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A novel method for the risk assessment of human evacuation from cruise ships in maritime transportation

Xinjian Wang [a,b,c], Guoqing Xia [a,b], Jian Zhao [a], Jin Wang [d], Zaili Yang [d,e,*], Sean Loughney [d], Siming Fang [a,b], Shukai Zhang [f], Yongheng Xing [g], Zhengjiang Liu [a,b]

[a] Navigation College, Dalian Maritime University, Dalian 116026, PR China
[b] Key Laboratory of Navigation Safety Guarantee of Liaoning Province, Dalian 116026, PR China
[c] Seafarers Research Centre, Shipping Research Institute, Dalian Maritime University, Dalian 116026, PR China
[d] Liverpool Logistics, Offshore and Marine (LOOM) Research Institute, Liverpool John Moores University, L3 3AF, UK
[e] Transport Engineering College, Dalian Maritime University, Dalian 116026, PR China
[f] Division of Cruise Business, CMSK, China Merchants Group, Shenzhen 518067, PR China
[g] Liaoning Maritime Safety Administration, Dalian 116113, PR China

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ABSTRACT

In maritime transport, evacuation, escape and rescue play a crucial role in protecting people's lives when a passenger ship is involved in a serious accident. The study aims to develop a new method to identify hazards, quantify and rank the associated risks in the process of Human Evacuation from Passenger Ships (HEPS). Firstly, based on extensive literature review and marine accident investigation reports, the risk factors affecting passenger ship evacuation were analysed and identified, and an analysis framework based on Human, Ship, Environment and Organization (HSEO) for HEPS was proposed. Secondly, a risk assessment model was proposed to quantify and rank risk factors in the process of HEPS. Finally, a large-scale evacuation drill of a cruise ship was taken as a case study to demonstrate the applicability of the proposed evaluation model, and accuracy of the results. The results reveal that (1) evacuation decision, operation of Life-Saving Appliances (LSAs) are the main risks affecting the safety of HEPS; (2) the behaviours of passengers have a relatively lower risk priority; and (3) future HEPS research should focus on the development of a multi-attribute decision system to address the issue on when to evacuate and when to abandon a ship.

1. Introduction

Maritime transport is an important part of the world economy and transportation network [1–3]. Due to the increase of maritime trade, traffic density and ship size, maritime transport is facing new challenges related to safety [4,5]. As a mode of maritime transport, passenger ship transport is listed as the fourth largest mode of passenger transport after bus, rail and air [6,7]. Although modern passenger ships are equipped with advanced accident prevention systems, passenger ship accidents still occur from time to time, as shown in Table 1, and many of which have caused a large number of casualties [8,9]. As one of the most important issues in maritime emergency response, Human Evacuation from Passenger Ships (HEPS) has attracted great attention because of the huge losses caused by many passenger ship accidents [10,11].

When a passenger ship is involved in a serious accident, evacuation, escape and rescue (EER) jointly play a crucial role in protecting people's lives [12,13]. In order to improve the safety of passenger ship, the International Maritime Organization (IMO) has approved a series of guidelines for existing and new passenger ships to conduct evacuation analysis [14,15]. However, HEPS as a complex process ranging from the triggering of evacuation events to the completion of the rescue at sea, includes the assembly stage (Ab), ship abandonment stage (Ad) and search and rescue stage (Re) [16], as shown in Fig. 1. Compared with land-based evacuation operations, HEPS has many unique features, especially in the process of abandoning the ship, which increases the deployment (boarding and release) time of Life-Saving Appliances (LSAs).

- Firstly, it involves the participation of the captain and crew. The captain should accurately assess the disaster risk before issuing an

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* Corresponding author at: Liverpool Logistics, Offshore and Marine (LOOM) Research Institute, Liverpool John Moores University, L3 3AF, UK.
E-mail address: Z.Yang@ljmu.ac.uk (Z. Yang).

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Table 1
Major worldwide maritime transport accidents with fatal casualties.

No.	Year	Ship name	Accident type	Casualties
1	1992	Royal Pacific	Collision	30 dead, 70 injured
2	1992	Estonia	Sinking	852 dead
3	1993	Jan Heweliusz	Sinking	55 dead
4	2000	Express Samina	Sinking	80 dead
5	2006	Al Salam Boccaccio 98	Fire	1031 dead
6	2008	Princess of the Stars	Capsizing	814 dead
7	2011	M/V Bulgaria	Sinking	122 dead
8	2011	Spice Islander I	Sinking	1529 dead
9	2011	Costa Concordia	Contact	32 dead
10	2012	M/V Shariatpur 1	Collision	146 dead
11	2012	Norman Atlantic	Fire	23 dead, 31 injured
12	2014	Sewol	Capsizing	304 dead
13	2014	Pinak-6	Capsizing	46 dead
14	2015	Eastern Star	Sinking	442 dead
15	2015	Caribbean Fantasy	Fire	49 injured

evacuation order, and the crew should participate in guiding and organizing the evacuation of passengers [1,17].

- Secondly, the evacuation process is complicated. Passengers need to wear life jackets and use LSAs [18]. According to the requirements of the muster card, they need to choose upper or lower decks or move to another side of the ship according to the accident situation [19,20].
- Thirdly, there are many adverse factors, such as weather conditions, ship motion, and ship listing. Furthermore, the evacuation movement of personnel is more likely to be affected by falling obstacles, ship listing and other adverse factors, resulting in the evacuation process being more complex or more dangerous [10,21,22].
- Finally, the degree of familiarity of passengers on HEPS is usually not high, since passengers are not familiar with the whole process of evacuating from the ship by lifeboat or life raft, which brings great threats to the evacuation process, such as personnel panic and crowding [6,23].

Evacuation presents an important research topic in reliability and safety areas. However, the currently available studies in the field focus on the reliability analysis and safety assessment of emergency evacuation from buildings [24,25], offshore platforms [26,27] and land-based transport facilities [28,29]. In contrast to the extensive literature on emergency evacuation of those fields, HEPS has received limited attention in emergency situations. In those limited studies, researchers have carried out a series of studies on evacuation decision analysis, passengers' perception and behaviours, and individuals' walking speeds in view of the special features of HEPS. In terms of evacuation decision analysis, Sarvari et al. [10] developed a multi-module ferry evacuation decision support system by providing comprehensive methods, which not only revealed the important factors of emergency evacuation performance, but also proved the effectiveness of the developed decision support system. Kim et al. [30] used the "Sewol" passenger ship accident as an example to evaluate the risk of evacuation of the highest deck with the opposite listing direction during the ship sinking. They pointed out the existing problems and limitations of the existing evacuation system, and proposed a new evacuation scheme. Akyuz [17] proposed a fuzzy success likelihood index method (SLIM) technique, analysed the human error during ship abandonment, and summarized the measures to evaluate and reduce the possibility of human error. In terms of passenger perception and behaviour, Galea et al. [31,32] carried out three evacuation drills on passenger ships to collect the response time data of passengers and test the difference of reaction activities among passengers of different genders and ages; Ni et al. [33] studied the process of HEPS under the influence of life jackets, and established an agent-based human evacuation simulation model considering counter flow and life jackets wearing behaviours; Wang et al. [14,15] established logistic regression models to study passengers' safety awareness, their perception of emergency pathfinding tools, as well as their likely evacuation behaviours. In terms of individuals' walking speeds, some researchers conducted human walking experiments on ship corridor simulators [21,34] or moving ships [35–37] to obtain individuals' walking speeds under different ship listing angles and moving conditions, so as to study

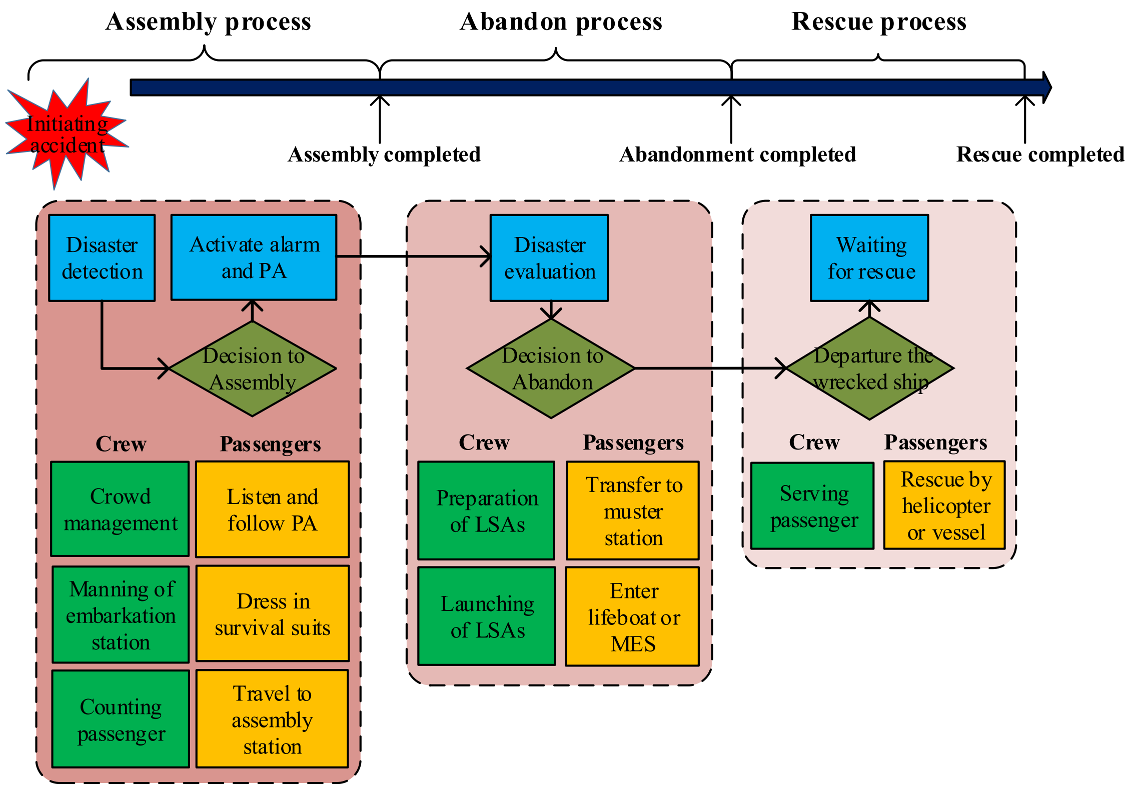

Fig. 1. The assembly, abandonment and rescue process of HEPS.

the influence of adverse factors such as ship listing or ship motion during the evacuation process. The current studies on the evacuation analysis of HEPS in in the shipping sector mainly focus on the evacuation analysis at the ship design stage and modelling of personnel movement at the assembly stage. There are few studies associated with the activities at the ship abandonment and rescue stage, and fewer involving the risk factors in the HEPS process from the perspective of risk assessment. The available marine accident investigation reports emphasized the captain's evacuation instruction, the crew's abandoning operation, and the organization of maritime authorities' rescue force with a significant difference. It results in the inconsistence of the results obtained from the existing HEPS studies and the marine accident investigation reports, causing the argument on the evacuation efficiency and rational of the state-of-the-art methods. Simultaneously, it is witnessed that the reliability and safety issues on passenger ships have been attracting increasing attention in recent years partly due to the occurrence of a few relevant accidents (e.g. Eastern Star, Sewol and Costa Concordia), including operational vulnerability and accident susceptibility [3], watertight door operation monitoring [38], and fire safety risk assessment model at ship design stage [39,40]. Given this research need, this paper aims to study the reliability issues and conduct risk assessment of HEPS from the perspective of emergency response practice of passenger ships.

