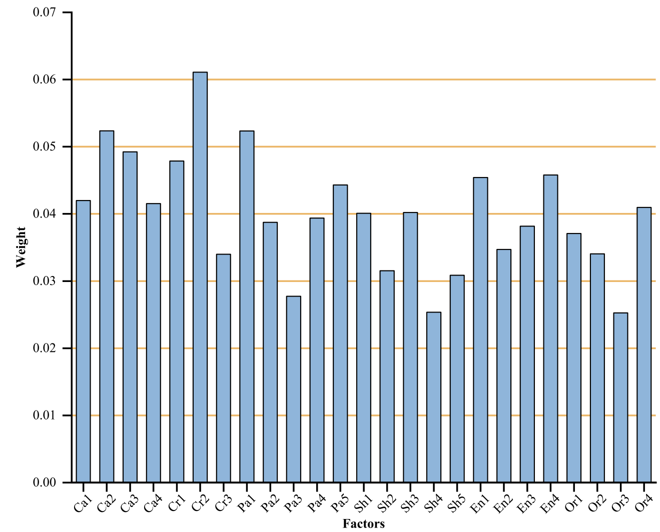

Fig. 4. The importance degree of RIFs.

4.3. The results of BN modeling

4.3.1. Construct the network structure

The topology structure and CPTs of the network are the main components of the BN model. Based on the mapping method in Fig. 2, this study transforms the multi-level network diagram of DEMATEL-ISM into a BN network structure, using a directed graph to represent the dependency relationships between variables. Since the BN model is used to quantify the impact of RIFs on HEPS, in this study, the target node "Type-of-casualty" is assigned to the hierarchical network model. Then, the state of each BN node is specified as two states, and specific explanations can be referred to those in Table 1. Next, based on the Marine Casualties and Incidents module in the IMO-GISIS, data on passenger ship accidents from 1990 to 2023 are obtained. A total of 67 passenger ship accident reports related to casualties during the evacuation process are selected. Referring to the states of nodes in Table 1, a matrix of passenger ship accident data is constructed, and based on this matrix, the prior probabilities of the root node in the BN structure are determined. Subsequently, this study uses Equations (19) and (20) to calculate the CPTs of other sub-nodes in the BN structure. Importing the obtained prior probabilities and CPTs into Netica software, the network structure model of HEPS accidents is obtained, as shown in Fig. 6. As in Fig. 5, the factors in Layer 4 (L4) are not connected to other layers. For clarity in representation, in Fig. 6, the L4 factors are placed at the top position, directly connected to the target node. Regarding the target node "Type-of-casualty," this study refers to the Severity Index in Formal Safety Assessment (FSA) proposed by IMO, categorizing the casualties of accidents into three types, as explained in Table 5.

From Fig. 6, it can be observed that the probability of casualties exceeding 10 people (Type-of-casualty = PSA) is 48.8%, indicating that the overall risk of passenger ship evacuation is at a relatively high level. In the constructed BN model, forward reasoning can be performed to

Table 4
The hierarchical structure of RIFs.

Level	RIFs
L1	Pa5
L2	Cr2, Pa1, Pa2, Pa4
L3	Ca4, Pa3, Sh2, Sh4
L4	Ca1, Ca2, Ca3, Cr1
L5	Sh3, Sh5, Or2
L6	Cr3, Sh1, Or3
L7	En2, En3, En4, Or1, Or4
L8	En1

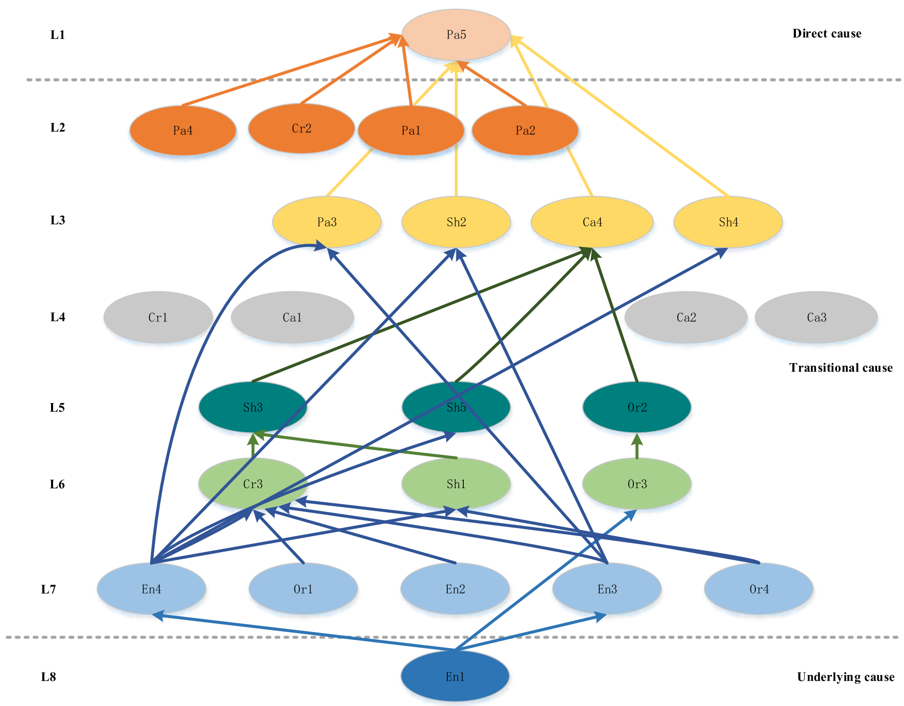

Fig. 5. Multi-level structure of RIFs.

calculate the extent of casualties in the evacuation process under different scenarios. To validate the established BN model, this study selected the sinking accident of M/V "AL SALAM BOCCACCIO 98″ on February 3, 2006, for a case study. The ship, a Panamanian roll-on/roll-off passenger vessel, sank during a journey across the Red Sea. A fire occurred approximately 2 h and 20 min into the voyage, and during the firefighting process, a large amount of water accumulation resulted from clogged drainage holes. Combined with adverse weather conditions, it ultimately led to the sinking of the vessel. According to the accident investigation report, it was revealed that passengers on M/V "AL SALAM BOCCACCIO 98″ did not timely wear LSA (Pa5) and evacuate promptly, which were the direct causes of casualties. Additionally, among the indirect causes identified in the accident investigation report, RIFs such as accident hazard assessment (Ca1), assembly, evacuation, and abandon-ship decision-making (Ca2), personnel communication and action arrangements (Ca3), and ship fire hazard (En4) were identified. Based on this evidence, by updating the BN model, the probability of the target node Type-of-casualty = PSA occurring is 64.2%, as shown in Fig. 7. This can demonstrate the correctness of the established BN model.

4.3.2. Reverse diagnostic reasoning

Given the severity of the accident, this study takes advantage of BN's backward reasoning to perform causal inference through probabilistic updating. The posterior probability of each risk factor can be inferred. Taking the target node Type-of-casualty = PSA = 100% as an example, the reverse analysis results of the BN model are shown in Fig. 8. Analysing Fig. 8 reveals that RIFs such as ship safety management plans (Or4), accident hazard disposal (Cr1), severe sea condition (En1), accident hazard assessment (Ca1), and ship emergency plan (Or1) are prone to cause a significant number of casualties. The result also aligns with the reality of passenger ship accidents, exemplified by notable shipwrecks such as M/V Viking Sky, M/V Costa Concordia, and M/V Sewol occurring in rough sea conditions and generating large numbers of casualties. In addition, by analysing the causes of accidents in these accident reports, keywords such as ship safety management system, accident hazard disposal, and accident hazard assessment can all be found. By setting the target nodes to Type-of-casualty = MA = 100% and Type-of-casualty = SA = 100%, the probability that RIFs may occur in the corresponding target node state can be obtained. This method enables the prediction of which RIFs are most likely to result in accidents and casualties. Upon analysing the changes in the posteriori probabilities of RIFs when the target nodes transition through SA, MA, and PSA states sequentially, it is found that the posteriori probabilities of these three factors, accident hazard assessment (Ca1), personnel communication and action arrangements (Ca3), and accident hazard disposal (Cr1), increased significantly.

4.4. Discussion and implications

Improving the safety level of passenger ships and reducing casualties has always been the focus of international and national maritime authorities. Identifying the key RIFs and their interaction mechanisms that lead to evacuation failure or low efficiency is crucial for enhancing safety management and reducing casualties. While existing literatures do include some studies analysing the RIFs of HEPS, research on the reasons for evacuation failure or low efficiency is fewer from the perspective of the importance and interactions of RIFs. This study adopts a novel hybrid approach combining Fuzzy DEMATEL, ISM, and BN to comprehensively identify and rank the RIFs causing evacuation failure or low efficiency. The analysis results from DEMATEL reveal that the top 5 RIFs contributing to casualties in the process of HEPS are crowd management (Cr2), assembly, evacuation, and abandon-ship decision-making (Ca2), panic and herd mentality (Pa1), personnel communication and action arrangements (Ca3), and accident hazard disposal (Cr1). The normalized importance weights for these RIFs are 6.11%, 5.24%, 5.23%, 4.92%, and 4.79%, respectively. This discovery is consistent with existing literatures on the research results of RIFs in HEPS (Ventikos et al., 2023; Wang et al., 2023). For instance, in the study carried out by Wang et al. (2023), the timely decision-making of the captain is one of the main RIFs influencing the safety of HEPS. Making