The essence of risk assessment is to quantify the possible impact of an event on people's life, lives, property and other aspects from the perspective of systems engineering, which is an effective way to formulate mitigation measures [25,41,42]. Research on HEPS based on risk assessment can help stakeholders understand the possible losses in the process of HEPS and provide scientific guidance for developing effective control measures. Based on literature reviews and analysis of marine accident investigation report, this study aims to identify risk factors in the process of HEPS, and develop a new evaluation framework to quantify and rank risk factors in the process of HEPS. It will undoubtedly aid to address the safety issues that most concerned with stakeholders in passenger ship operations. The contributions and originalities of this study to such issues are evident from four perspectives.

(1) For the first time, the reliability issues in the HEPS process are studied from the perspective of a whole evacuation system (assembly, abandonment and rescue) in general, the evacuation of passenger ship in particular. A new method for hazard identification and risk assessment of HEPS is developed to identify, quantify and rank the risks in the HEPS process.
(2) The knowledge framework of risk assessment is newly applied to a HEPS process, and the risk factors influencing the HEPS process are identified based on both marine accident investigation reports and literature review. The finding is then used to guide the establishment of a new HSEO analysis framework for hazard identification of HEPS.
(3) In view of the limitations of research data, BBN and ER algorithms are introduced to address the uncertainty of expert knowledge, and a risk assessment model is proposed by taking the advantages of integrated FMEA, BBN, ER and utility function. A large-scale evacuation drill of a cruise ship is taken as a real case study to demonstrate the applicability of the proposed assessment model.
(4) Based on the research results, the research gap between existing HEPS studies and emergency response practice of passenger ships is clearly revealed, and it discloses that future HEPS research should focus more on the provision of evacuation decision support for ship captains from the perspective of emergency response practice, and address the decision support problems as to when to evacuate and when to abandon a ship.

2. Hazards in the human evacuation from ships

Accidents are often caused by unsafe acts, unsafe conditions and a lack of management [43,44], and maritime accidents are generally considered to be the result of complex human, technical, environmental and organizational factors [45]. Based on extensive analysis of literature review and marine accident investigation reports, main risk categories for HEPS are identified and listed in Table 2. It should be noted that the complexity factor that must be considered in the emergency response to an accident is human behaviour. Personnel's decisions and actions always have a huge impact on catastrophic events [46], for example, when and how to evacuate can have a considerable impact on the consequences of an evacuation event. Thus, human behaviour is divided into "the performance of captain", "the operation of crew", and "behaviours of passenger", according to the task of different groups.

2.1. The performance of captain

When a ship encounters a collision, grounding, flooding or fire and other maritime disasters, the captain shall organize the crew to investigate the disaster situation and make an evaluation of the hazard [12, 47]. If the danger is out of control, the captain needs to order an evacuation to prevent loss of life. In this process, the captain needs to sound the evacuation alarm through the Public Address (PA) system, issue a distress signal to the maritime authorities and shipping company, and

Table 2
The category of hazard in HEPS.

Hazard category	Marine accident investigation report	Description
The performance of captain (Captain)	Al Salam Boccaccio 98 (2006); Costa Concordia (2012); Dashun (1999); Lisco Gloria (2010); Norwegian Dawn (2005); Sorrento (2015); Sewol (2014)	After the initial incident, the captain's emergency operation, decision making and command play a decisive role in the human evacuation process.
The operation of crew (Crew)	Costa Concordia (2012); Caribbean Fantasy (2016); Carnival Liberty (2015); Norman Atlantic (2014); Pearl of Scandinavia (2010); Sally albatross (1994)	In the process of emergency evacuation, the crew's performance of competence and emergency operation also have a considerable effect on the safety of human evacuation.
Behaviours of passenger (Passenger)	Al Salam Boccaccio 98 (2006); Costa Concordia (2012); Dashun (1999); Dover Harbour (2002); Lisco Gloria (2010); Norman Atlantic (2014); P&OSL Aquitaine (2003)	Under the stimulation of dangerous events, the diversity of passengers' behaviours has an impact on their own safety or the safety of others.
Ship factors (Ship)	Caribbean Fantasy (2016); Costa Mediterranean (2015); Harmony of the Seas (2016); Norwegian Breakaway (2016); Norman Atlantic (2014); Pride of America (2015); Thomson Majesty (2013)	The condition of ship, especially the availability of LSAs becomes one of the important factors affecting evacuation safety.
Environmental factors (Environment)	Commodore Clipper (2010); Express Samina (2003); Knossos Palace (2003); Mecklenburg Vorpommern (2010); Pearl of Scandinavia (2010);	Weather and sea conditions, spread of disaster on ships will also affect the safety of human evacuation process.
Organization factors (Organization)	Al Salam Boccaccio 98 (2006); Commodore Clipper (2010); Costa Concordia (2012); Caribbean Fantasy (2016); Lisco Gloria (2010); Sorrento (2015); Salem Express (1991)	The effectiveness of ship emergency plan, the performance of shipping company or search and rescue coordination centre also have a certain impact on the safety of the evacuation process.

command the crew to organize the orderly evacuation of passengers to the assembly station [17]. If the disaster expands further, the captain needs to make a decision to abandon the ship, command the crew to organize passengers on board the LSAs in an orderly manner, abandon and stay away from the ship. At the same time, the captain should also maintain constant communication with the shipping company and maritime authorities to coordinate rescue efforts [13,23]. For example, a fire broke out on the Ro-Ro passenger ship "Sorrento" on April 2, 2015. The captain immediately organized the fire brigade to put out the fire. When the fire was out of control, the captain decided to evacuate the passengers, resulting in minor casualties.

SOLAS Convention (SOLAS, 2009, Chapter III Life-saving Appliances and Arrangements) requires all passenger ships to have a decision support system on the bridge to deal with emergency situations, provide emergency plan for fire, flooding, pollution and other predictable disasters, and provide decision support to deal with various emergencies. A study found that 75.8% of shipboard accidents and 80.4% of human error accidents were related to the captain's mistakes and violations [48]. Since the captain is responsible for evacuation decisions, it is clear that mistakes or violations by the captain can affect the working procedures, operation and emergency response of the crew. On October 8, 2010, a fire accident occurred on the Ro-Ro passenger ship "Lisco Gloria". Due to the uncontrollable fire, the captain decided to evacuate passengers 35 min after discovering the fire, and finally evacuated all 235 people in 81 min. On the contrary, in the accidents of "Al Salam Boccaccio 98", "Sewol" and "Costa Concordia", the captain underestimated the danger of the situation and failed to effectively order the crew to organize personnel evacuation, which led to serious consequences [14]. The captain of the "Al Salam Boccaccio 98" in particular did not follow the advice of the officers and did not communicate with nearby ships, companies or authorities, resulting in the death of 1031 people [18].

2.2. The operation of crew

SOLAS Convention (SOLAS, 2009, Chapter III Life-saving Appliances and Arrangements) provides that there shall be sufficient trained crew or staff on board to gather and assist untrained passengers. Existing studies have shown that passengers' familiarity with the location of assembly stations and their decision to follow crew instructions are the main factors affecting passengers' choice of evacuation routes [49]. Due to passengers' low familiarity of the layout of passenger ships and evacuation procedures, crew need to take the key positions of ships during evacuation, organize and guide passengers to the assembly station in an orderly manner [14]. In this process, the effective communication between the captain, crew and passengers is particularly important. For example, in the "Norman Atlantic" and "Costa Concordia" accidents, there was no effective communication between crew and passengers due to language problems, and the evacuation process was inefficient. In contrast, in the "Sally Albatross" and "Pearl of Scandinavia" accidents, the crew kept passengers informed about the development of the accident. During the evacuation, the crew took position in all stair areas in advance to guide passengers to the assembly station and the evacuation process was effectively carried out.

In the process of abandoning ship, the crew shall organize passengers on board and release the LSAs according to their duty. If a Marine Evacuation System (MES) is used, the crew will need to organize the safe evacuation of passengers through slipways to lifeboats [10]. In this process, the crew's competency plays a crucial role in safe evacuation. However, some accidents highlighted the crew's inadequacy in operating LSA. For example, in the "Costa Concordia" accident, some crew in charge of the lifeboat either did not have the correct safety certificate or the certificate had expired. In addition to the technical and operational challenges of emergency response, the crew under the command of the captain should have good quality and sufficient training to manage crowds and guide passengers to avoid offensive behaviour. For example, in the "Carnival Liberty" fire accident, crew and staff were stationed at intersections in each area to guide passengers away from cabins, while the crowd management in the "Costa Concordia" accident was ineffective and the evacuation efficiency was also low [23].

2.3. Behaviours of passengers

As a unique feature of HEPS, wearing life jackets has a great impact on personnel response, evacuation motion, boarding process. Wearing life jackets correctly can effectively improve personnel safety, however, improper operation may bring additional risks, such as in the evacuation drill of "P&O SL Aquitaine" Ro-Ro ferry, a woman died when she got stuck in a MES slide because of failure to wear a life jacket correctly. In addition, passengers returning to cabins to get life jackets or look for valuables will form counter flow among the evacuation crowd, which will hinder the evacuation process, and make passengers miss the best time window of evacuation [33]. For example, in the "Costa Concordia" accident, one passenger spent 1.5 h searching for her daughter [15].

Existing studies on evacuation issues have shown that people behave with competitive behaviours in an emergency, such as pushing and trampling [15]. For example, in the "Costa Concordia" accident, when the crew allowed passengers to enter the lifeboat, people began to push and shove to get on the boat, and the interaction between people became physical [23]. In the real evacuation process, passengers escape with luggage will affect their evacuation speed. In the "Costa Concordia" accident, many elderly passengers refused to leave their belongings behind, despite the ship listing seriously, until rescuers forced them to give up their belongings [15,23].

In addition, some passengers may choose to jump into the water to save themselves in the process of emergency evacuation, which has been seen in the marine casualty accidents of "Al Salam Boccacio 98", "Costa Concordia" and "Dashun" [19,23].

2.4. Ship factors

Other major factors affecting the safety of HEPS are the ship's anti-disaster ability and the availability of LSAs. For the ship's anti-disaster ability, it mainly refers to the ship's ability to operate safety under heavy weather conditions and fire hazards. For example, many key cables of Ro-Ro passenger ships pass through the Ro-Ro space. If a fire spreads on the vehicle deck, it can lead to the failure of the electrical system, which can lead to the failure of navigation or power systems [50]. This has been seen in marine accidents such as "Al Salam Boccaccio 98", "Knossos Palace" and "Vincenzo Florio".

LSAs play a crucial role in EER, especially in the stages of abandoning ship and rescue. As for the availability of LSAs, SOLAS Convention stipulates that adequate maintenance, testing and inspection of LSAs shall be carried out to ensure the reliability of such equipment [12]. However, the failure of LSAs often occurs in the evacuation process of passenger ships [19]. For example, the "Thomson Majesty" was conducting an evacuation drill in port when a wire cable suddenly snapped, killing five people and injuring three. Four crew members of the "Norwegian Breakaway" fell overboard after their rescue boat broke off during a safety drill in the harbour. One person died and four others were seriously injured when corroded cables caused a lifeboat on the "Harmony of the Seas" to fall off during a weekly safety drill in Marseille port, France. In the "Lisco Gloria" incident, the port lifeboat, although successfully launched, stalled after 500 m in the water due to engine failure.