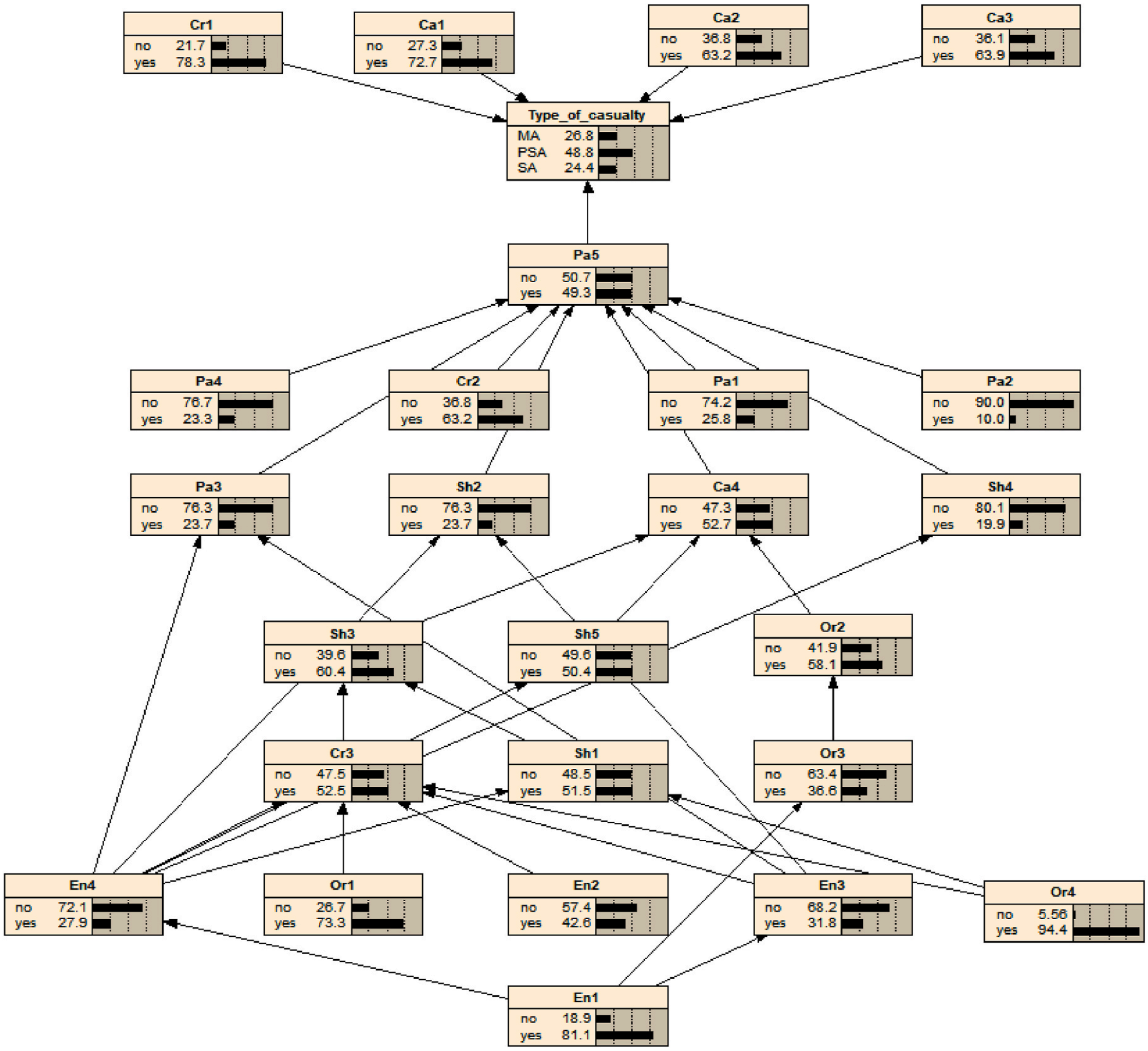

Fig. 6. The forward analysis results of BN model.

Table 5
The classification of accident severity.

Classification	Explanation	Number of casualties
SA	Serious accidents	1 person and less than 1 person dead; Multiple injuries.
MA	Major accidents	Less than 10 deaths.
PSA	Particularly serious accidents	More than 10 deaths.

timely decisions for assembly and abandon-ship in uncontrollable risks can secure a significant amount of time for the safe evacuation of HEPS. However, the existing literatures on HEPS considers the captain's evacuation decisions, the crew's crowd management and accident hazard disposal, attention to the passengers remains insufficient. During HEPS process, passengers need to remain calm and not panic to follow the crew's guidance, evacuate to the assembly station on time, and safely obtain life-saving equipment. To alleviate panic and herd mentality among passengers, countermeasures need to be taken before and during the voyage. For example, brief safety education should be provided before sailing, safe evacuation procedures are introduced through videos, lectures, and manuals, and passengers should be taught to follow crew evacuation arrangements in the event of an accident. During the long voyages, passengers should also participate in evacuation drills to familiarize themselves with the procedures and routes.