2.5. Environmental factors

Environmental factors mainly include heavy weather, spread of the disaster (mainly refers to fire), ship listing or motion, the influence of obstacles, etc. Heavy weather will not only affect the navigation ability of ships, but also have a great impact on the evacuation process. For example, on March 23, 2019, the "Viking Sky" experienced a power outage and loss of propulsion in storm conditions. The captain considered evacuating passengers and crew to lifeboats, but this was deemed too dangerous due to environmental conditions. The spread of the disaster, such as flooding, grounding and fire, will affect the stability and floating state of the ship, and then affect the motion of passengers, and even the availability of LSAs. For example, in the "Norman Atlantic" accident, the fire burned the guide rope, thus hindered boarding and the use of LSAs [50].

As one of the unique features, the condition of ship listing and motion is one of the adverse factors for HEPS. As described in previous studies, the listing and motion state of ships significantly affect the walking speed of passengers, and at the same time, obstacles may fall, resulting in injuries or obstruction of the route [15,49]. In the later evacuation stages of the "Costa Concordia" and "Sewol" accidents, the evacuation process was difficult due to the severe listing of the ship, which resulted in heavy casualties [21,23].

2.6. Organization factors

Organizational factors mainly include ship emergency plan, company decision support and search and rescue (SAR) force. The International Safety Management (ISM) Code requires shipping companies to establish and formulate emergency plans for the safety and pollution prevention of ships, provide guidance for emergency decision-making of ships. The SOLAS Convention requires shipping companies and ships to organize regular emergency training and drills for crew and passengers. Although there are many international and national regulations detailing the standard evacuation procedures to be followed during an emergency, the media continues to report casualties of HEPS. The reason may be that the process of HEPS is affected by a variety of complex factors, and the emergency plan is not reasonable enough, or the company cannot provide effective decision support [51]. The rationality of emergency plan, regular emergency drill, regular safety training and other organizational issues are the factors that cannot be ignored to increase the probability of successful evacuation [19].

After abandoning the ship, search and rescue resources have a significant effect on the consequence of an accident. In well-resourced and well-managed areas or countries, search and rescue efforts often respond more quickly and manage to save more lives [18]. As we can see from the "Caribbean Fantasy", "Lisco Gloria", "Sorrento", "Norman Atlantic" and "Costa Concordia" cases, accidents that happen in countries with good search and rescue resources and management, usually produce better results. In the cases of "Al Salam Boccaccio 98" and "Salem Express", search and rescue operations began late after the incident, resulting in a total of 1495 deaths.

In this section, all the risk factors influencing HEPS are identified in a new way in which all the factors from the relevant previous studies have to appear in real accidents to be included in this study, and vice versa. It ensures the validity of the included factors and justify their inclusion as the foundation to develop the new risk assessment framework in Section 3.

3. Methodology

In order to comprehensively and scientifically analyse the risks for HEPS, a two-stage risk analysis framework is proposed in this study, as shown in Fig. 2. The first stage is hazard identification, based on the findings from Section 2, and a HSEO framework suitable for risk analysis is proposed to determine the risk factors for HEPS. The second stage is risk assessment. A risk assessment model is put forward, in which FMEA, AHP, BBN and ER are used in a combined way to quantitatively rank the risks in the process of HEPS.

3.1. Determine evaluation indicators

On the basis of literature review, expert judgment and comprehensive analysis of marine accident investigation reports, a HSEO framework for HEPS risk assessment with hierarchical structure is constructed. The HSEO framework consists of three levels according to

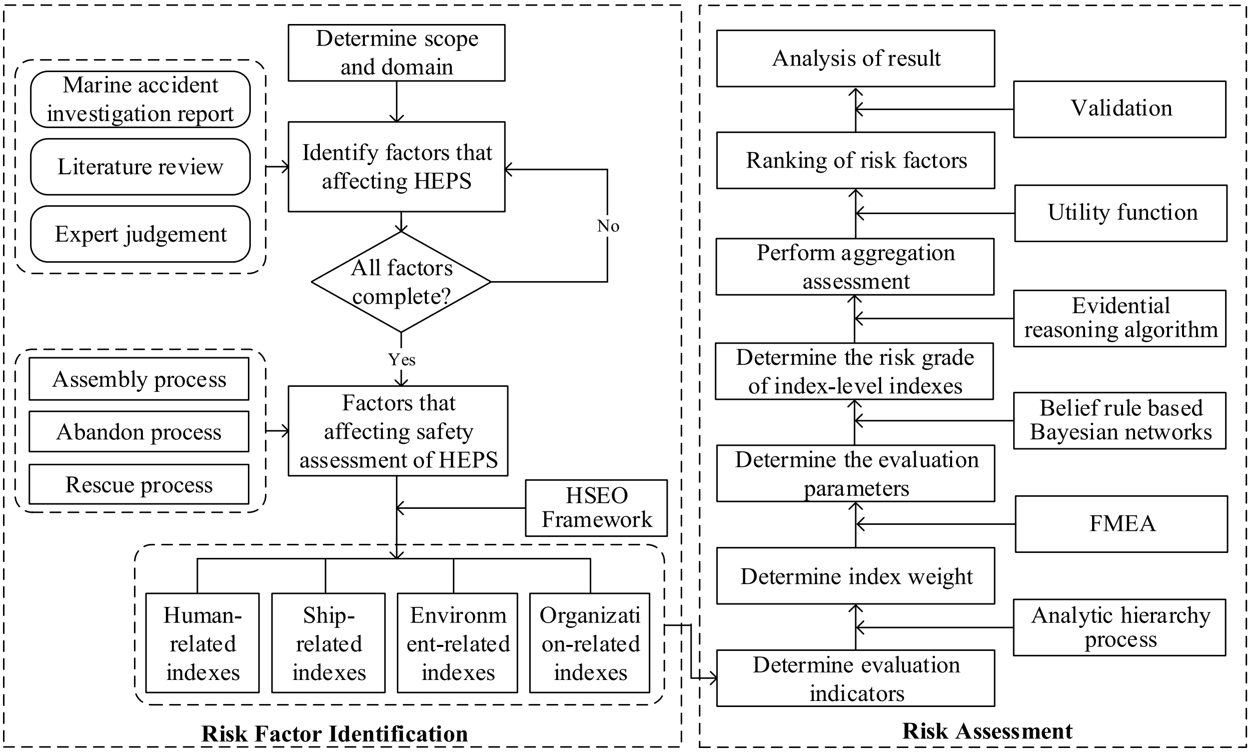

Fig. 2. Methodological framework of risk assessment for HEPS.

the tasks and operations of personnel in the evacuation process, and the risk factors of HEPS. The first level is goal-level, which is the research target of this study. The second level is the criteria-level, which consists of six aspects: captain, crew, passengers, ship, environment and organization. According to these criteria, combined with the three stages of HEPS, different indexes can be obtained in the third level, i.e., index-level. Since certain tasks or operations occur only in certain stages, certain indexes are applicable only to one or certain evacuation stages, such as the index "Make evacuation/ ship abandonment decisions (Ab/ Ad)" indicating that this index is applicable to the assembly (Ab) stage and ship abandonment (Ad) stage.

Based on the above work, a hierarchical model for HEPS risk assessment is established, and a set of evaluation indexes of HSEO framework is shown in Fig. 3. All evaluation indexes are obtained from marine accident investigation reports and literature review. The detailed description of these indexes is described in Section 2. During the screening process, domain experts are invited to rate the likelihood of appearing indexes in accident reports and literature on a Likert scale from “1” (Very unlikely) to “5” (Very likely). Indexes with an average score greater than 3 are retained and used to establish the HSEO framework. Considering the stakeholders of passenger ship emergency response, as well as the needs of scientific research, the domain experts are selected from the manager of passenger shipping companies, officer of maritime search and rescue coordination agencies, captain of passenger ships, navigational officers of cruise ship and researcher in the field of passenger ship safety, whose details are shown below. All experts have extensive working or research experience in the field, based on similar studies [52–60], it is believed that the number and authority of experts are suitable for this study.

- 1 experienced shipping company manager, more than 8 years management experience of passenger ship operation.
- 1 professor, engaged in ship safety research, with 10 years research experience, especially safety research of passenger ship.
- 1 captain of passenger ship with more than 10 years working experience in passenger ship.
- 1 maritime agency officer, responsible for maritime search and rescue coordination, with more than 10 years of working experience.
- 2 cruise officers in charge of safety affairs with 8 years working experience.

3.2. FMEA

Risk is a complex concept, in which not only the likelihood of catastrophic events but also the associated consequences must be considered [61]. FMEA is a systematic method to identify known and potential failure modes and analyse the impact of the failure on the system and the end user. It has been used as a powerful tool to evaluate the risk ranking of potential failure of products and has been widely used in the field of reliability engineering [62–66]. Although showing some attractiveness, it reveals some problems in this applications. For instance, the same value of RPN may have different risk implications, and it is difficult to obtain the precise values of the parameters (i.e., *L*, *C*, and *P*). This study therefore incorporates BBN and ER methods to extend the classical FEMA and propose a new risk assessment model for the HEPS of the whole evacuation process of a passenger ship. Therefore, FMEA is used for risk assessment in this study. FMEA is one of the most popular methods for risk assessment due to its strong pertinence, practicability and operability [56,67]. The traditional FMEA has three basic parameters: failure probability (*L*), consequence severity (*C*) and undetected failure probability (*P*) [65]. It is widely used to evaluate the risk level of each failure mode and determine its risk priority number (RPN), which is defined as Eq. (1).

$$RPN = L_i \times C_j \times P_k \tag{1}$$

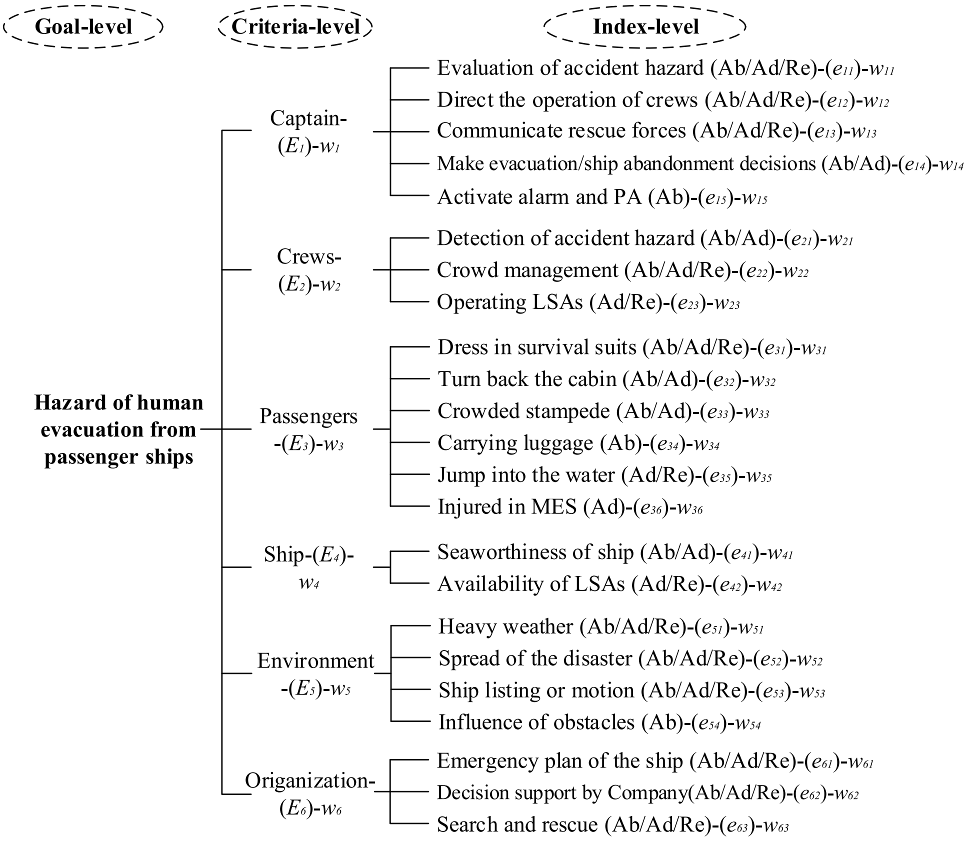

Fig. 3. The HSEO framework .3for risk assessment of HEPS.

The classical RPN approach has some serious shortcomings, such as insufficient quantification of the effectiveness of preventive actions [68]. In order to overcome these shortcomings, many new methods have been proposed, such as fuzzy logic, Bayesian network, grey theory, and Markov model [52,68,69].

Since indexes of the HSEO framework are qualitative, and expert knowledge is usually required to assist risk data input by their judgment. At this point, linguistic variables are often used for quantization. In this study, five linguistic scales $\{H_1, H_2, H_3, H_4, H_5\}$ are used to evaluate these indexes [52–54]. The linguistic terms used for each parameter (*L, C, P* and *R*) are shown in Table 3, where *R* is the risk status of indexes, which are defined in Table 5 of the Chang et al.'s [52] research. For example, Eq. (2) summarizes the five evaluation terms of parameter *R*, where R_n represents the n^{th} evaluation grade.

$$R_n = \left\{ \begin{matrix} Vevy\ low\ (R_1), & Low\ (R_2), & Average\ (R_3), \\ High\ (R_4), & Very\ high\ (R_5) & \end{matrix} \right\} \tag{2}$$

3.3. Belief rule based Bayesian networks

As an effective method to overcome the shortcomings of FMEA, Yang et al. [68] proposed a BBN method for describing the inference system between input (*L, C* and *P*) and output (*R*) variables. Due to its easiness and visibility, it has been widely used in various risk analysis and model development in the past decade. The core of the method is described as follows. The k^{th} IF-THEN rule in the traditional fuzzy rule can be shown as Eq. (3).

$$\begin{aligned} R_k:\ & IF\ \ A_1^k\ \ and\ \ A_2^k\ \ and\ \ \cdots\ \ A_M^k, \\ & Then\ \ D_k \end{aligned} \tag{3}$$

where, $A_i^k (i = 1, 2, \cdots, M)$ is the linguistic variables of the i^{th} antecedent attribute, and M is the number of antecedent attributes in the k^{th} rule. D_k represents the result of the k^{th} rule.

The result of the traditional fuzzy rule system is usually a single output. The result of the fuzzy rule base may not always reflect the slight change of linguistic variables in the antecedent attribute. In view of this, by introducing a concept of belief degree, some researchers put forward a new method of expressing knowledge for the rule base to enhance its ability to deal with uncertainty in a complex system [56,70].

On this basis, the rules in Eq. (3) can be extended to belief rules, thus associating all possible outcomes with belief degrees, which can be shown in Eq. (4).

$$\begin{aligned} R_k:\ & IF\ \ A_1^k\ \ and\ \ A_2^k\ \ and\ \ \cdots\ \ A_M^k, \\ & Then\ \ \left\{ \left(D_1, \beta_1^k\right),\ \ \left(D_2, \beta_2^k\right),\ \ \cdots,\ \ \left(D_N, \beta_N^k\right) \right\} \end{aligned} \tag{4}$$

where, β_j^k $(j = 1, 2, \cdots, N)$ is the belief distribution to which D_j is considered as the result in the k^{th} rule when the input meets the antecedent attribute $A^k = \{A_1^k, A_2^k, \cdots, A_M^k\}$. N is the number of possible outcomes.

In view of the advantages of Bayesian networks in expressing nonlinear causality, Bayesian inference can be used as a tool to synthesize the belief distribution of different rules in the evaluation process of multiple rules for a particular risk factor [56]. In order to realize the rule fusion, the rules in the belief rule base are expressed in a form of conditional probability. For example, the k^{th} rule in Eq. (4) can be paraphrased as: "under the condition that the antecedent attributes are $A_1^k, A_2^k, \cdots, A_M^k$ respectively, $(\beta_1^k, \beta_2^k, \cdots, \beta_N^k)$ are the probability of the risk state $R_n (n = 1, 2, \cdots, N)$ of this factor at different evaluation levels, respectively", as shown in Eq. (5).

Table 3
Linguistic scale for parameter L, C, P and R.

Parameter	H_1	H_2	H_3	H_4	H_5
L	Very low	Low	Average	High	Very high
C	Negligible	Marginal	Moderate	Critical	Catastrophic
P	Highly unlikely	Unlikely	Average	Likely	Highly likely
R	Very low	Low	Average	High	Very high

$$p\left(R_n \middle| A_1^k, A_2^k, \cdots, A_M^k\right) = \left(\beta_1^k, \beta_2^k, \cdots, \beta_N^k\right) \tag{5}$$

where, the symbol "|" given stands for conditional probability.

Through Bayesian network modelling, the belief rule base can be transformed into a Bayesian network graph with *M* parent nodes and one child node, and the risk reasoning process based on belief rules can be simplified to the calculation of the marginal probability of child nodes [70]. The evaluation information of risk parameters can be used as the prior probability of each parent node. On this basis, the marginal probability of child node can be obtained according to Eq. (6), that is, the risk state of risk factors.

$$p(R_n) = \sum\nolimits_{i=1}^{I} \sum\nolimits_{j=1}^{J}, \cdots, \sum\nolimits_{k=1}^{K} p\left(R_n \middle| A_i, B_j, \cdots, C_k\right) \times p(A_i) p\left(B_j\right), \cdots, p(C_k) \tag{6}$$

where, A_i, B_j, $\cdots$, $C_k$represent antecedent attributes (such as *L, C* and *P*) in the belief rule base respectively, $I, J, \cdots, K$ represent the number of linguistic variables respectively, and $p(A_i)$ represents the probability of antecedent attribute A_i taking the i^{th} linguistic variable. $p(R_n)$ is the probability for the risk state (e.g., parameter *R*) takes the n^{th} linguistic variable. Due to its inference rigor and easiness by the computer software, it has been chosen to use as a basis to develop the new HEPS framework in this paper.

3.4. Index weight based on AHP

Analytic Hierarchy Process (AHP) is proposed by operational research expert Saaty [71] in the 1980s. This method is to express and deal with people's subjective judgment in quantitative form and is often used in the decision-making of multi-plan or multi-objective. Based on the established hierarchy of influential factors, the method utilizes less quantitative information to mathematize the decision-making process, and providing an effective decision-making method for solving complex decision-making problems with multi-plan or multi-objective. As a result, due to its strong applicability, this method has been widely used in green port development assessment [58], strategic transport passages assessment [53], the site selection of offshore floating wind farm [54] and analysis of climate change response measures [59].

In this study, according to the relative importance scale, the relative importance of influential factors can be qualitative evaluated through expert judgment. Pairwise comparison (PC) can be conducted on indexes at all levels of HSEO framework, and PC matrix can be constructed accordingly. Then, the PC matrix can be transformed into a single value comparison matrix, and the weight of indexes in different levels are determined by calculating the relative weight of influential factors under a single criterion.

3.5. Evidential reasoning algorithm

More recently, due to fuzzy and incomplete data, the trend in risk research in science and industry has been shifted from the pure precise quantification of probabilities and consequences, towards the quantification of risks using both precise data and data with uncertainties and incompleteness [38,72]. In this process, the ER approach has shown its advantages in dealing with the incompleteness and uncertainties in the judgments, especially for Likert-based rating sets, and hence is used in the framework to stimulate input data fusion [52,67]. After obtaining belief in the risk status of the index-level indexes, we need to combine subjective judgements from multiple experts. Firstly, it is necessary to establish a belief function of evaluation grade and related belief degree so as to link them together [53]. Assuming that there are *J* index-level indexes $e_{ij}(j = 1, 2, \ldots, J)$ associated with the i^{th} criteria-level index E_i $(i = 1, 2, \ldots, Q)$, the index-level indexes set can be defined by Eq. (7), and the normalized weights of the index-level indexes are given by Eq. (8).

$$E_i = \{e_{i1},\ e_{i2},\ \ldots,\ e_{ij},\ \ldots,\ e_{iJ}\} \tag{7}$$

$$\omega_i = \{\omega_{i1},\ \omega_{i2},\ \ldots,\ \omega_{ij},\ \ldots,\ \omega_{iJ}\} \tag{8}$$

where, ω_i is the i^{th} weight of the criterion E_i with $0 \le \omega_i \le 1$; ω_{ij} is the weight of index-level index e_{ij} with $0 \le \omega_{ij} \le 1$ [55]. As shown in Fig. 2, ω_1 is the weight of criterion E_1 "Captain", and ω_{13} is the weight of the third index-level index e_3 "Communicate rescue forces" under E_1.

Assuming $\beta_{n,j}$ represents the belief of the index-level index e_{ij} to the evaluation grade H_n, where $\beta_{n,j} \ge 0$, $\sum_{n=1}^{N} \beta_{n,j} = 1$, and N is the number of linguistic scale. Finally, $S(e_{ij})$ is the evaluation of alternative schemes under the index-level index e_{ij}, which can be expressed by Eq. (9) [54,67,70]. When the sum of belief degrees is 1, the evaluation of the criterion $S(e_{ij})$ is complete, i.e., $\sum_{n=1}^{N} \beta_{n,j} = 1$.

$$S(e_{ij}) = \{(H_n,\ \beta_{n,j}), n = 1, 2, \ldots, N\} \tag{9}$$

$m_{n,j}$ is a basic probability mass which represents the degree to which the j^{th} index-level index e_{ij} supports the criterion E_i to be evaluated as the n^{th} grade H_n, and can be expressed as Eq. (10). For index-level indexes, Eq. (10) can be rewritten as Eq. (11).

$$m_{n,i} = \omega_i \beta_{n,i} \qquad i = 1, 2, \ldots, Q \tag{10}$$

$$m_{n,j} = \omega_{ij} \beta_{n,j} \qquad j = 1, 2, \ldots, J \tag{11}$$

where, $m_{n,i}$ is the probability mass evaluated as H_n by the criteria-level index E_i, $m_{n,j}$ is the probability mass evaluated as H_n by the index-level index e_{ij}. At the same time, $E_{I(j)}$ is defined as a subset of j index-level indexes under the i^{th} criterion, as shown in Eq. (12).

$$E_{I(j)} = \{e_{i1}, e_{i2}, \cdots, e_{ij}\} \tag{12}$$

$m_{n,I(i)}$ represents the probability mass that all the index-level indexes in $E_{I(i)}$ support the hypothesis of E_i being evaluated as a grade H_n. $m_{H,I(i)}$ is the residual probability mass that has not been assigned to each grade after all the criteria $E_{I(i)}$ are evaluated [53,54,58]. The term $m_{n,I(i)}$ and $m_{H,I(i)}$ are obtained by combining all the basic probabilistic masses m_n and $m_{H,j}$. Therefore, the ER algorithm can be represented by Eqs. (13)–(16).

$$K_{I(i+1)} = \left[1 - \sum_{t=1}^{N} \sum_{\substack{j=1 \\ j \ne t}}^{N} m_{t,I(i)} m_{j,i+1}\right]^{-1} \qquad i = 1, 2, \cdots, Q-1 \tag{13}$$

$$m_{n,I(i+1)} = K_{I(i+1)} \left(m_{n,I(i)} m_{n,i+1} + m_{n,I(i)} m_{H,i+1} + m_{H,I(i)} m_{n,i+1}\right) \tag{14}$$

$$m_{H,I(i+1)} = K_{I(i+1)} \times m_{H,I(i)} \times m_{H,i+1} \tag{15}$$

$$\beta_n = \frac{m_{n,I(L)}}{1 - m_{H,I(L)}} \tag{16}$$

where, $K_{I(i+1)}$ is the normalization factor, so as to make $\sum_{n=1}^{N} m_{H,I(i+1)} + m_{n,I(i+1)} = 1$, β_n is the combinatorial belief degree evaluated by the criterion aggregation.