Subsequently, using the DEMATEL-ISM model to analyse the RIFs in the process of HEPS, the study innovatively analyses the correlation between RIFs and identifies the categories of RIFs. The research results indicate that adverse sea conditions are the fundamental cause of casualties during the evacuation process, and this RIF has a direct or indirect impact on other RIFs, thereby affecting the overall safety of the HEPS process. Therefore, it is crucial for shipping companies to establish comprehensive weather navigation for vessels, reducing voyage arrangements in adverse weather conditions such as strong winds and heavy rain. Additionally, the lack of or incorrect wearing of LSA by passengers is a direct cause of casualties during the evacuation process, and this RIF is highly susceptible to the influence of other RIFs. Therefore, having an ample supply of well-maintained life jackets on the vessel, placed in appropriate locations, can effectively address the RIF Pa5. In addition, on the foundation of well-maintained life-saving equipment, passengers should receive instructional guidance on the use of life-saving appliance to better align with the RIF Pa5. Specifically, shipping companies should establish detailed safety training plans to

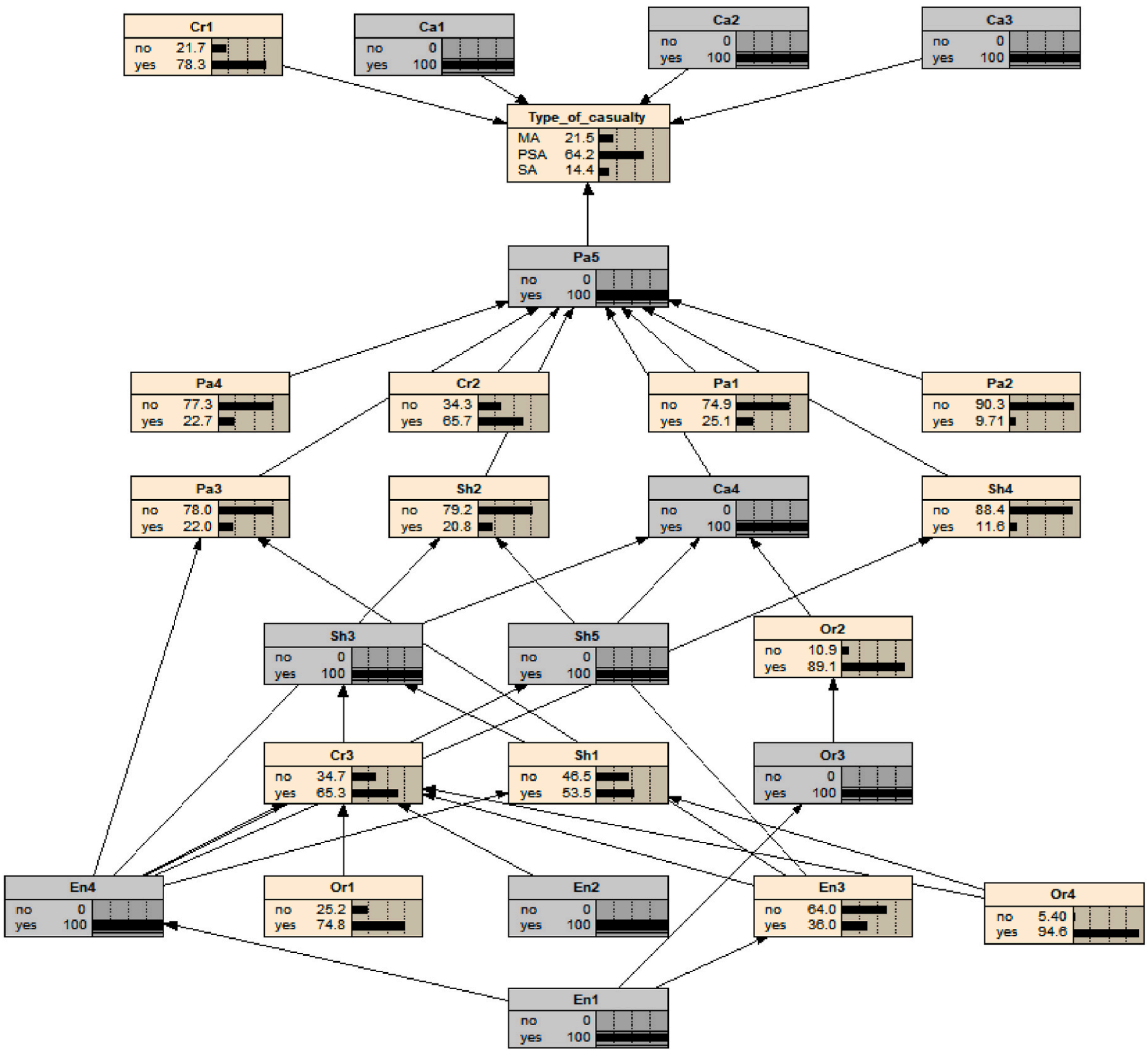

Fig. 7. The result of positive causal reasoning.