It should be noted that, for all $n = 1, 2, \cdots, N$, $m_{1,I(1)} = m_{1,1}$, $m_{H,I(1)} = m_{H,1}$ [53,54,67,70,73]. This reasoning process can also be realized through the Intelligent Decision System [74].

3.6. Utility ranking

All indexes must be ranked according to their aggregation belief [55]. In order to achieve accurate ranking of risk factors, it is necessary to introduce a risk priority index (*RPI*) for risk ranking [56], as shown in Eqs. (17) and (18). It can be concluded from Eq. (18) that the higher the RPI value of risk factors is, the higher the risk degree is, and the higher the risk of evacuation accidents.

$$RPI = \sum_{n=1}^{N} \beta_n \times u(H_n) \tag{17}$$

$$u(H_n) = \frac{n-1}{N-1} \tag{18}$$

where, β_n is the belief degree to which H_n is assigned. The priority of the utility function $u(H_n)(n = 1, 2, \cdots, N)$ is linearly assigned as $u(H_1) = 0$, $u(H_2) = 0.25$, $u(H_3) = 0.5$, $u(H_4) = 0.75$ and $u(H_5) = 1$ [58].

3.7. Validation

After completing the modelling process, it is necessary to carefully test its reliability, and test the risk assessment process of HEPS [57,58]. In the current literature, there is a verification program based on axioms, which is useful for the verification process. The axiom settings are applied to conduct the sensitivity analysis in this study [42,52,56,58,68,75,76]. Within the context, three axioms are used and presented as follows:

Axiom 1: The RPI value of the indexes at the goal-level can increase/decrease with the slight increase/decrease of the grades of brief degree at the index-level.
Axiom 2: The effect of the changes of the grade of brief degree at the index-level on the index RPI value at the goal-level is proportional to the weight of the concerned indexes.
Axiom 3: The effect of the change combination (x evidence) of a grade of brief degree on the index RPI value at the goal-level should always be greater than the effect of the changes of any subset of the combination (y sub-evidence, $y \in x$) on the RPI value.

4. Case study

4.1. The definition of evaluated scenario

The ship abandonment drill is one of the most important practical training exercises on a ship, and the ship abandonment procedure is generally considered to be the main operational weakness of the crew and can lead to casualty accidents [17]. In addition to real marine accidents, ship abandonment drills are the best way to understand the process of HEPS. Therefore, the "2019 Shanghai international cruise ship large-scale emergency evacuation drill" was taken as a case to investigate and analyse the risks in the process of HEPS.

The drill was held in "Wusongkou" anchorage area of Shanghai, simulating a container ship collision with an international cruise ship (about 1500 people in distress) due to improper operation. The accident caused a fire on the container ship, and the hull of the cruise ship was damaged and seriously listed after flooding, causing injuries and falling overboard. After the incident, the captain of the cruise ship began to evaluate the hazard, communicate rescue force and evacuate passengers. The No. 4 lifeboat in port side was launched, and the MES was released. At the same time, other rescue forces were involved in the search and rescue process.

In order to effectively and accurately rate and weight the risk factors of the evacuation process, the drill plans were improved to fully reflect the entire process of HEPS, then all event data (video data and drill plans) was presented to the domain experts in Section 3.1 for evaluation.

4.2. Calculation of the risk values of index-level indexes

On the basis of the five-grade evaluation scale, risk factors at the index-level can be evaluated in different stages (such as Ab, Ad and Re) according to the judgment of experts, and each risk factor is evaluated by parameters *L, C* and *P*, namely antecedent attributes. For example, an expert might evaluate *L* of "evaluation of accident hazard" as "Very high, 3.3%; High, 30.0%; Average, 60.0%; Low, 6.7%; Very low, 0.0%", *C* as "Catastrophic, 16.7%; Critical, 60.0%; Moderate, 23.3%; Marginal, 0.0%; Negligible, 0.0%", and *P* as "Highly likely, 10.0%; Likely, 50.0%; Average, 40.0%; Unlikely, 0.0%; Highly unlikely, 0.0%". Expert knowledge is influenced by individual perspectives and goals [77]. When the group of experts shows a strong heterogeneous characteristic in terms of their age, education, experience, a utility scoring method [78] can be applied to assign different weights to them to improve the rational of their combined judgement. In this study, when synthesizing the judgments of the domain experts, their experience was taken into account as the dominant factor, and hence the same weight is given to all the experts due to all the experts due to their similar work experience, processing without losing generality. In this way, the evaluation value of risk factors at the index-level can be calculated. For example, the results of the standard E_1 in stage Ab are shown in Table 4.

According to the rules formulated by Eqs. (3) and (4), and with reference to the Tables 6 and 7 of Chang et al.'s [52] research, a belief structure for transforming experts' evaluation on specific hazards is established. Then, IF-THEN rules are used to derive the conditional probability table of risk factors at the index-level.

Eq. (6) is used to calculate the risk status of factors in each index-level. Taking index e_{15} in Table 4 as an example, its risk value can be calculated as $R(e_{15}) = (0.022, 0.244, 0.523, 0.211, 0.000)$. This reasoning process can be demonstrated by using Bayesian modelling software ***GeNIe*** 2.0, as shown in Fig. 4. Similarly, risk states of all factors in Table 4 can be calculated, as shown in Table 5.

4.3. Calculation of the weights of evaluation indexes

Through in-depth interviews with domain experts, the PC matrix of each index was obtained. AHP was used to calculate the weights of indexes in the evaluation model, and the consistency test was conducted. Similarly, given the equivalent working background of the experts, the normalized relative weights of each expert are evenly distributed when combined with their judgments. After similar processing for each stage and level, weight vectors of all PC matrices can be calculated to obtain the local weights of indexes. Table 6 shows the weight distribution of all indexes in the Ab stage.

Table 4
Distribution of the brief degree of risk parameters of E_1 in the Ab stage.

Indexes in the index-level	Parameter	Brief degree
Evaluation of accident hazard (e_{11})	*L*	(0.000, 0.067, 0.600, 0.300, 0.033)
	C	(0.000, 0.000, 0.233, 0.600, 0.167)
	P	(0.000, 0.000, 0.400, 0.500, 0.100)
Direct the operation of crew (e_{12})	*L*	(0.200, 0.700, 0.100, 0.000, 0.000)
	C	(0.000, 0.200, 0.600, 0.200, 0.000)
	P	(0.000, 0.300, 0.567, 0.133, 0.000)
Communicate rescue forces (e_{13})	*L*	(0.200, 0.533, 0.267, 0.000, 0.000)
	C	(0.000, 0.000, 0.033, 0.534, 0.433)
	P	(0.000, 0.333, 0.567, 0.100, 0.000)
Make evacuation decisions (e_{14})	*L*	(0.000, 0.200, 0.534, 0.233, 0.033)
	C	(0.000, 0.000, 0.033, 0.367, 0.600)
	P	(0.000, 0.000, 0.167, 0.600, 0.233)
Activate alarm and PA (e_{15})	*L*	(0.033, 0.267, 0.533, 0.167, 0.000)
	C	(0.033, 0.167, 0.500, 0.300, 0.000)
	P	(0.000, 0.300, 0.533, 0.167, 0.000)

4.4. Aggregate evaluation based on ER

After obtaining the risk status of the factors at the index-level and the weights between the indexes, the ER algorithm, namely Eqs. (7)–(16), is used to carry out the risk aggregation from the index-level to the criteria-level, and from the criteria-level to the goal-level. Taking the data in Table 5 as an example, the value of E_1 can be obtained as $R(E_1) = (0.0171, 0.1119, 0.3666, 0.3512, 0.1532)$, where the numerical calculation process is illustrated in Appendix A. The results can also be realized through IDS, as shown in Fig. 5. Similarly, risk states of all criteria-level indexes in stage Ab can be calculated, as shown in Table 7.

4.5. Calculation of the RPI

To compare the risk factors of the index-level, criteria-level and goal-level, the RPI is used to transform the risk state belief distribution into numerical value, so as to facilitate risk ranking. Taking E_1 in the Ab stage as an example, the utility value of risk can be calculated by using the belief data and Eqs. (17) and (18) in Table 7, as shown below.

$$RPI(E_1) = u(H_1)\beta_1 + u(H_2)\beta_2 + u(H_3)\beta_3 + u(H_4)\beta_4 + u(H_5)\beta_5$$
$$= 0 \times 0.017 + 0.25 \times 0.112 + 0.5 \times 0.367 + 0.75 \times 0.351 + 1 \times 0.153 = 0.6278.$$

In this way, the risk utility values of all index, criteria and the goal level can be obtained and ranked. The risk results of the index-level are shown in Fig. 6, the risk results of the criteria-level are shown in Fig. 7, and the risk results of the goal-level are summarized in Fig. 8. It can be seen from Fig. 6 that in the Ab stage, "Make evacuation decisions (e_{14})", "Evaluation of accident hazard (e_{11})", "Crowded stampede (e_{33})", "Spread of the disaster (e_{52})" and "Emergency plan of the ship (e_{61})" were among the top 5 risk factors. In the Ad stage, "Operating LSAs (e_{23})", "Make ship abandonment decisions (e_{14})", "Availability of LSAs (e_{42})", "Ship listing or motion (e_{53})" and "Evaluation of accident hazard (e_{11})" were among the top 5 risk factors. In the Re stage, "Availability of LSAs (e_{42})", "Communicate rescue forces (e_{13})" and "Operating LSAs (e_{23})" were among the top 3 risk factors. It can be seen from Fig. 7 that in the Ab stage, "The performance of captain (E_1)", "Organization factors (E_6)" and "The operation of crew (E_2)" were among the top 3 risk factors. In the Ad stage, "The operation of crew (E_2)", "The performance of captain (E_1)" and "Ship factors (E_4)" were among the top 3 risk factors. In the Re stage, "Ship factors (E_4)", "The operation of crew (E_2)" and "Organization factors (E_6)" were among the top 3 risk factors. It can be seen from Fig. 8 that in the goal-level, the risk of Ad is the largest, followed by the Ab and Re stages.

4.6. Validation

The three axioms described in Section 3.7 are used to verify the robustness of established model applied to the risk assessment process. Furthermore, in order to avoid the possible bias or uncertainty caused by the subjective judgment of experts, statistical analysis of marine accident investigation reports is adopted to compare the results of model analysis, so as to verify the robustness of the established model.

Axiom 1: Reassign a brief degree of 0.1 to each index at the index-level and move in the direction of the maximum increase in the RPI value at the goal-level. If the model is rational, the RPI value should increase accordingly. In the case of the Ab stage, if the brief degree of "e11" belongs to "Very High" increases by 0.1, accordingly, the brief degree of "Low" and "Average" needs to decrease by 0.1 (0.023 and 0.077, respectively), and the RPI value increases from

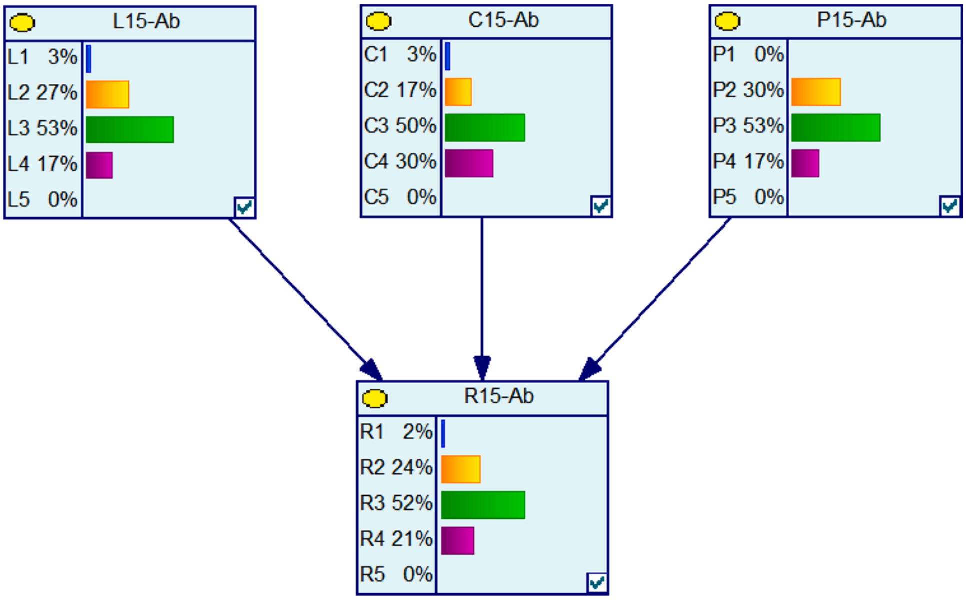

Fig. 4. The aggregated evaluation result of E_1 in the Ab stage.

Table 5
Distribution of the brief degree of risk values of E_1 in the Ab stage.

Indexes in the index-level	R_1	R_2	R_3	R_4	R_5
Evaluation of accident hazard (e_{11})	0.000	0.023	0.411	0.467	0.099
Direct the operation of crew (e_{12})	0.067	0.401	0.422	0.110	0.000
Communicate rescue forces (e_{13})	0.068	0.291	0.289	0.210	0.143
Make evacuation decisions (e_{14})	0.000	0.005	0.271	0.436	0.287
Activate alarm and PA (e_{15})	0.022	0.244	0.523	0.211	0.000

Table 6
Weights of each index in the Ab stage.

Criteria-level	Weight	Index-level	Weight
Captain (E_1)	0.352	Evaluation of accident hazard (e_{11})	0.198
		Direct the operation of crew (e_{12})	0.080
		Communicate rescue forces (e_{13})	0.204
		Make evacuation decisions (e_{14})	0.405
		Activate alarm and PA (e_{15})	0.203
Crew (E_2)	0.175	Detection of accident hazard (e_{21})	0.500
		Crowd management (e_{22})	0.500
Passengers (E_3)	0.067	Dress in survival suits (e_{31})	0.580
		Turn back the cabin (e_{32})	0.070
		Crowded stampede (e_{33})	0.239
		Carrying luggage (e_{34})	0.111
Ship (E_4)	0.219	Seaworthiness of ship (e_{41})	1.000
Environment (E_5)	0.066	Heavy weather (e_{51})	0.459
		Spread of the disaster (e_{52})	0.325
		Ship listing or motion (e_{53})	0.149
		Influence of obstacles (e_{54})	0.067
Origanization (E_6)	0.121	Emergency plan of the ship (e_{61})	0.750
		Decision support from company (e_{62})	0.250

0.6055 to 0.6095. Similar analysis are repeated for the other indexes at the index-level, as well as for all the indexes of the Ad and Re stages. The obtained results are consistent with Axiom 1 in Section 3.7, as shown in Appendix B.

Axiom 2: The brief degree of 0.1 is reassigned to each index at the index-level and moved towards the direction of the maximum increment of the RPI value at the goal-level with a step of 0.02. The selection of 0.02 as a step is referred to Wan et al. [56,57]. The RPI value is calculated respectively, and the result is shown in Fig. 9. It can be seen from Fig. 9 that there is a significant difference in the influence level of brief degree changes of indexes at the index-level on the RPI value, and the influence level is consistently related to the weight distribution of indexes at the index-level in Table 6. This is harmony with Axiom 2 described in Section 3.7.

Axiom 3: To test the influence of index change combination on the RPI value, taking the "E5" in the Ab stage as an example, 15 possible combinations $(C_4^1 + C_4^2 + C_4^3 + C_4^4)$ of the four indexes are divided into four categories. The number of indexes with reassigned brief degree is set as 1, 2, 3 and 4, respectively, i.e., four kinds of change combinations, the change of the first kind of brief degree only deals with a single index, the second with two indexes of brief degree changes, the third with three indexes, and the fourth with all brief degree changes of the four indexes. Wherein this process, #0 is set as the baseline benchmark referring to the case of no brief degree change. For each index, the brief degree of 0.1 is reassigned among different grades in the way that the RPI value increases towards maximum. The corresponding RPI value change results are shown in Table 8, and the four kinds of change combinations are distinguished by different colors.

By comparing the data in Table 8, the relationship between the effect degrees of different change combinations on the RPI value can be witnessed. Taking combination #11 as an example, the change of the RPI value corresponding to this combination is 0.0037 (0.6092-0.6055), and the subsets of this combination are #1, #2, #3, #5, #6 and #8, respectively. Their corresponding changes of the RPI value are 0.0021, 0.0011, 0.0003, 0.0031, 0.0024 and 0.0017, respectively. It is evident that all such values are less than 0.0037, meaning the model strictly follows Axiom 3. Repeatedly, similar comparison and analysis are conducted to test the other indexes and their combinations at the index-level, and the results are all proven to be consistent with Axiom 3, revealing that the established model is tested robust through the sensitivity analysis.

After completing the validation according to the axioms, in order to avoid the possible bias or uncertainties brought about by the subjective judgment from experts, based on 20 marine accident investigation reports, the frequencies of risk factors in these marine accidents of HEPS that resulted in deaths (including passenger evacuation drill accidents) were counted. Taking the top 5 risk factors in the Ad ship stage as example, the results of the proposed evaluation model are compared with the results of statistical analysis (normalized proportion), as shown in Fig. 10. While the results from two sources showing the consistency

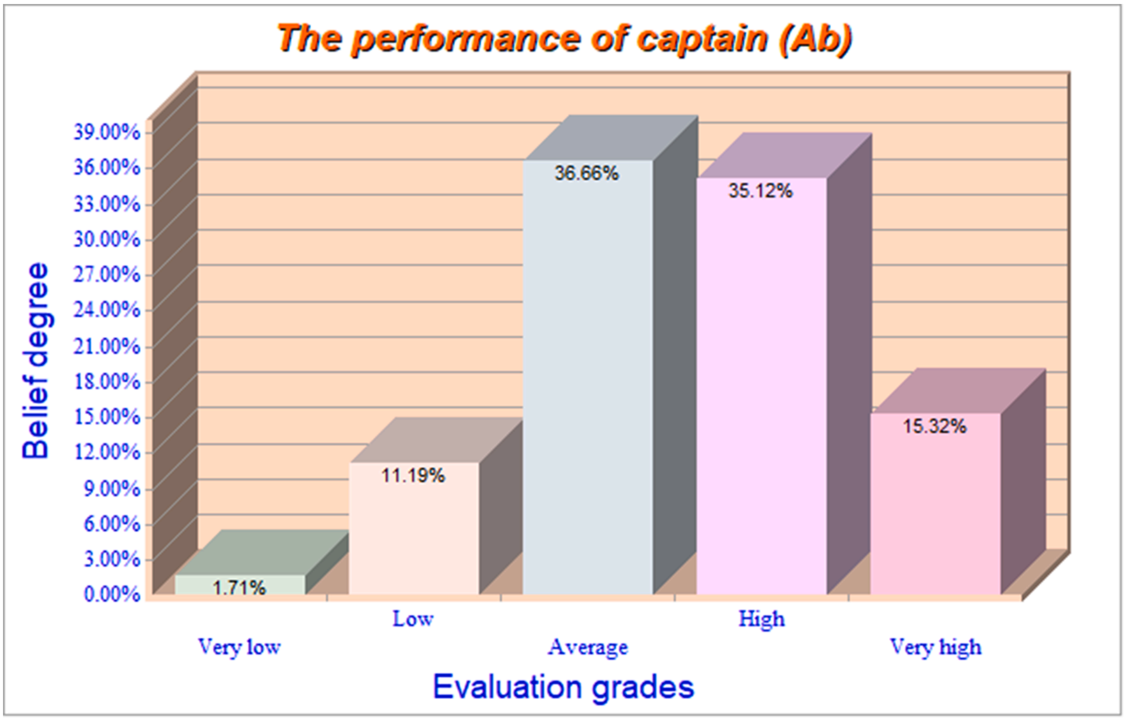

Fig. 5. The index RPI values in index-level in different stages.

Table 7
The aggregated evaluation result of criteria-level in the Ab stage.

Hazard category	R_1	R_2	R_3	R_4	R_5
The performance of captain (E_1)	0.017	0.112	0.367	0.351	0.153
The operation of crew (E_2)	0.000	0.128	0.439	0.370	0.063
Behaviours of passenger (E_3)	0.012	0.156	0.396	0.364	0.073
Ship factors (E_4)	0.158	0.223	0.244	0.254	0.121
Environmental factors (E_5)	0.000	0.117	0.480	0.326	0.077
Organization factors (E_6)	0.000	0.164	0.428	0.294	0.114

aid the validation of the input subjective data and the model, they also reveal the superiority of the proposed model over the basic statistical analysis in a sense that it can disclose much more in-depth risk information (such as those relating to the different risk factors) than the statistical means.

The results of Fig. 10 show that the evaluation results of this model are consistent with the statistical analysis, i.e., the rank of risk factors is the same, which proves the feasibility of the proposed model. Although the ranking or frequency of risk factors can be obtained from marine accident investigation reports, the model proposed in this study can provide quantitative data analysis and has advantages in dealing with uncertain data and providing performance benchmarking tools.