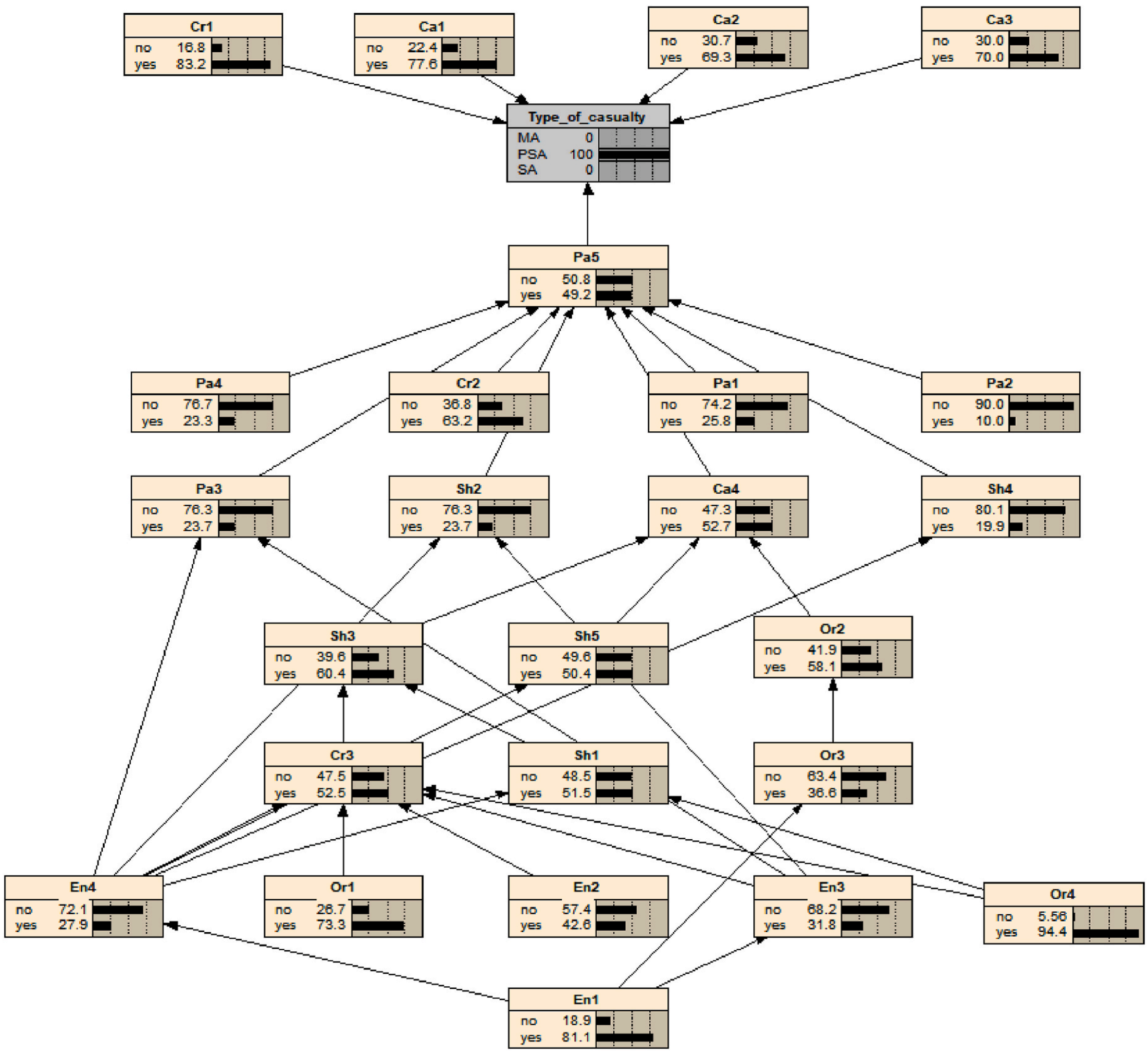

Fig. 8. The result of reverse diagnostic reasoning.

ensure passengers can master the correct usage of key equipment such as lifeboats, lifebuoys, and life jackets. In addition, it is recommended that shipping companies should provide multilingual instruction with graphic and visual support to ensure all passengers can understand. This study also recommended that shipping companies should increase information displays by placing signs in key locations on the ship, clearly indicating the location of life-saving equipment and providing concise usage instructions; set up an emergency safety hotline, regularly collect and analyse passenger feedback to improve safety training and enhance the user experience of life-saving equipment.