4.7. Discussion and implications

The results of this study show that in the process of HEPS, “make evacuation decisions”, “evaluation of accident hazard”, “operating LSAs” and “availability of LSAs” are the main risk factors affecting the safety of HEPS. Abandoning ship is a most important and difficult decision a captain needs to make [17]. Accurately assessing the risk of an accident and making timely decisions to assemble and abandon ship when the risk is not manageable can buy a lot of time for the safe evacuation of personnel. The developed HEPS framework and the supporting approaches can deliver a realistic solution to addressing this demand thanks to the development of the associated software packages such as Intelligent Decision System. For example, in the Ro-Pax "Sorrento" fire accident in 2015, when the fire spread faster, the captain resolutely ordered the timely gathering of passengers and abandoning the ship. Therefore, only four people were injured and no body died in this accident [23]. On the contrary, in the case of the "Sewol" accident in 2014, possibly due to the captain’s insufficient analysis of the accident situation, passengers were required to wait in the cabin and the captain issued the order to abandon ship half an hour after the incident occurred, which delayed the evacuation time and resulted in a large number of deaths [14]. The reason for this, from a certain point of view, is that decision makers may believe that the ocean environment is so bad that staying in the ship and waiting for rescue is the best option for survival [10]. However, in the case that the ship can withstand the maximum degree of disaster, when to evacuate and when to abandon the ship become a problem that the captain have to solve. It can be seen that evacuation decision based on accident risk assessment has an important impact on passenger ship evacuation, and this is different from existing HEPS academic research, which focuses more on evacuation analysis in passenger ship design stage and evacuation route optimization in passenger ship operation stage. In view of this, it is suggested that future research on HEPS should carry out multi-scene evacuation simulation and data statistical analysis to establish a multi-attribute decision support system for HEPS from the perspective of navigation practice, evaluate the evacuation safety of passenger ships after accidents, weigh and evaluate the influential factors of different situations, and provide the most appropriate evacuation decision for the captain and decision makers of the maritime agency.

LSAs are important parts of safety on board, and it is very important to carry out regular maintenance of LSAs on board. According to the 2017 Tokyo Memorandum of Understanding (MOU) report, LSAs remain one of the top three deficiencies found in ships [2]. It is the crew’s responsibility as well as the manager’s responsibility to ensure that all LSAs on board are maintained and in good condition. Unfortunately, issues of LSAs’ unavailability continue to arise. For example, in the "Caribbean Fantasy" and "Sorrento" accidents, the lifeboat suffered engine failure, but fortunately rescue force was on hand to help overcome the problem [18]. At the same time, there is a high risk of launching lifeboats because adequate practical training is not provided on board or

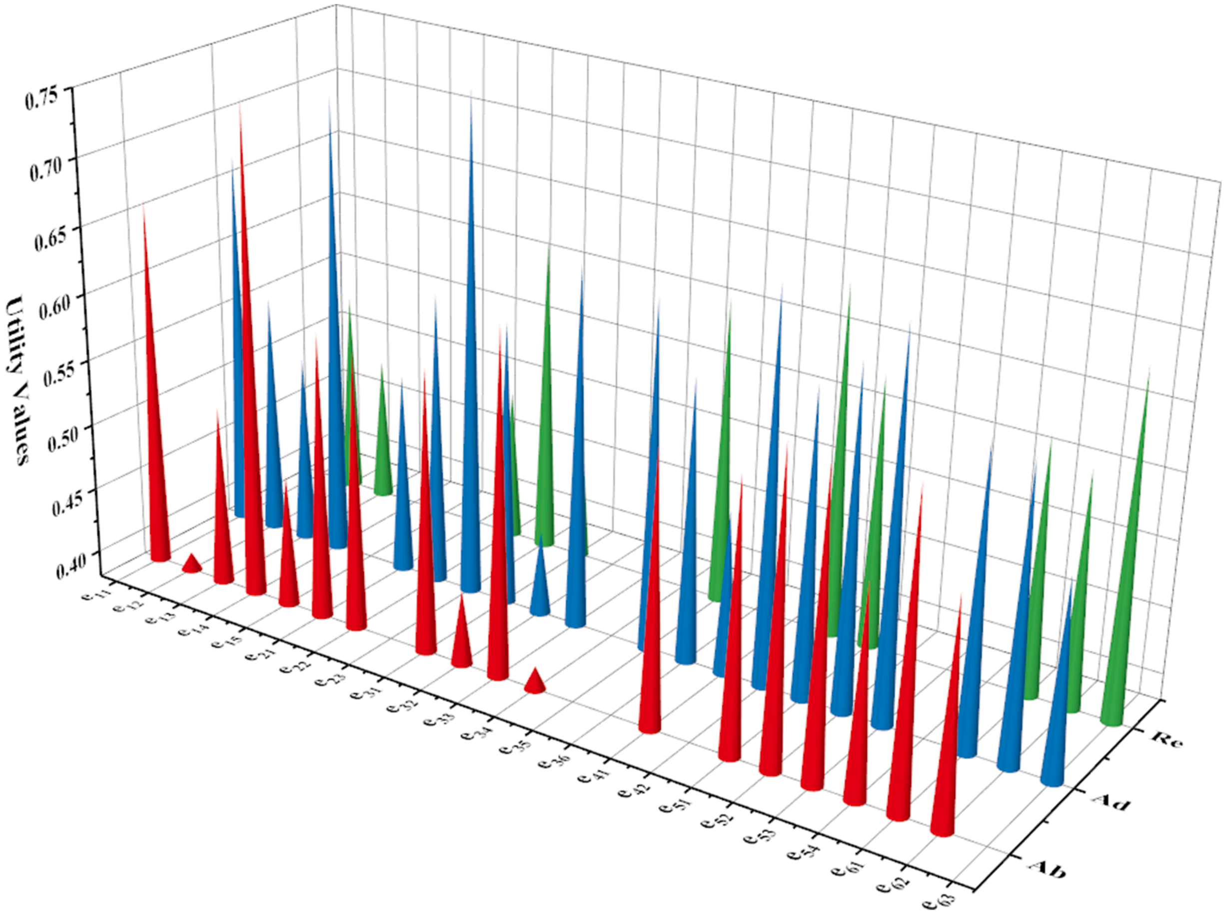

Fig. 6. The index RPI values in criteria-level in different stages.

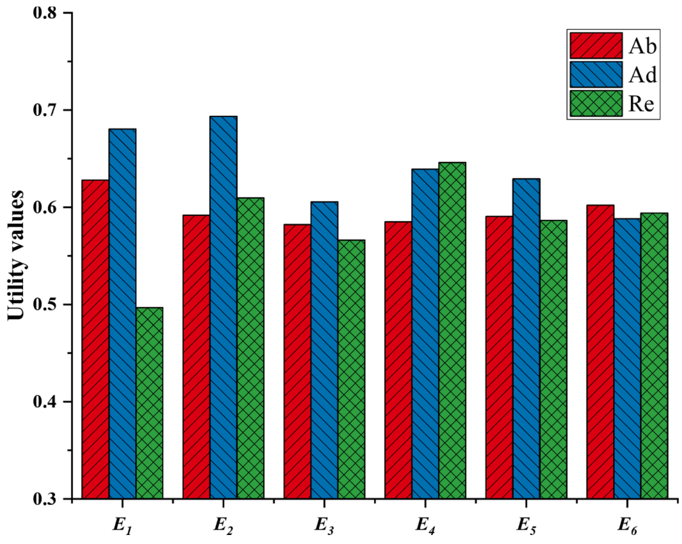

Fig. 7. The index RPI values in goal-level.

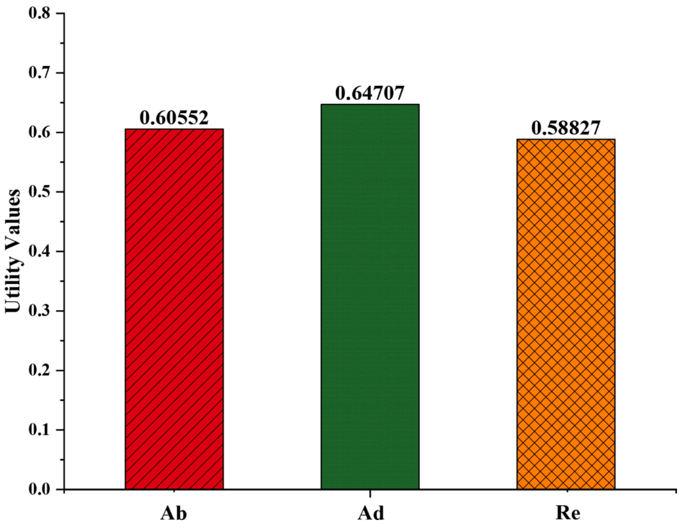

Fig. 8. The sensitivity analysis of the RPI values at the index-level in Ab stage.

on shore. For example, in the "Caribbean Fantasy" accident in 2016, No. 1 lifeboat was launched into water, but the crew of the lifeboat could not release the hook for a period of time. In 2015, when the "Pride of America" was performing an abandonment drill in the port, the wire was accidentally free to release due to operational problems, causing the lifeboat to fall to the water surface and seriously injuring two crew members [23]. All these analyses highlight that the availability of LSAs and crew's proficiency in operating LSAs are important factors affecting the safety of HEPS. Therefore, from the perspective of passenger ship emergency response practice, it is recommended that stakeholders pay more attention to LSAs, enhance maintenance of LSAs, the crew operations and emergency drills to make the deployment of LSAs a safe process.

This study is helpful to improve the safety level of passenger ships, and the above presented contributions can be appliable to all the

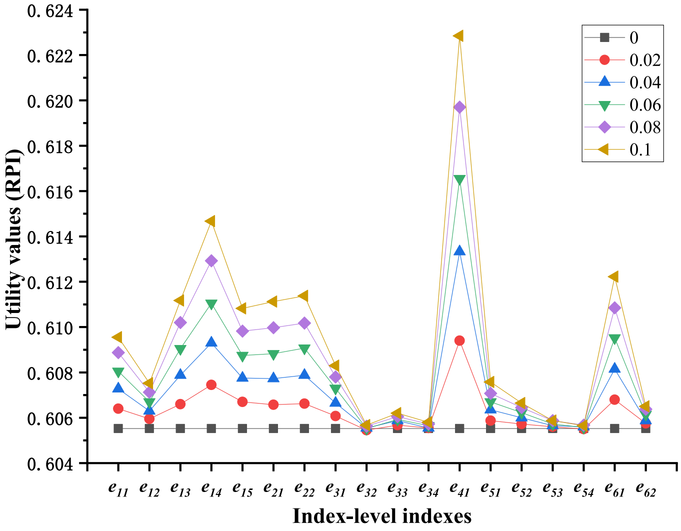

Fig. 9. The comparison of risk ranking at the index-level in the Ad stage.

Table 8
The variation sensitivity analysis of the RPI values of E_5 in Ab stage.