Finally, mapping the hierarchy of DEMATEL-ISM to the BN model, after inputting prior probabilities and CPTs, the posterior probabilities of each node and the probability distribution under different levels of accident severity can be obtained. The posterior probability of each node at different accident severity states can be obtained through backward reasoning. Shipping companies and maritime authorities can predict the most likely factors and develop countermeasures for factors with a high posteriori probability of occurrence. In different states of the target node, the probability of occurrence of Or4 (i.e., Ship Safety Management Plan) is the highest. In the case of the sinking of the M/V PRINCESS ASHIKA, it has been clearly documented in the Fiji Maritime Authority that the vessel was unfit for operation. If the operating company of the vessel had not been compelled to put vessels in poor condition into operation in order to save costs; or if the local authorities had not signed off on the procurement and operating documents and implemented stricter regulations, a large number of casualties would not have been caused. Furthermore, the posterior probabilities of three RIFs, accident hazard assessment (Ca1), personnel communication and action arrangements (Ca3), and accident hazard disposal (Cr1), exhibit a notable increase with rising accident severity. This implies that these factors play a crucial role in determining the extent of casualties, necessitating shipping companies and maritime authorities to allocate additional resources and implement targeted measures to mitigate the resulting damage and casualties. For the RIF Ca1 (Accident hazard risk assessment), shipping companies can utilize simulation technology to conduct accident scenario-based training, enhance crew's emergency response capability through multiple drills. Regarding the RIF Cr1 (Accident hazard disposal), crew members should familiar with the handling processes for various types of accidents (such as fires, collisions, and stranding) and develop countermeasures during emergency drills. The shipping company should conduct regular psychological training to help the crew stay calm in emergency situations.

5. Conclusion

This study employs a hybrid approach combining Fuzzy DEMATEL, ISM, and BN to systematically analyse the RIFs influencing the HEPS. Initially, 25 RIFs are identified based on an extensive literature review, analysis of ship accident investigation reports, and expert knowledge. Next, using triangular fuzzy numbers to defuzzify the results of expert survey questionnaires, describing the logical relationships among identified RIFs with DEMATEL, the influence degree, being influenced degree, centrality, and causal relationships between RIFs are obtained. Further analysis revealed that crowd management; decision-making for assembly, evacuation and abandonment of ships; passenger panic and herd mentality; communication and action arrangements; accident hazard disposal are the top five ranked factors. Thirdly, using the ISM method, a multi-level hierarchical network structure consisting of 8 levels is established, identifying the direct, transitional, and root causes of casualties during the process of HEPS. The ISM results show that rough sea conditions are the root cause of most passenger ship accidents, and that passengers not wearing or incorrectly wearing LSAs are the direct cause of HEPS casualties. Finally, the ISM results are mapped into a BN structure, Netica is used to establish the BN model. The BN model is used to validate the reliability of the model through forward reasoning and also to quantify the results of the ISM analysis. The RIFs most likely to cause injuries and fatalities during HEPS are obtained using backward diagnostic reasoning. From this study, it can be observed that the proposed method allows for an effective and rapid safety assessment of the RIFs in the process of HEPS from multiple dimensions.

Additionally, despite the integration of DEMATEL, ISM, and BN to leverage their advantages in dealing with uncertain RIFs, there are still some limitations that need further improvement in future research. For instance, the identification of RIFs relies mainly on collected passenger ship accident investigation reports and expert experiences, and the identified RIFs may not cover all those present during the process of HEPS. Therefore, in further research, there is a need to accumulate more objective data related to the safety and reliability of passenger ship evacuation, refining the set of RIFs in the process of HEPS. On the other hand, this study assigned equal weights to expert data without considering the impact of different weights on the results. Thus, in future research, the varying weights of domain experts should be taken into account. In addition, considering that the database in the IMO GISIS module has some errors with some other commercial databases, this study will be based on other databases to further improve the accident data in the HEPS process.

CRediT authorship contribution statement

Shuang Wang: Investigation, Formal analysis. **Jiashi Wang:** Writing – original draft, Visualization, Supervision, Software, Data curation, Conceptualization. **Xinjian Wang:** Writing – review & editing, Visualization, Resources, Funding acquisition, Formal analysis, Writing – original draft.

Declaration of competing interest

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

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Appendix A

Table A1
The direct influence matrix.