Row number	Heavy weather (e_{51})	Spread of the disaster (e_{52})	Ship listing or motion (e_{53})	Influence of obstacles (e_{54})	Utility values (RPI)
#0	0	0	0	0	0.6055
#1	1	0	0	0	0.6076
#2	0	1	0	0	0.6067
#3	0	0	1	0	0.6059
#4	0	0	0	1	0.6057
#5	1	1	0	0	0.6087
#6	1	0	1	0	0.6079
#7	1	0	0	1	0.6077
#8	0	1	1	0	0.6072
#9	0	1	0	1	0.6069
#10	0	0	1	1	0.6060
#11	1	1	1	0	0.6092
#12	1	1	0	1	0.6089
#13	1	0	1	1	0.6081
#14	0	1	1	1	0.6073
#15	1	1	1	1	0.6092

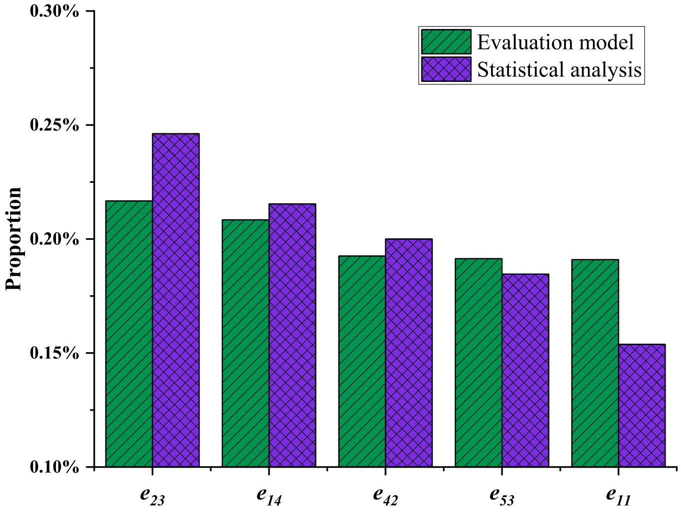

Fig. 10. The comparison of risk ranking at the index-level in the Ad stage.

stakeholder groups including the captain, shipping company and the maritime transport authorities. Its significance are as follows. In the theoretical level, this study is the first one to study the reliability issues of the HEPS process from a perspective of the holistic passenger ship evacuation system, and innovatively apply the knowledge framework of risk assessment to the HEPS process, establish a new advanced risk assessment framework for HEPS, in which one can identify the risk factors in the evacuation process, and conduct a quantitative risk assessment for rational evacuation decision. This study also reveals the gap between existing HEPS academic research and passenger ship emergency response practice, and points out that future HEPS research should consider HEPS vulnerability, service area and rescue force deployment factors, focusing on the establishment of passenger ship emergency evacuation decision support system based on multi-attribute support. From a practical perspective, the ranking of risk utility value can help stakeholders understand the risks of different evacuation stages, groups or events, help managers to formulate management strategies, optimize emergency plans, and improve the safety level of passenger ships. This study also reveals that in the assembly stage, the passenger ship managers should pay more attention to the decision-making of emergency response of passenger ships and provide decision support services for captains as much as possible. The ship manufactures need to pay more attention to the seaworthiness of passenger ships, especially the reliability of LSAs. In the daily operation of the ship, the management company and the captain should sufficiently carry out the emergency drill and training of crew, especially in the abandonment stage, with a focus on the release operation of the lifeboat. The maritime authority, who needs to lead the task of SAR coordination at the scene of the passenger ship accident, shall coordinate as many rescue forces as possible. In the case of the further spread of the accident, it needs to take a prudent way to organize the passengers to get away from the ship as soon as possible after coordination with the captain. The maritime investigation officers should also well consider passenger statements in their post-accident investigations to present a more comprehensive view of the accident investigation report.

5. Conclusion

This paper proposes a new assessment method to identify hazards, quantify and rank the associated risks in the process of HEPS. Based on extensive literature review and analysis of marine accident investigation reports, the new HSEO framework for the risk analysis of HEPS was used to determine the risk index system in the evacuation process. A risk assessment model using FMEA, AHP, BBN and ER is proposed to quantitatively rank the risks of HEPS. The validity of the model is demonstrated by a real case study, and the results of axiom-based verification analysis and accident report statistics show that the risk assessment model proposed in this study is robust and applicable.

Based on the risk assessment results obtained in this study, emergency response measures for HEPS is proposed, and it is suggested that shipping companies develop a passenger ship evacuation decision support system to provide technical support for the captain's decision. It is suggested that passenger ships strengthen the maintenance of LSAs to ensure its availability. It is recommended that shipping companies and passenger ships carry out emergency evacuation planning and drills to improve crew's proficiency in operating LSAs. This study also puts forward the HEPS research trend on evacuation decision support, and the risk assessment model for HEPS which can help researchers elicit the research directions and stakeholders understand the risk factors in the process of HEPS to develop reasonable risk control measures.

In future, the existence of any interaction between the risk influential factors can be investigated with more accident reports are collected. Further, Bayesian parameter learning can be used to study the coupling effect between different influential factors.

CRediT authorship contribution statement

Xinjian Wang: Writing – review & editing, Writing – original draft, Validation, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Guoqing Xia:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Jian Zhao:** Writing – review & editing, Validation, Methodology, Investigation, Formal analysis. **Jin Wang:** Writing – review & editing, Validation, Supervision, Methodology. **Zaili Yang:** Writing – review & editing, Validation, Supervision, Methodology. **Sean Loughney:** Writing – review & editing, Validation, Methodology. **Siming Fang:** Writing – review & editing, Writing – original draft, Investigation. **Shukai Zhang:** Writing – review & editing, Supervision, Data curation. **Yongheng Xing:** Writing – review & editing, Validation, Data curation. **Zhengjiang Liu:** Writing – review & editing, Validation, Supervision, Formal analysis.

Declaration of Competing Interest

We can confirm that there is no conflict of interest in publishing this submitted manuscript.

Data availability

Data will be made available on request.

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Appendix A. Illustration of the ER algorithm

The belief distribution of e_1 and e_2 is obtained from Table 5.

$$\beta_{1,1} = 0,\ \beta_{2,1} = 0.023,\ \beta_{3,1} = 0.411,\ \beta_{4,1} = 0.467,\ \beta_{5,1} = 0.099$$

$$\beta_{1,2} = 0.067,\ \beta_{2,2} = 0.401,\ \beta_{3,2} = 0.422,\ \beta_{4,2} = 0.110,\ \beta_{5,2} = 0$$

The weight values calculated from Table 6 and the basic probability mass can be determined by Eq. (11).

$$m_{1,1} = 0,\ m_{2,1} = 0.0045,\ m_{3,1} = 0.0814,\ m_{4,1} = 0.0924,\ m_{5,1} = 0.0197,\ \sum_{n=1}^{N} m_{n,1} = 0.1980,\ m_{H,1} = 0.8020$$

$$m_{1,2} = 0.0054,\ m_{2,2} = 0.0320,\ m_{3,2} = 0.0338,\ m_{4,2} = 0.0088,\ m_{5,2} = 0,\ \sum_{n=2}^{N} m_{n,2} = 0.0800,\ m_{H,2} = 0.9200$$

The combinatorial probability mass and the normalized factor K can now be calculated using Eqs. (13)–(15).

$$\sum\nolimits_{\substack{t=1 \\ j\neq t}}^{5} m_{t,I(1)} m_{j,2} = 0 + 0 + 0 + 0 = 0$$

$$\sum\nolimits_{\substack{t=2 \\ j\neq t}}^{5} m_{t,I(1)} m_{j,2} = 0 + 0.0002 + 0 + 0 = 0.0002$$

$$\sum\nolimits_{\substack{t=3 \\ j\neq t}}^{5} m_{t,I(1)} m_{j,2} = 0.0004 + 0.0005 + 0.0011 + 0.0043 = 0.0063$$

$$\sum\nolimits_{\substack{t=4 \\ j\neq t}}^{5} m_{t,I(1)} m_{j,2} = 0.0005 + 0.0030 + 0.0031 + 0 = 0.0066$$

$$\sum\nolimits_{\substack{t=5 \\ j\neq t}}^{5} m_{t,I(1)} m_{j,2} = 0.0001 + 0.0006 + 0.0007 + 0.0002 = 0.0016$$

$$K_{I(2)} = [1 - (0.0002 + 0.0063 + 0.0066 + 0.0016)]^{-1} = 1.0149$$

Given that the value of $K_{I(2)}$ is determined, the basic probability mass can be determined by using Eqs. (14) and (15).

$$m_{1,I(2)} = 1.0149 \times (0 \times 0.0054 + 0 \times 0.9200 + 0.8020 \times 0.0054) = 0.0044$$

$$m_{2,I(2)} = 1.0149 \times (0.0045 \times 0.0320 + 0.0045 \times 0.9200 + 0.8020 \times 0.0320) = 0.0304$$

$$m_{3,I(2)} = 1.0149 \times (0.0814 \times 0.0338 + 0.0814 \times 0.9200 + 0.0820 \times 0.0338) = 0.1063$$

$$m_{4,I(2)} = 1.0149 \times (0.0924 \times 0.0088 + 0.0924 \times 0.9200 + 0.0820 \times 0.0088) = 0.0943$$

$$m_{5,I(2)} = 1.0149 \times (0.0197 \times 0 + 0.0197 \times 0.9200 + 0.8020 \times 0) = 0.0184$$

$$m_{H,I(2)} = 1.0149 \times 0.8020 \times 0.9200 = 0.7488.$$

The two indexes in the index-level, e_1 and e_2, have been aggregated, and the combined belief of this aggregation can be determined. These belief values are calculated by Eq. (16).

$$\beta_1 = 0.0044/(1 - 0.7488) = 0.0174$$

$$\beta_2 = 0.0304/(1-0.7488) = 0.1210$$

$$\beta_3 = 0.1063/(1-0.7488) = 0.4233$$

$$\beta_4 = 0.0943/(1-0.7488) = 0.3754$$

$$\beta_5 = 0.0184/(1-0.7488) = 0.0731$$

$$\sum_{n=1}^{5}\beta_n = 1, \quad \beta_H = 0$$

If $\sum_{n=1}^{L}\beta_n \neq 1$, β_H is the residual of the belief calculated.

The calculation process outlined represents the aggregation of two indexes in index-level. Given the indexes under the criteria-level *Captain* (E_1), the above results can be combined with the third index, and then aggregated with other indexes one by one. After fully aggregating the indexes $e_{11}, e_{12}, e_{13}, e_{14}, e_{15}$, the overall evaluation of the criteria-level *Captain* (E_1) in the Ab stage can be obtained.

$$S(E_1) = S(e_{11} \otimes e_{12} \otimes e_{13} \otimes e_{14} \otimes e_{15})$$
$$= \{(Very\ low,\ \ 0.017);\ \ (Low,\ \ 0.112);\ \ (Average,\ \ 0.367);\ \ (High,\ \ 0.351);\ \ (Very\ high,\ \ 0.153)\}$$

It should be noted that if the indexes were aggregated in a different order, the results would not change. This calculation process applies to the Ad stage and Re stage, including all the indexes of the criteria-level and the index-level.

Appendix B. Sensitivity analysis of the RPI values at the index-level in Ab stage given the variation in [0.00, 0.10]

Indexes at the index-level	0.00	0.10
Evaluation of accident hazard (e_{11})	0.6055	0.6096
Direct the operation of crew (e_{12})	0.6055	0.6075
Communicate rescue forces (e_{13})	0.6055	0.6112
Make evacuation decisions (e_{14})	0.6055	0.6147
Activate alarm and PA (e_{15})	0.6055	0.6108
Detection of accident hazard (e_{21})	0.6055	0.6111
Crowd management (e_{22})	0.6055	0.6114
Dress in survival suits (e_{31})	0.6055	0.6083
Turn back the cabin (e_{32})	0.6055	0.6057
Crowded stampede (e_{33})	0.6055	0.6062
Carrying luggage (e_{34})	0.6055	0.6058
Seaworthiness of ship (e_{41})	0.6055	0.6229
Heavy weather (e_{51})	0.6055	0.6076
Spread of the disaster (e_{52})	0.6055	0.6067
Ship listing or motion (e_{53})	0.6055	0.6059
Influence of obstacles (e_{54})	0.6055	0.6057
Emergency plan of the ship (e_{61})	0.6055	0.6122
Decision support from company (e_{62})	0.6055	0.6065

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