Z	Ca1	Ca2	Ca3	Ca4	Cr1	Cr2	Cr3	Pa1	Pa2	Pa3	Pa4	Pa5	Sh1	Sh2	Sh3	Sh4	Sh5	En1	En2	En3	En4	Or1	Or2	Or3	Or4
Ca1	0.008	0.055	0.051	0.054	0.054	0.053	0.012	0.038	0.037	0.006	0.035	0.024	0.008	0.011	0.010	0.009	0.009	0.002	0.003	0.007	0.004	0.007	0.020	0.008	0.007
Ca2	0.021	0.012	0.045	0.040	0.044	0.048	0.019	0.049	0.043	0.006	0.047	0.048	0.008	0.009	0.010	0.005	0.011	0.002	0.002	0.004	0.004	0.004	0.028	0.005	0.004
Ca3	0.041	0.050	0.013	0.041	0.047	0.054	0.027	0.055	0.038	0.007	0.042	0.042	0.006	0.009	0.012	0.024	0.013	0.003	0.003	0.004	0.004	0.014	0.028	0.020	0.008
Ca4	0.022	0.032	0.038	0.008	0.021	0.029	0.025	0.050	0.025	0.005	0.035	0.032	0.004	0.007	0.007	0.005	0.011	0.002	0.002	0.004	0.004	0.007	0.031	0.017	0.007
Cr1	0.021	0.043	0.027	0.041	0.011	0.055	0.032	0.039	0.027	0.006	0.024	0.031	0.014	0.016	0.033	0.020	0.020	0.003	0.003	0.004	0.016	0.007	0.018	0.008	0.007
Cr2	0.018	0.035	0.031	0.033	0.031	0.015	0.011	0.052	0.053	0.017	0.050	0.053	0.004	0.017	0.006	0.005	0.005	0.002	0.002	0.007	0.004	0.007	0.018	0.007	0.006
Cr3	0.020	0.027	0.020	0.018	0.023	0.035	0.005	0.029	0.019	0.005	0.020	0.035	0.013	0.007	0.047	0.011	0.011	0.002	0.002	0.003	0.003	0.003	0.009	0.003	0.003
Pa1	0.010	0.028	0.017	0.012	0.019	0.048	0.016	0.011	0.038	0.022	0.048	0.038	0.007	0.032	0.012	0.008	0.007	0.002	0.002	0.013	0.003	0.003	0.009	0.003	0.003
Pa2	0.005	0.016	0.016	0.009	0.016	0.043	0.014	0.015	0.006	0.010	0.024	0.014	0.003	0.017	0.010	0.004	0.003	0.002	0.002	0.003	0.002	0.002	0.004	0.003	0.002
Pa3	0.013	0.022	0.021	0.014	0.022	0.041	0.016	0.038	0.038	0.005	0.041	0.045	0.004	0.026	0.012	0.011	0.004	0.002	0.002	0.013	0.006	0.003	0.005	0.003	0.003
Pa4	0.019	0.022	0.024	0.021	0.027	0.051	0.016	0.042	0.027	0.014	0.009	0.011	0.004	0.031	0.012	0.005	0.004	0.002	0.002	0.006	0.003	0.003	0.005	0.003	0.003
Pa5	0.004	0.010	0.012	0.011	0.006	0.029	0.007	0.019	0.020	0.029	0.013	0.006	0.003	0.030	0.004	0.004	0.003	0.002	0.002	0.003	0.002	0.002	0.003	0.003	0.002
Sh1	0.051	0.054	0.045	0.053	0.045	0.046	0.026	0.053	0.031	0.019	0.042	0.057	0.006	0.024	0.041	0.039	0.038	0.012	0.012	0.018	0.017	0.004	0.009	0.005	0.004
Sh2	0.010	0.019	0.021	0.008	0.021	0.050	0.012	0.039	0.041	0.012	0.017	0.031	0.022	0.006	0.009	0.031	0.012	0.002	0.002	0.003	0.003	0.003	0.005	0.003	0.003
Sh3	0.045	0.057	0.045	0.048	0.042	0.057	0.037	0.047	0.025	0.016	0.050	0.047	0.026	0.019	0.007	0.013	0.016	0.003	0.003	0.004	0.004	0.004	0.008	0.005	0.004
Sh4	0.013	0.012	0.017	0.010	0.008	0.042	0.009	0.037	0.047	0.011	0.023	0.016	0.014	0.033	0.014	0.003	0.007	0.002	0.002	0.003	0.003	0.003	0.004	0.003	0.002
Sh5	0.040	0.025	0.043	0.026	0.042	0.052	0.015	0.047	0.042	0.013	0.031	0.038	0.019	0.024	0.020	0.016	0.004	0.003	0.003	0.007	0.010	0.004	0.007	0.004	0.003
En1	0.055	0.067	0.043	0.042	0.060	0.061	0.047	0.068	0.033	0.049	0.037	0.059	0.044	0.015	0.057	0.017	0.020	0.002	0.004	0.046	0.046	0.006	0.029	0.040	0.005
En2	0.049	0.056	0.050	0.036	0.054	0.065	0.046	0.055	0.045	0.035	0.024	0.050	0.013	0.038	0.013	0.025	0.010	0.003	0.001	0.011	0.011	0.008	0.009	0.017	0.004
En3	0.034	0.056	0.041	0.033	0.051	0.063	0.047	0.059	0.028	0.051	0.025	0.059	0.018	0.040	0.052	0.020	0.021	0.003	0.003	0.004	0.033	0.004	0.008	0.005	0.004
En4	0.054	0.065	0.059	0.051	0.053	0.069	0.041	0.062	0.039	0.041	0.032	0.049	0.047	0.048	0.052	0.045	0.044	0.007	0.007	0.037	0.005	0.008	0.010	0.006	0.004
Or1	0.046	0.055	0.053	0.044	0.055	0.055	0.048	0.042	0.024	0.011	0.024	0.037	0.025	0.023	0.039	0.030	0.029	0.003	0.003	0.011	0.012	0.004	0.034	0.024	0.026
Or2	0.041	0.052	0.040	0.043	0.036	0.040	0.021	0.025	0.017	0.007	0.014	0.026	0.018	0.016	0.026	0.017	0.021	0.003	0.006	0.011	0.026	0.022	0.008	0.037	0.029
Or3	0.017	0.049	0.023	0.025	0.019	0.026	0.016	0.020	0.017	0.012	0.016	0.016	0.010	0.011	0.012	0.010	0.010	0.006	0.009	0.014	0.017	0.033	0.046	0.004	0.025
Or4	0.051	0.054	0.052	0.041	0.055	0.064	0.048	0.034	0.022	0.009	0.022	0.042	0.046	0.035	0.050	0.037	0.037	0.006	0.007	0.012	0.013	0.036	0.038	0.031	0.004

Table A2
The comprehensive influence matrix.

H	Ca1	Ca2	Ca3	Ca4	Cr1	Cr2	Cr3	Pa1	Pa2	Pa3	Pa4	Pa5	Sh1	Sh2	Sh3	Sh4	Sh5	En1	En2	En3	En4	Or1	Or2	Or3	Or4
Ca1	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ca2	0	0	1	1	1	1	0	1	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Ca3	1	1	0	1	1	1	0	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Ca4	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cr1	0	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cr2	0	0	0	0	0	0	0	1	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Cr3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Pa1	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pa2	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pa3	0	0	0	0	0	1	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Pa4	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pa5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sh1	1	1	1	1	1	1	0	1	0	0	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0
Sh2	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sh3	1	1	1	1	1	1	0	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Sh4	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sh5	1	0	1	0	1	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
En1	1	1	1	1	1	1	1	1	0	1	0	1	1	0	1	0	0	0	0	1	1	0	0	1	0
En2	1	1	1	0	1	1	1	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
En3	0	1	1	0	1	1	1	1	0	1	0	1	0	1	1	0	0	0	0	0	0	0	0	0	0
En4	1	1	1	1	1	1	1	1	0	1	0	1	1	1	1	1	1	0	0	0	0	0	0	0	0
Or1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Or2	1	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Or3	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Or4	1	1	1	1	1	1	1	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0	0	0

Table A3
The accessibility matrix.

K	Ca1	Ca2	Ca3	Ca4	Cr1	Cr2	Cr3	Pa1	Pa2	Pa3	Pa4	Pa5	Sh1	Sh2	Sh3	Sh4	Sh5	En1	En2	En3	En4	Or1	Or2	Or3	Or4
Ca1	1	1	1	1	1	1	0	1	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Ca2	1	1	1	1	1	1	0	1	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Ca3	1	1	1	1	1	1	0	1	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Ca4	0	0	0	1	0	1	0	1	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Cr1	1	1	1	1	1	1	0	1	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Cr2	0	0	0	0	0	1	0	1	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Cr3	1	1	1	1	1	1	1	1	1	0	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0
Pa1	0	0	0	0	0	1	0	1	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Pa2	0	0	0	0	0	1	0	1	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Pa3	0	0	0	0	0	1	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Pa4	0	0	0	0	0	1	0	1	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Pa5	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Sh1	1	1	1	1	1	1	0	1	1	0	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0
Sh2	0	0	0	0	0	1	0	1	1	0	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0
Sh3	1	1	1	1	1	1	0	1	1	0	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0
Sh4	0	0	0	0	0	1	0	1	1	0	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0
Sh5	1	1	1	1	1	1	0	1	1	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0
En1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	0	1	1	0
En2	1	1	1	1	1	1	1	1	1	0	1	1	0	0	1	0	0	0	1	0	0	0	0	0	0
En3	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	0	0	0	0	1	0	0	0	0	0
En4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	1	0	0	0	0
Or1	1	1	1	1	1	1	1	1	1	0	1	1	0	0	1	0	0	0	0	0	0	1	0	0	0
Or2	1	1	1	1	1	1	0	1	1	0	1	1	0	0	0	0	0	0	0	0	0	0	1	0	0
Or3	1	1	1	1	1	1	0	1	1	0	1	1	0	0	0	0	0	0	0	0	0	0	1	1	0
Or4	1	1	1	1	1	1	1	1	1	0	1	1	1	0	1	0	0	0	0	0	0	0	0	0	1

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